IPM

Collider Phenomenology @ Top Sector

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August 2016,
5th School on LHC Physics, Pakistan

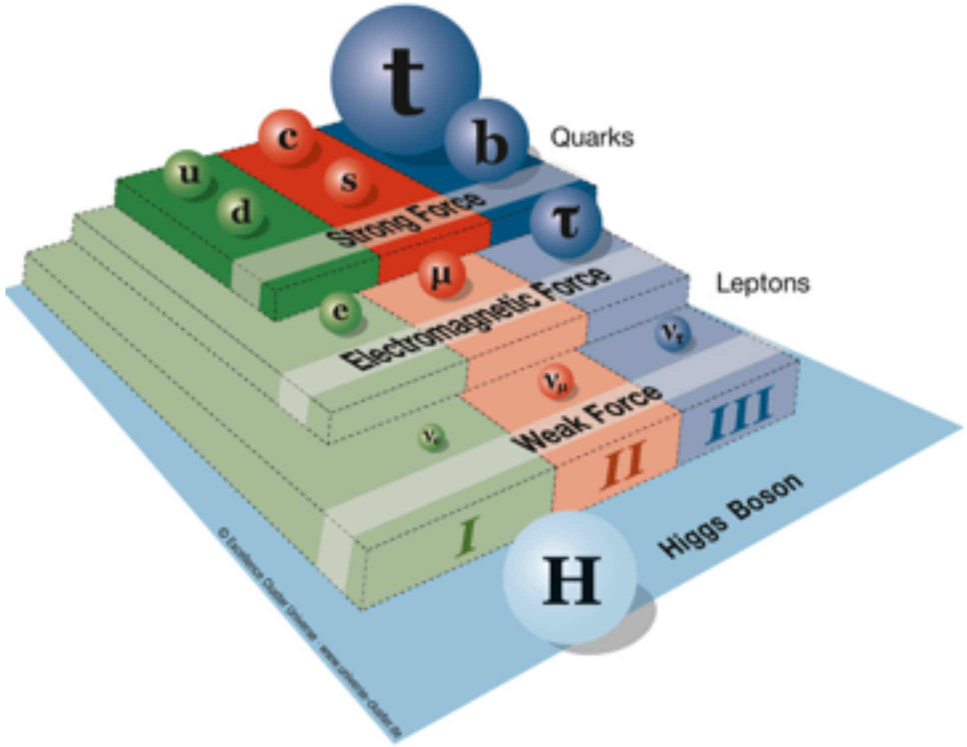
Motivations: SM and Higgs @ LHC Run I

- *Colliders have an important role to extend our knowledge about particles and their interactions.*

- *All measurements in different colliders are in good agreement with SM predictions so far.*

- *Finally, the last piece of SM puzzle was discovered at LHC Run I.*

- *SM has been confirmed to be a complete and successful framework to describe physics at energy scale around TeV.*



Motivations:
BSM @ LHC Run II

- *Experimental Observations:*
  - *Baryon Asymmetry in the Universe*
  - *Massive Neutrinos*
  - *Dark Matter*
  - *Dark Energy*

- *Theoretical Problem:*
  - *Gravity is not included*
  - *Hierarchy Problem*
  - *…*

Something New must appear in TeV Scale

History of Top quark

- 1973
Kobayashi/Maskawa:
Need for three quark generations
to incorporate CP violation into SM

- 1977
Discovery of bottom quark
[mb ≈ 4.5 GeV]

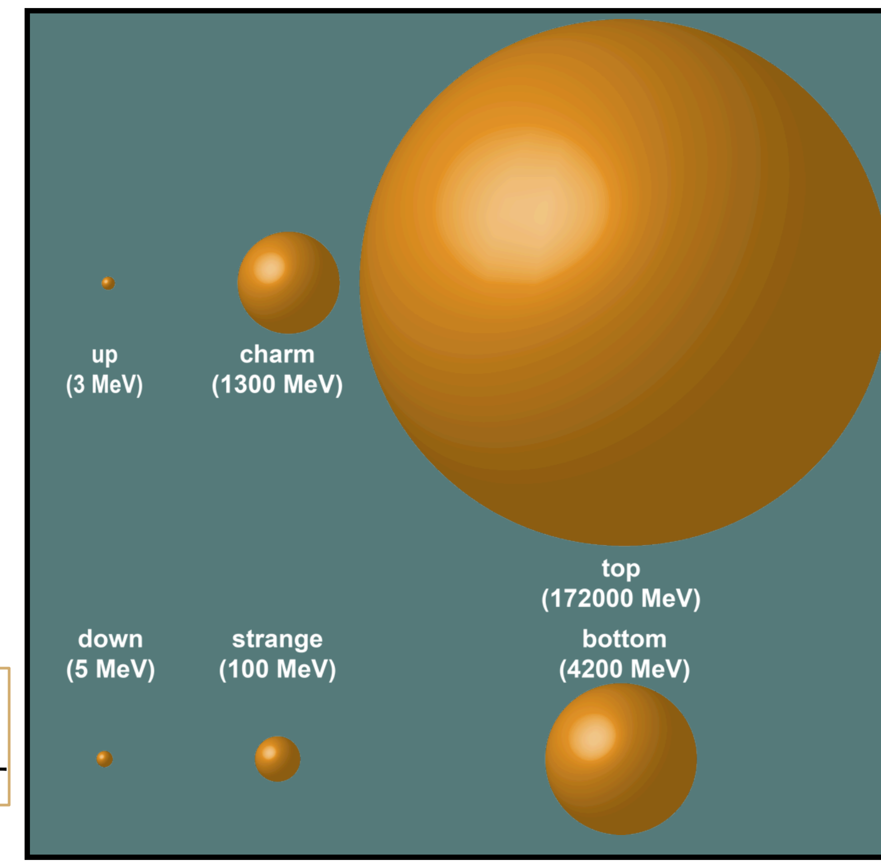
- 1980ies
Search for light top (mt < mW–mb)
in decays W → tb

- 1992
Tevatron Run I:
First indications for heavy top
quark decay t → Wb

- 1995
Official discovery, mt ≈ 175 GeV
[CDF and DØ @ Tevatron]
Top Quark Mass
SM fit vs. direct measurement
History of top searches

Motivation: Top physics @ Higgs Era

- *Due to its large mass, top quark is maximally coupled to the Higgs boson so studying top-Higgs interactions is highly motivated.*



$$m_{top} = y_t v/\sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$

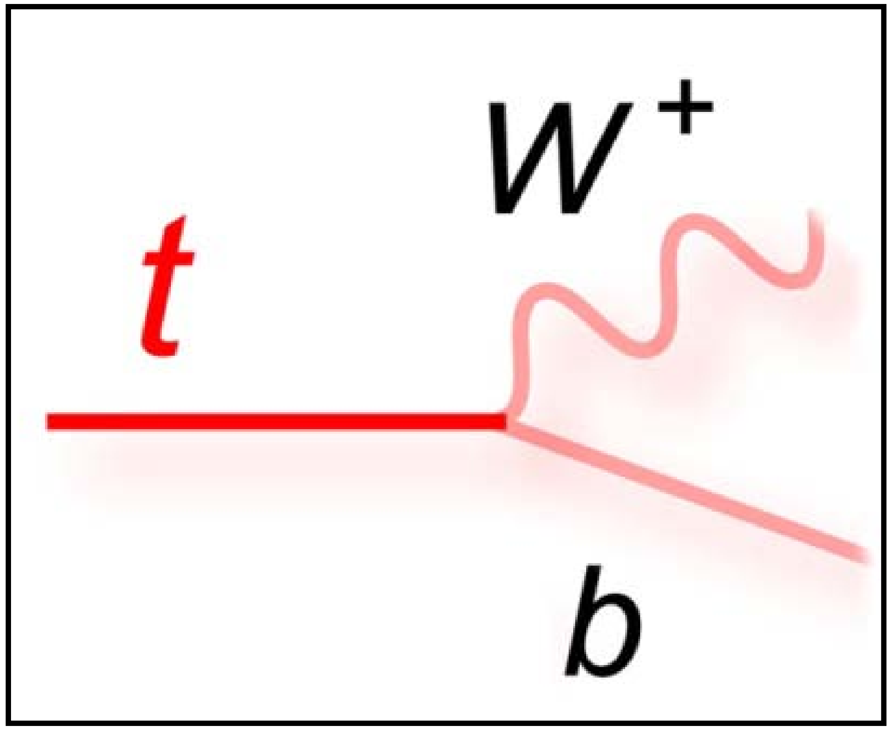
- *Special role in EWSB?*

$m_{top}/m_{up} \sim 100{,}000$

Motivation:
Top quark as bare quark

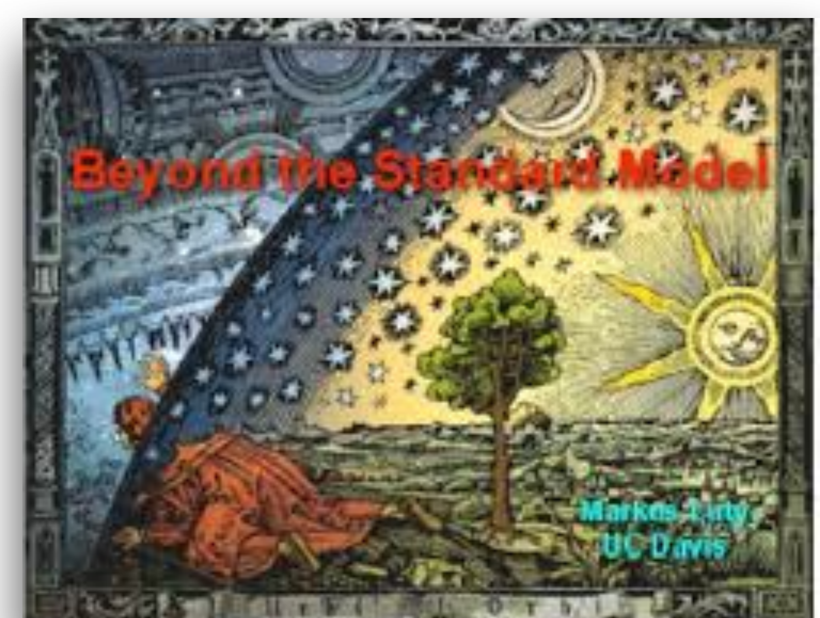
- *Top quark is short lived! (Decays almost exclusively to W b)*
- *Lifetime < hadronization*

$$\Lambda_{QCD}^{-1} \sim (100\ \mathrm{MeV})^{-1} \sim 10^{-23}\mathrm{s}$$
$$\Gamma_t^{NLO} = 1.42\ \mathrm{GeV}$$
$$\tau_t \sim 10^{-25}\ \mathrm{s} \ll 10^{-23}\ \mathrm{s}$$



Motivation: Other Top quark features

- *There is a strong motivation for precise measurements of the top quark properties (couplings and mass).*
- *Flavor studies in the top quark sector is very important due to new physics effects.*
- *Top is a background to many other searches.*
- *Still one of our best gateways to BSM physics at the weak scale....*



Top Physics @ Colliders

Outline

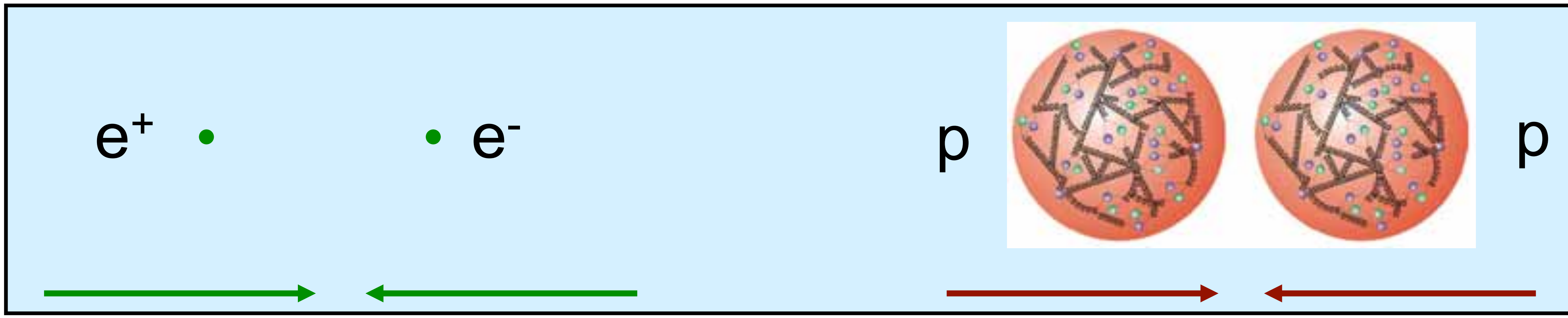
- *Collider Phenomenology*
- *Effective Lagrangian Approach*
- *Top Flavor Changing Neutral Current Processes*
- *CP-Violating in Top-Higgs Coupling*
- *Top Asymmetries*

Collider Phenomenology

Colliders

Lepton Collider

Hadron collider



collisions of point-like particles

- Clean environment

collisions of composite particles

- Can access higher energies

Electron-positron collisions and proton-proton collisions at high energy provide powerful and complementary tools to explore TeV-scale physics

Hadron Colliders

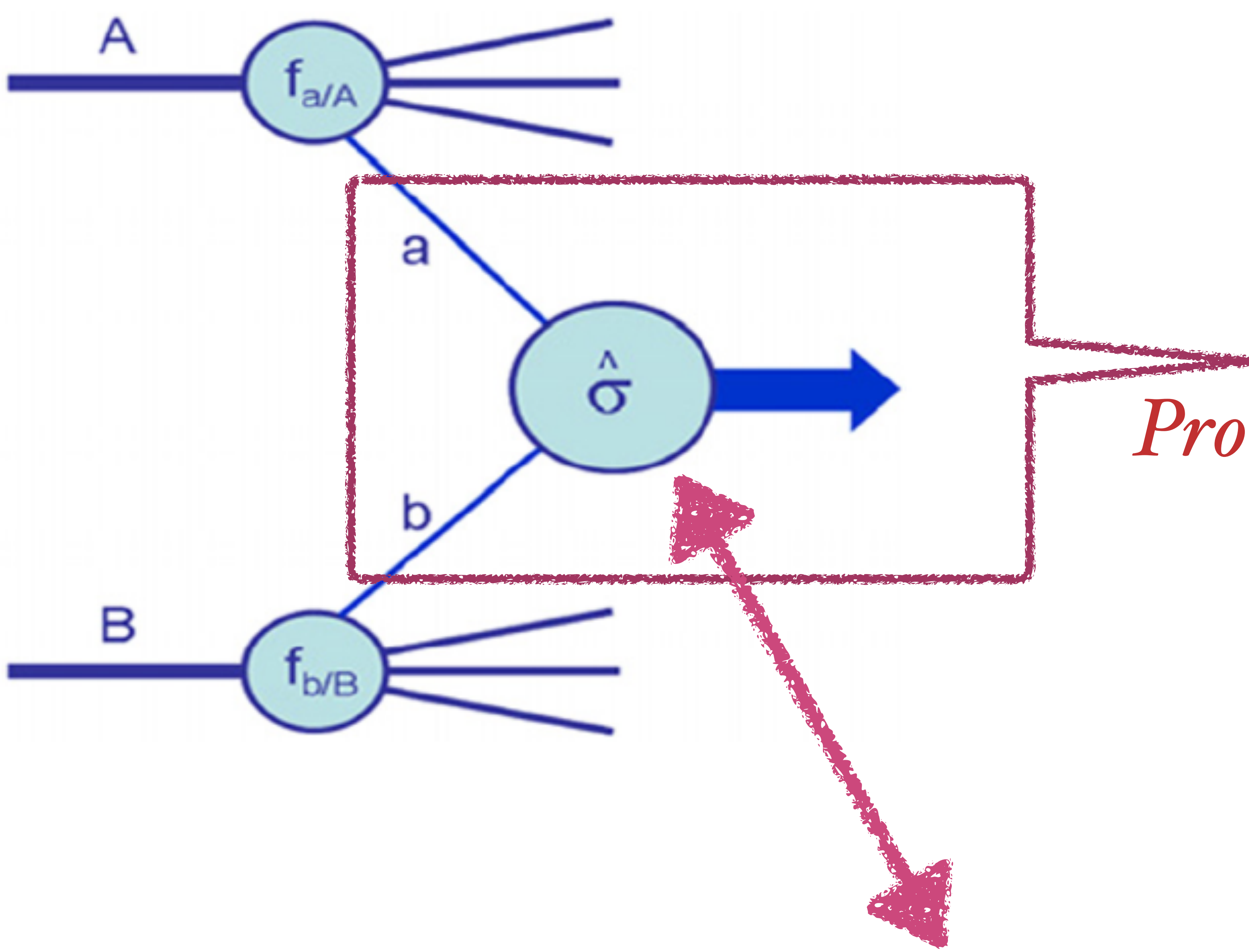
TeVatron:

- **P-Pbar collider @ 1.96 TeV**
- *Detectors : CDF and D0*
- *Shut down in 2011*

LHC:

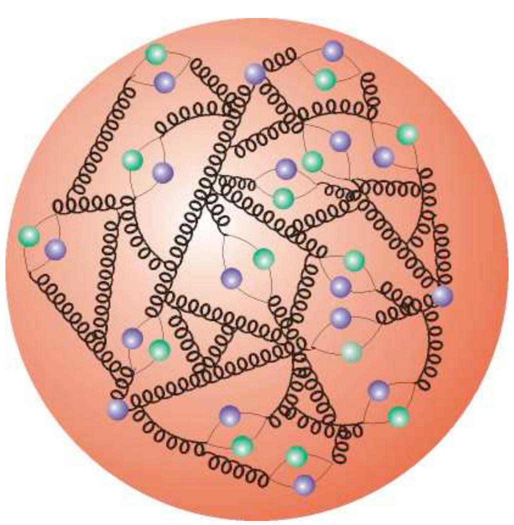
- **P-P collider @ 7,8,13 TeV**
- *Detectors : ATLAS and CMS*

Hard Scattering Process @ the Hadron Colliders

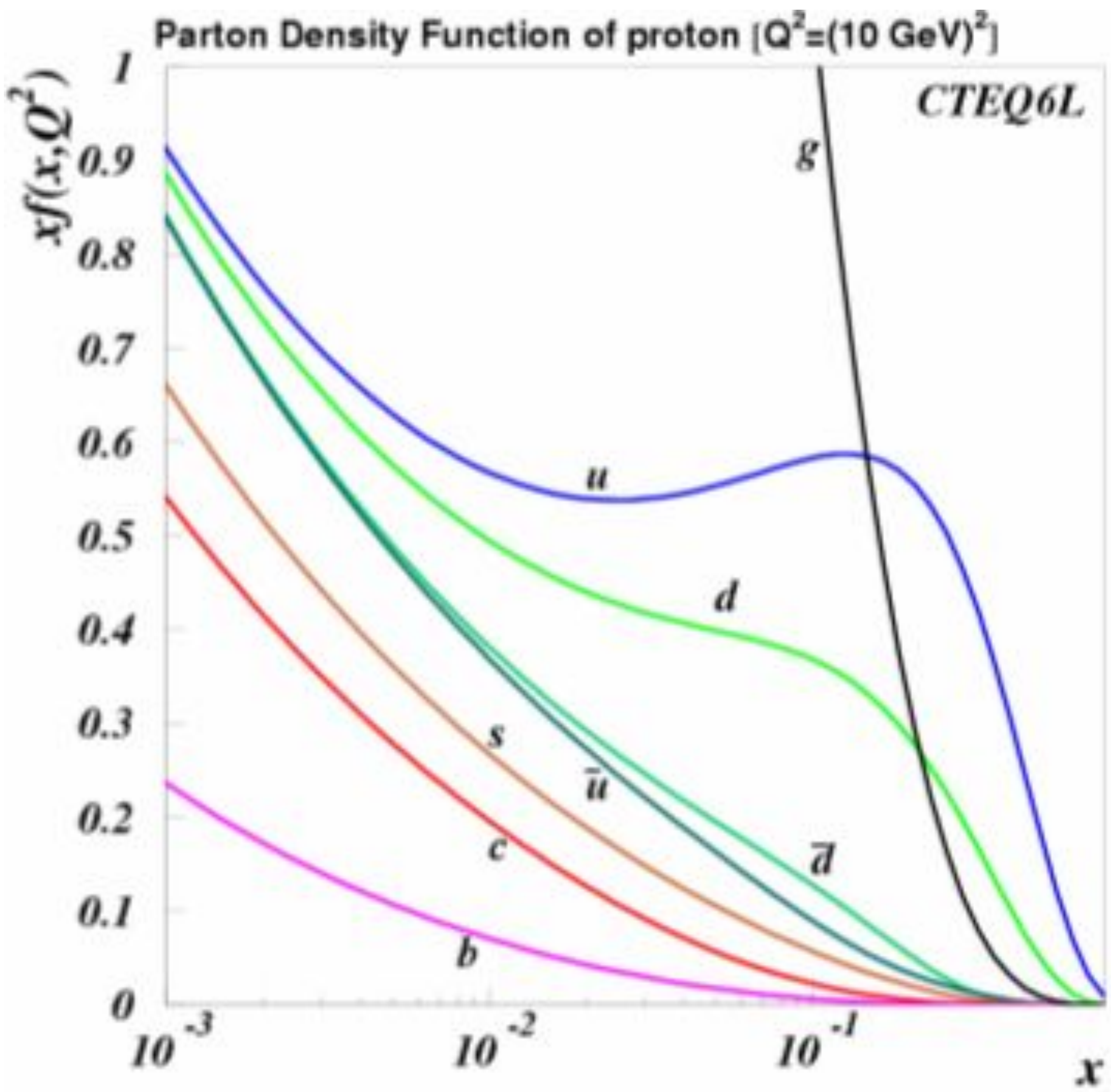


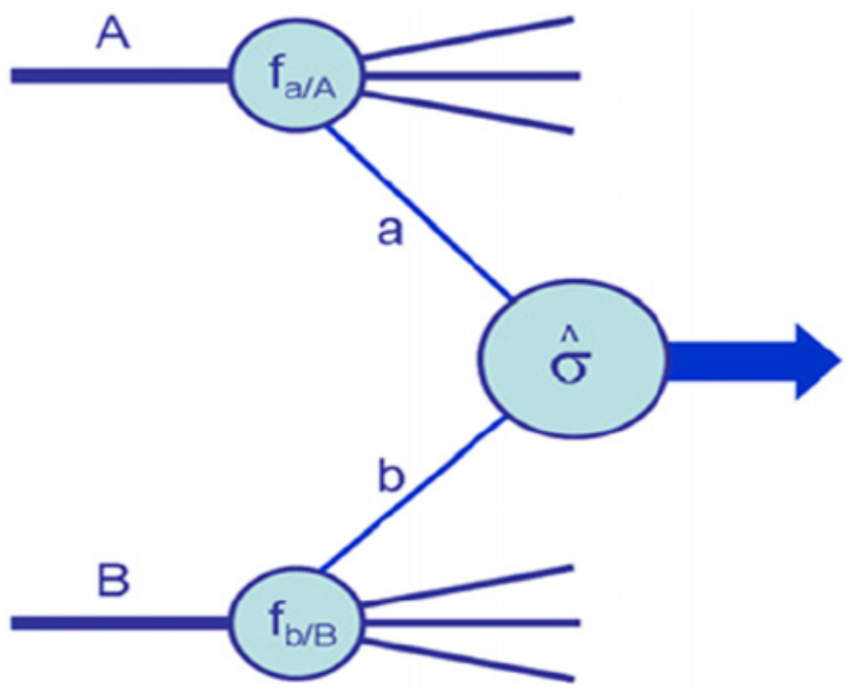
Proton process

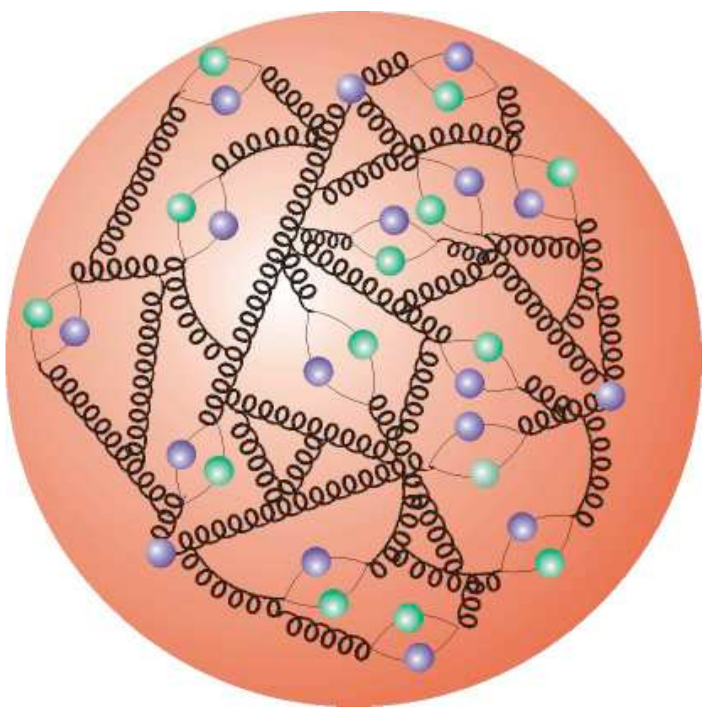
Protonic cross section



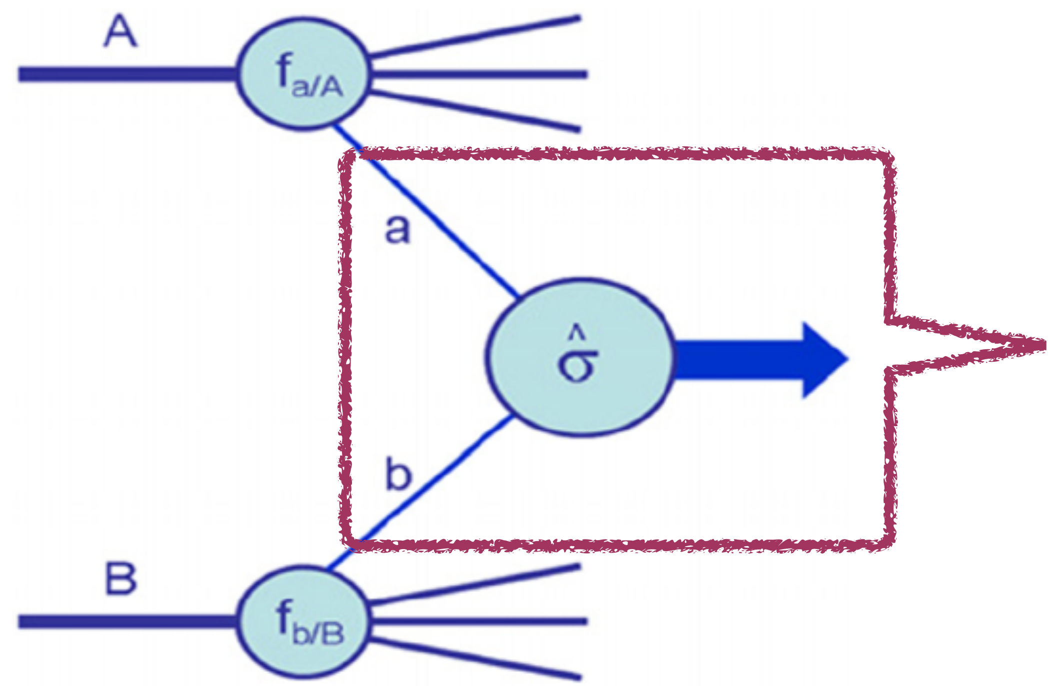
Proton Parton Distribution Function(PDF)







Hard Scattering Process @ the Hadron Colliders



Proton process

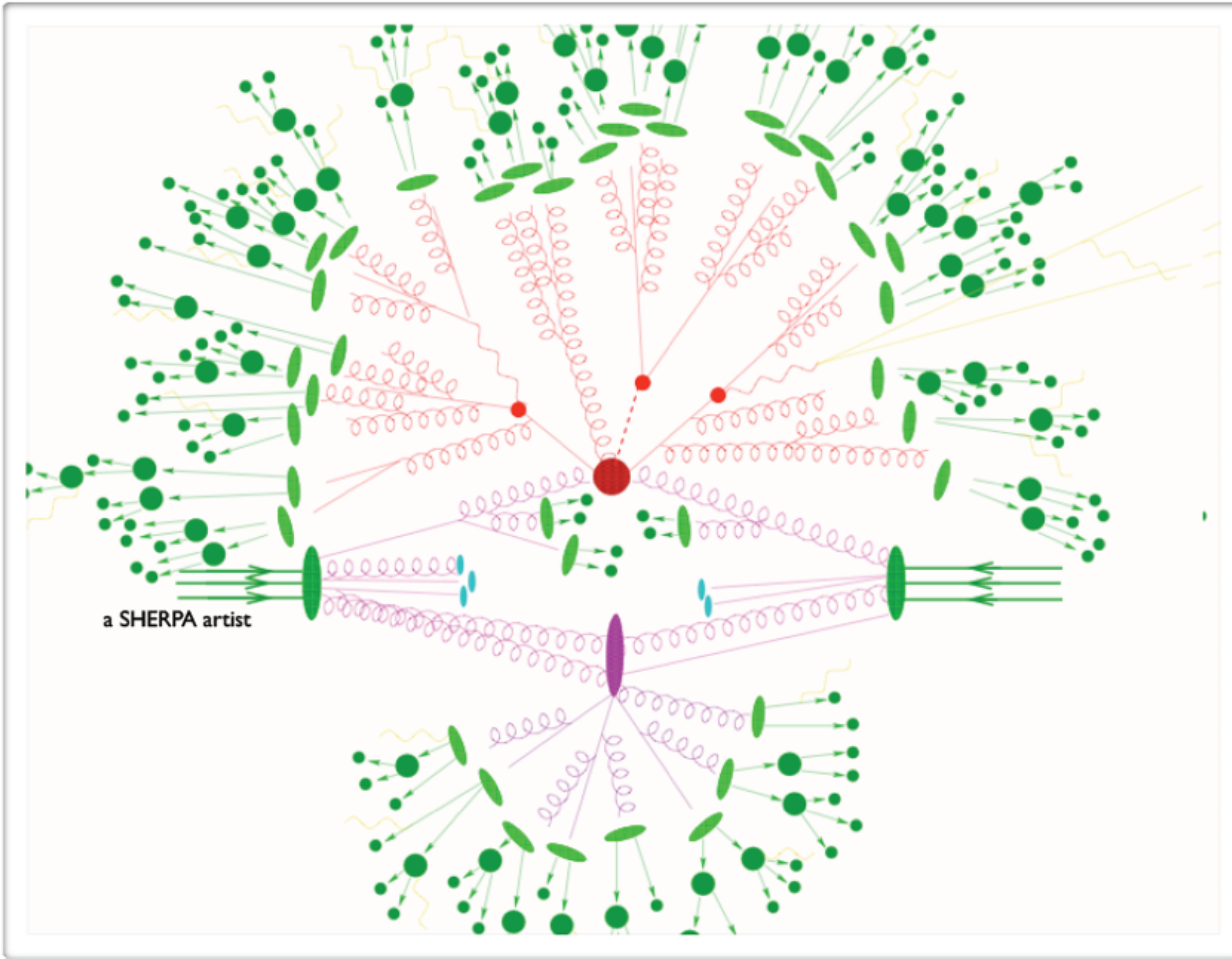
Momentum fraction of the parton

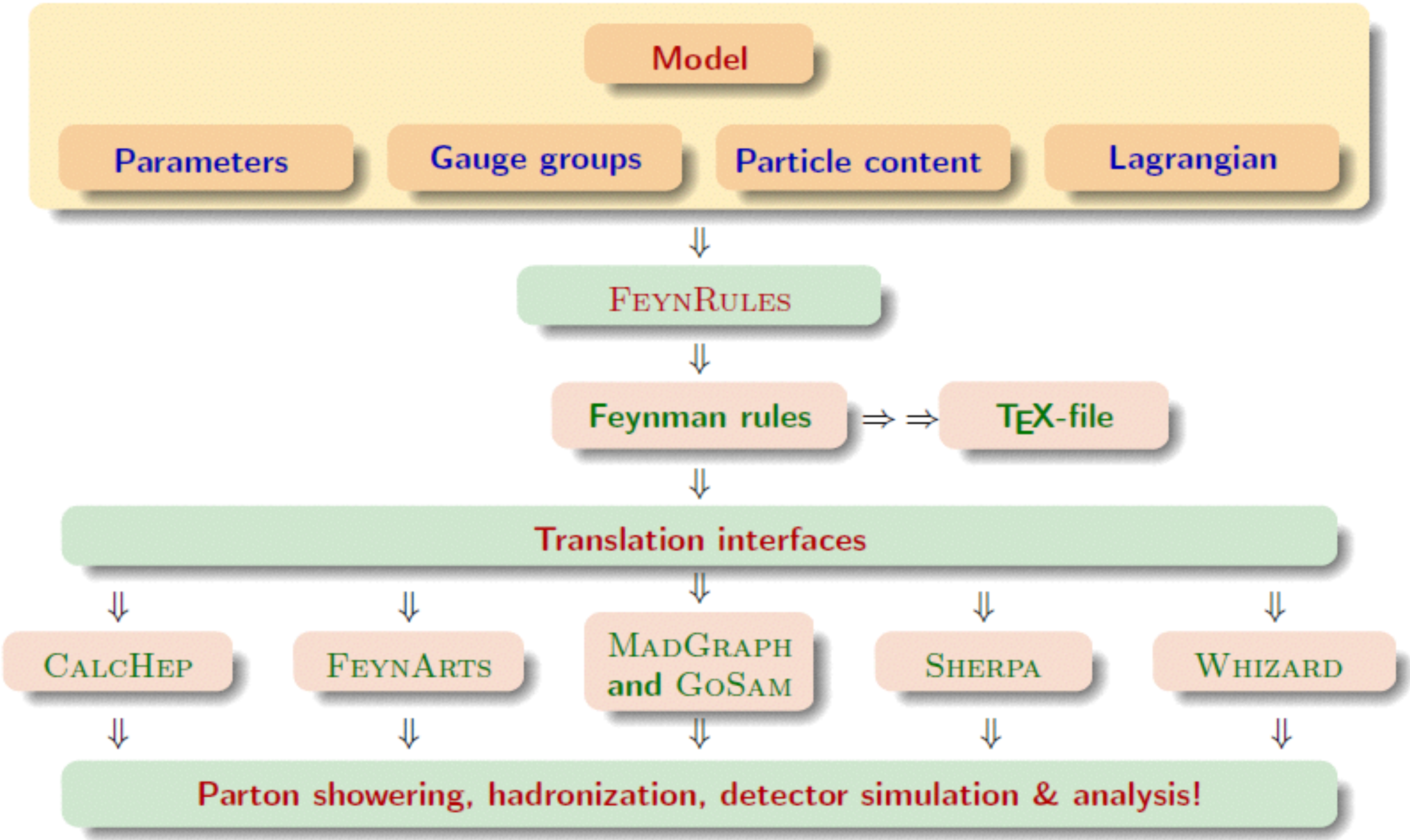
Protonic cross section

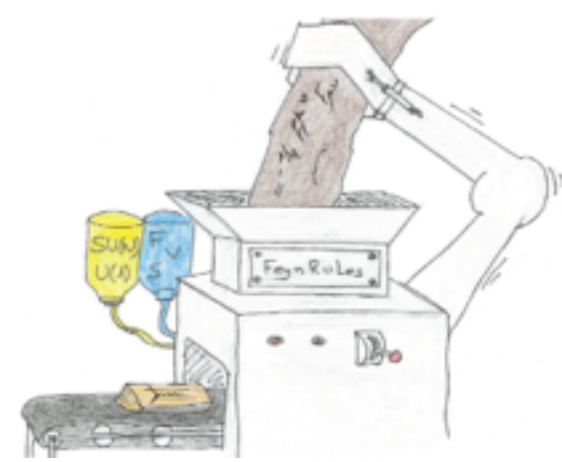
$$\sigma_{AB} = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, \mu_F^2) f_{b/B}(x_b, \mu_F^2) \hat{\sigma}_{ab}(x_a, x_b, \alpha_s(\mu_R^2)).$$

Sum over incoming partons

Proton Parton Distribution Function(PDF)


a SHERPA artist





borrowed from talk Benjamin Fuks

Effective Lagrangian Approach

Studying New Physics

- *There are **2 different approach**, depend On new physics energy scale*

1. *The scale of new physics is **accessible** in Tevatron or LHC experiments, and new degrees of freedom naturally can be produced at collider.* $\Lambda \leq E_{\exp}$

2. *The new degrees of freedom are **heavy** than our energy scale in the experiments. So the heavy particles can be integrated out and their effects can be parameterized in **model independent way by an effective Lagrangian.***

   $\Lambda >> E_{\exp}$

Studying New Physics

- *There are **2 different approaches**, depending on the new physics energy scale:*

I. Have a well defined and motivated model : 2HDM , MSSM, Composite Higgs , …

II. Parameterize the low energy effects of the large class of models as higher dimensional operators.

Effective Field Theory Approach

Dimensionless Coefficients

Higher order Operator

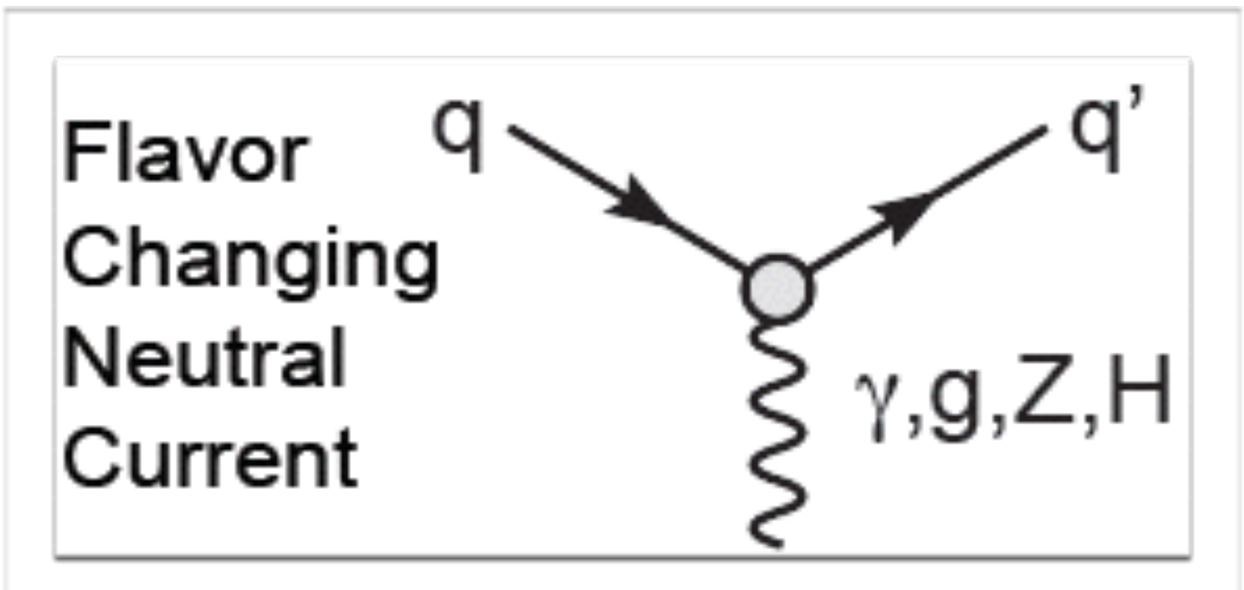
4+n

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \frac{1}{\Lambda^n} \sum_{i=1} C_i^{(n)} \mathcal{O}_i^{(n)},$$

New Physics Scale

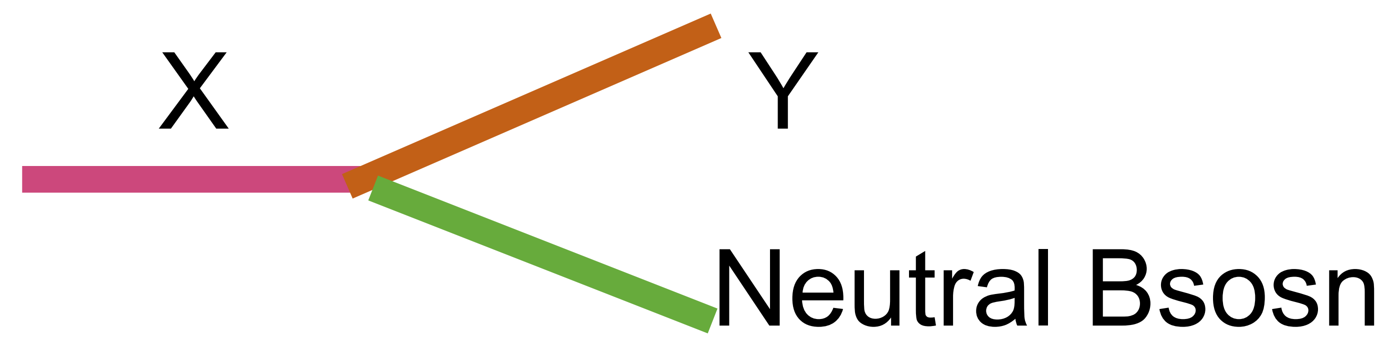
The effective Lagrangian should be ***invariant*** *under* ***SM gauge*** *transformation.*

Top Flavor Changing Neutral Current Processes

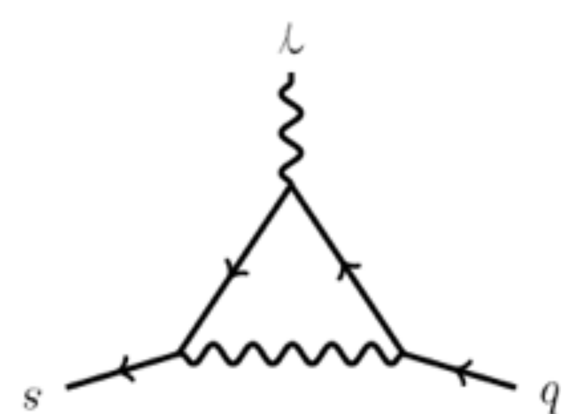


Flavor-Changing Neutral Current (FCNC)

- Transition from a quark with flavor-X and charge-Q to another quark of flavor-Y but with the same charge-Q.

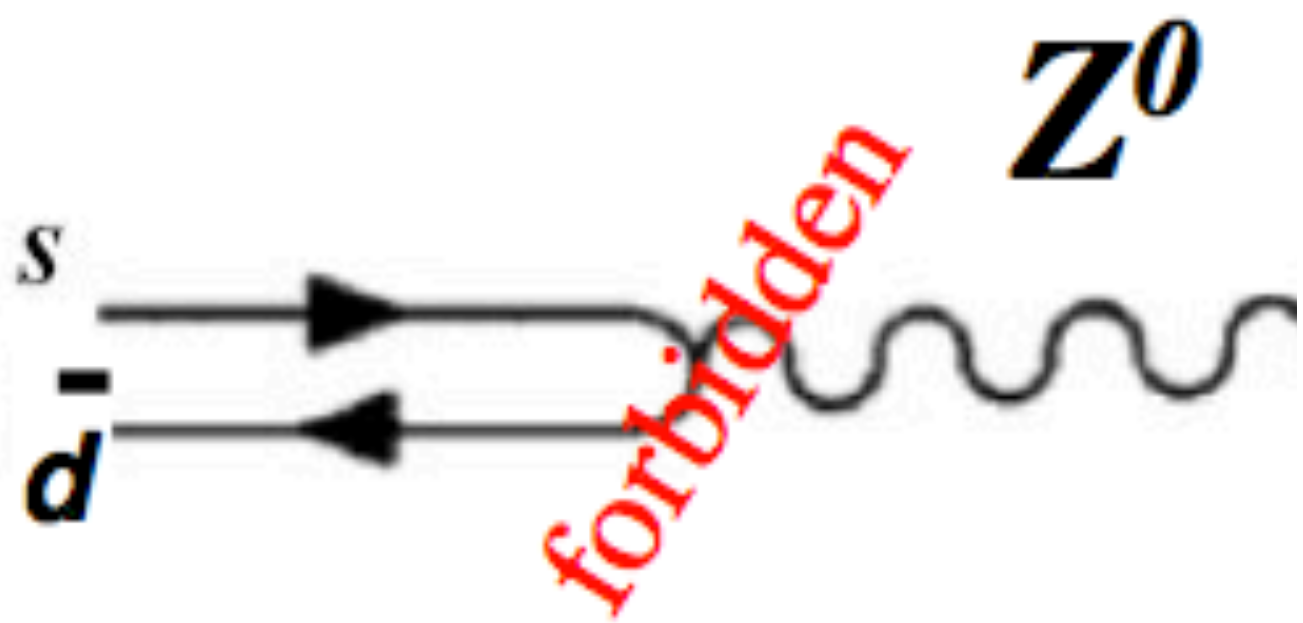


- For example: $b \rightarrow s\gamma$, $t \rightarrow u\gamma$, $t \rightarrow uZ$, …

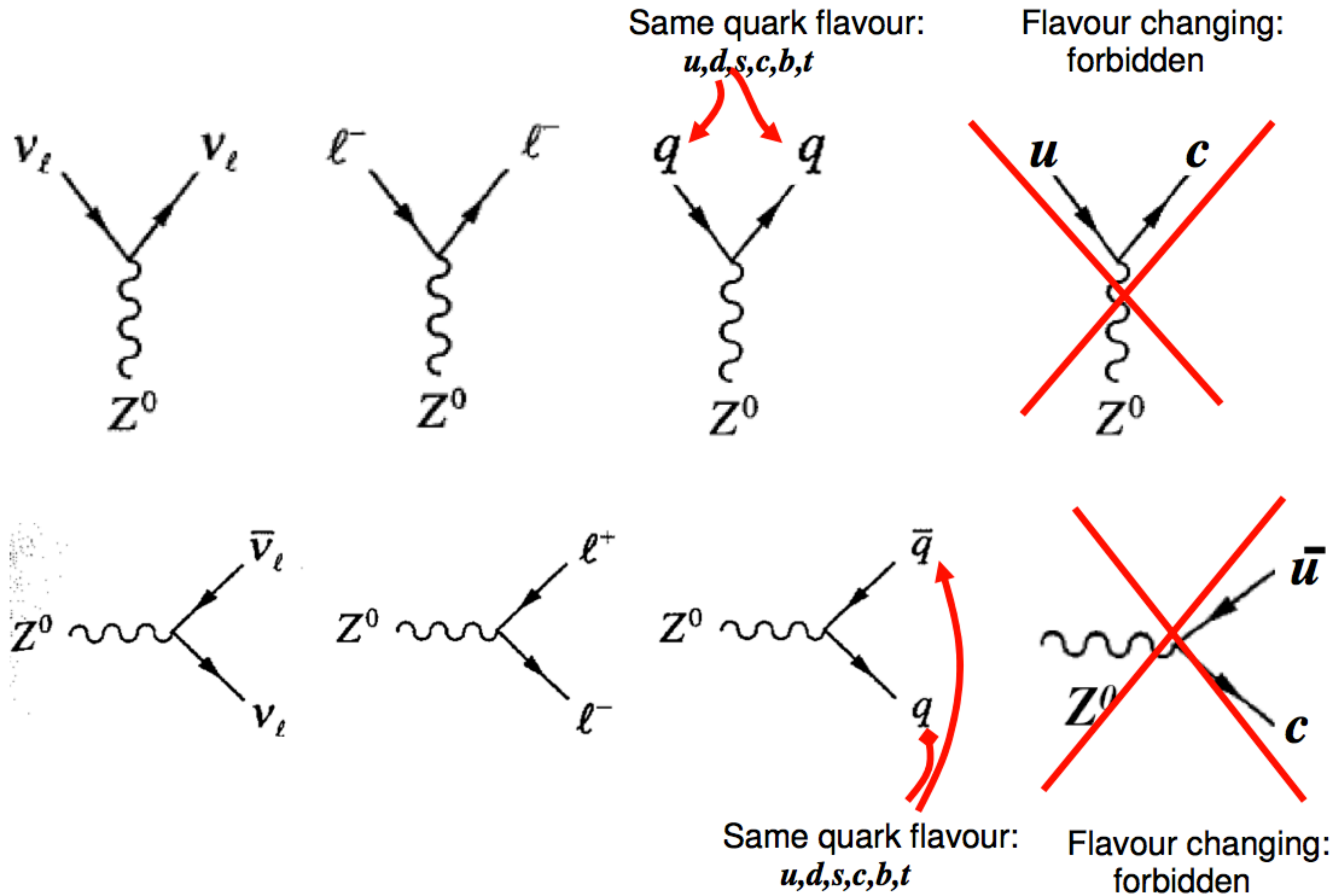


Charged Current

Neutral Current

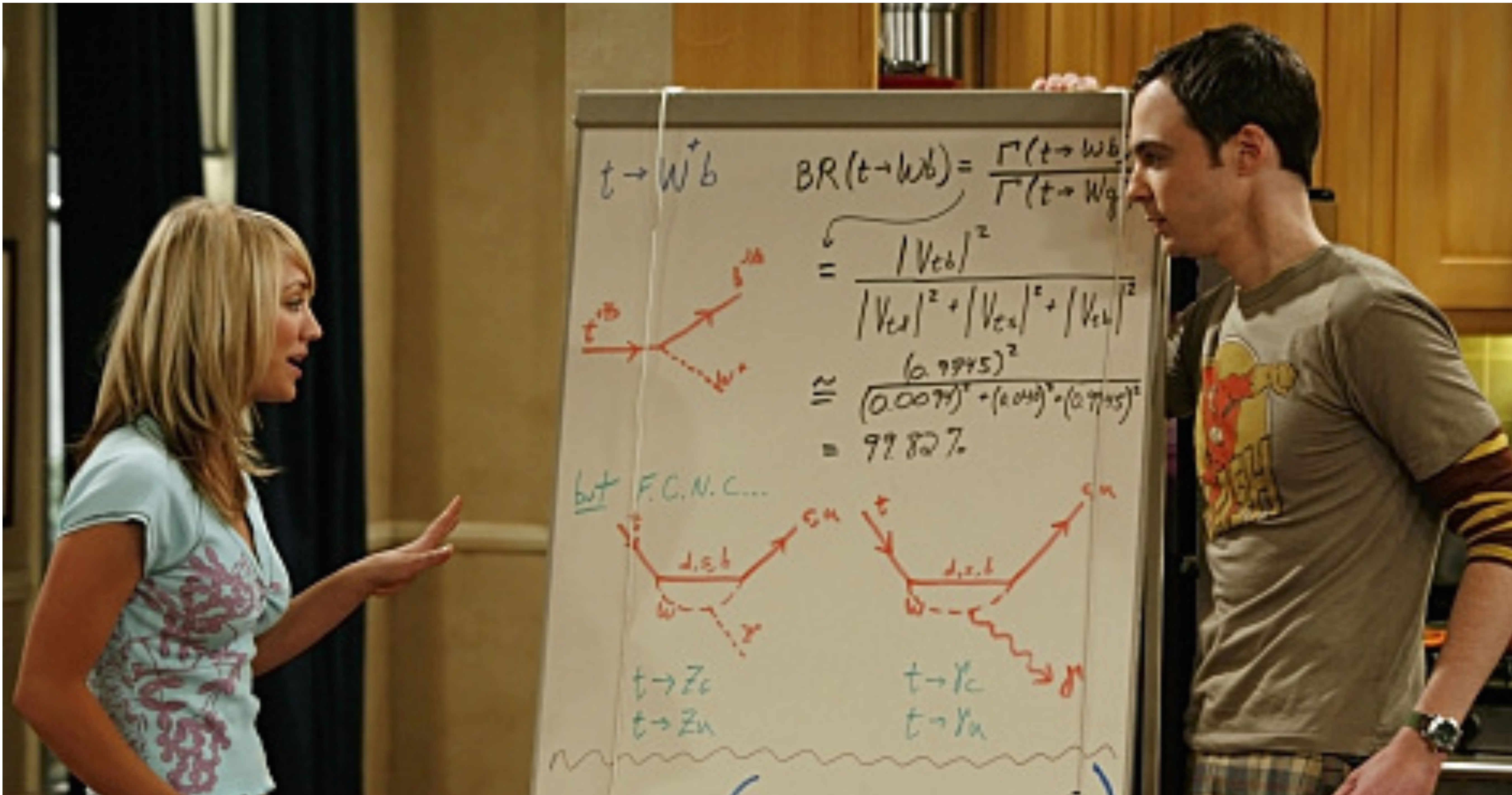


Weak Neutral Current



- Down type FCNC is severely constrained by the enhancement factor.
- Top FCNC has still much room for NP.
- It must be explored by collider physics (direct search) or by flavor physics (indirect search).

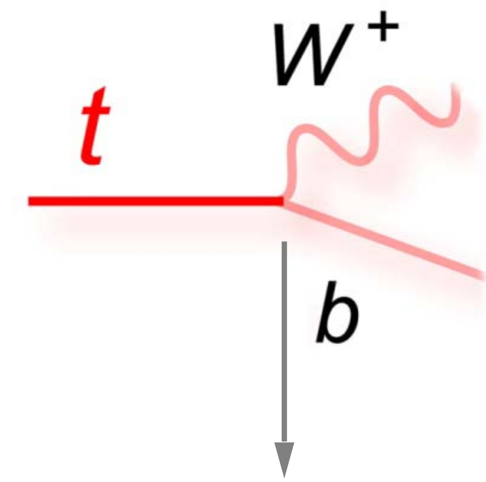
Top FCNC decays



SM prediction For Top decays

- Top-quark has unsuppressed decay width $t \to bW$:

$$\Gamma(t \to bW^+) = \frac{\alpha |V_{tb}|^2}{16 s_W^2} \frac{m_t^3}{m_W^2} \left(1 - \frac{3m_W^4}{m_t^4} + \frac{2m_W^6}{m_t^6}\right)$$



$$-i\frac{g}{2\sqrt{2}}|V_{tq}|\gamma_\mu(1-\gamma_5)$$

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

$$R = \begin{cases} 1.11^{+0.21}_{-0.19} & \text{(CDF)} \\ 1.03^{+0.19}_{-0.17} & \text{(D0)} \end{cases}$$

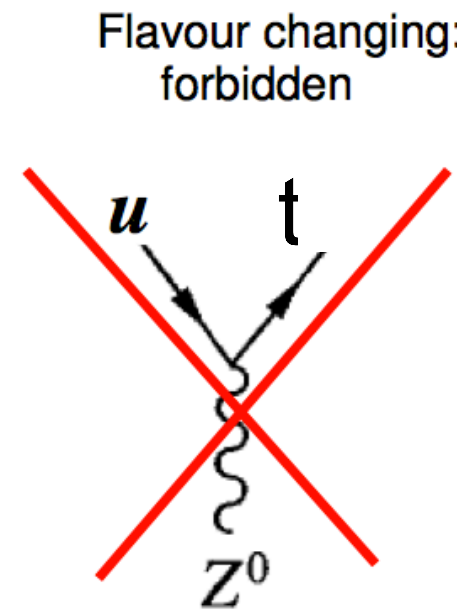
$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$$

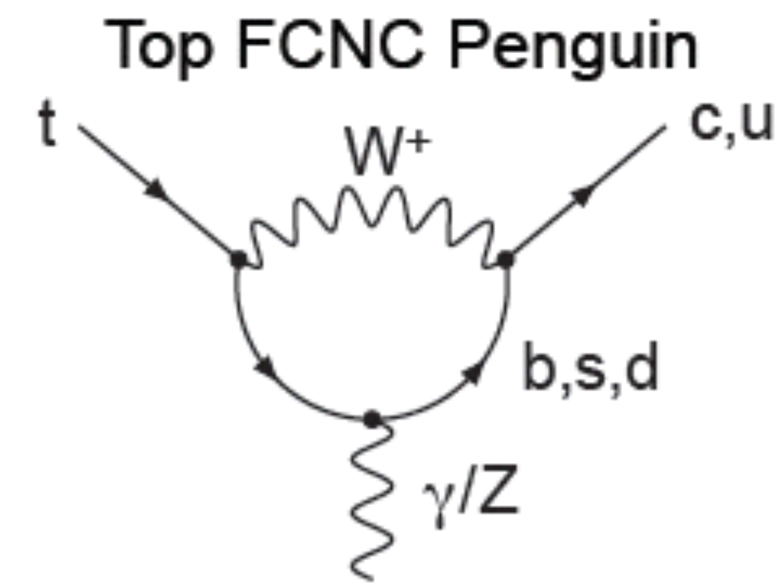
$$|V_{tb}| = \begin{cases} 1.05^{+0.10}_{-0.09} & \text{(CDF)} \\ 1.01^{+0.09}_{-0.09} & \text{(D0)} \end{cases}$$

GIM Mechanism
(Glashow–Iliopoulos–Maiani mechanism)

- Top FCNC interactions are absent at the tree level in the SM.

- They are extremely suppressed at the loop-level by the GIM mechanism.





$$A \sim V_{tb}V_{ub}^{*}f(\frac{m_b}{m_W}) + V_{ts}V_{us}^{*}f(\frac{m_s}{m_W}) + V_{td}V_{ud}^{*}f(\frac{m_d}{m_W})$$

$$V_{tb}V_{ub}^{*} + V_{ts}V_{us}^{*} + V_{td}V_{ud}^{*} = 0$$

$$m_d, m_s, m_b < m_W \therefore f(\frac{m_b}{m_W}) \sim f(\frac{m_s}{m_W}) \sim f(\frac{m_d}{m_W}) \therefore A \sim 0$$

FCNC @ Top Sector

- Top FCNC Modes :
  - ★ $t \to c Z$
  - ★ $t \to c h$
  - ★ $t \to c g$
  - ★ $t \to c \gamma$
  - ★ the modes with up-quark.

SM predictions For FCNC Transitions

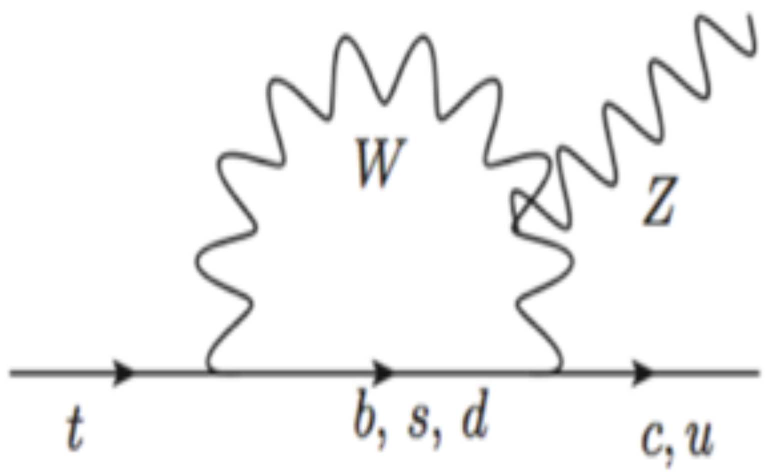
Branching Ratio Definition: $$Br(t \to cV) \equiv \frac{\Gamma(t \to cV)}{\Gamma(t \to bW^+)},$$

$$Br(t \to u\gamma) \simeq 4 \times 10^{-16} \qquad Br(t \to c\gamma) \simeq 5 \times 10^{-14}$$

$$Br(t \to uZ) \simeq 8 \times 10^{-17} \qquad Br(t \to cZ) \simeq 10^{-14}$$

$$Br(t \to uh) \simeq 2 \times 10^{-17} \qquad Br(t \to ch) \simeq 3 \times 10^{-15}$$

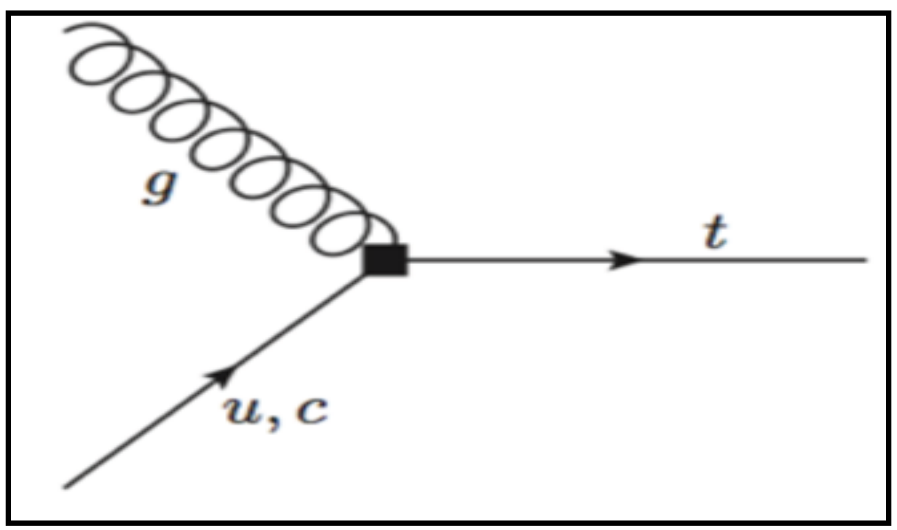
$$Br(t \to ug) \simeq 4 \times 10^{-14} \qquad Br(t \to cg) \simeq 5 \times 10^{-12}$$

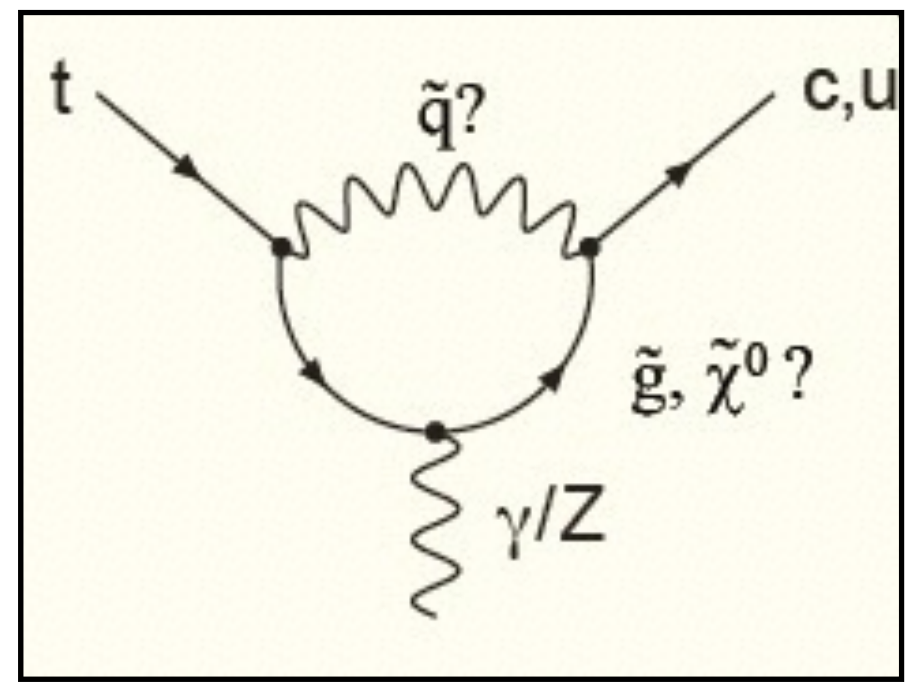


Aguilar-Saavedra, hep-ph/0409342

FCNC @ New Physics

- Top decays through FCNC are enhanced in many models beyond the SM.





FCNC @ New Physics

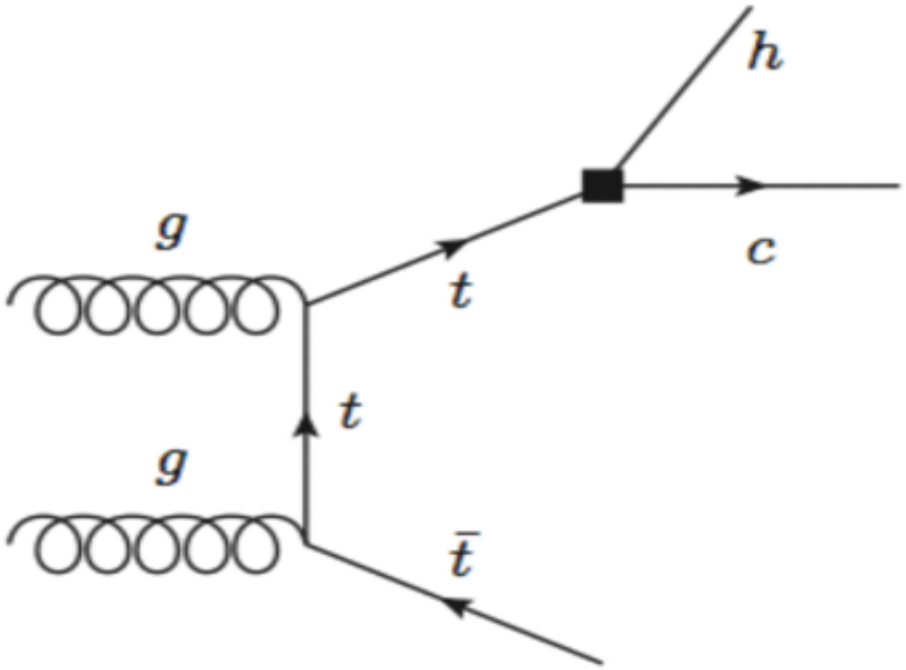
- Experimental tests of FCNC interactions : sensitive probes of new physics.
- Any signal above SM expectations would indicate new physics.
- Measurements of FCNC branching ratios allows to constrain new physics models.

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

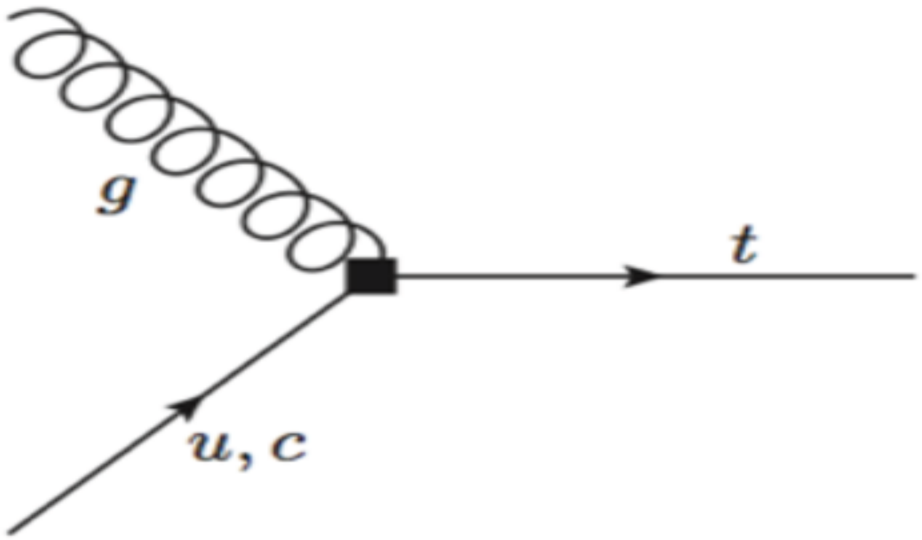
Snowmass 2013 Top quark WG report, 1311.2028

Collider Searches for Top FCNC

- Top FCNC in decay :



- Top FCNC in production:



Note: t → c and t → u can be distinguished from production!

$t \to gq$

- anomalous single top-quark production ($qg \to t$)

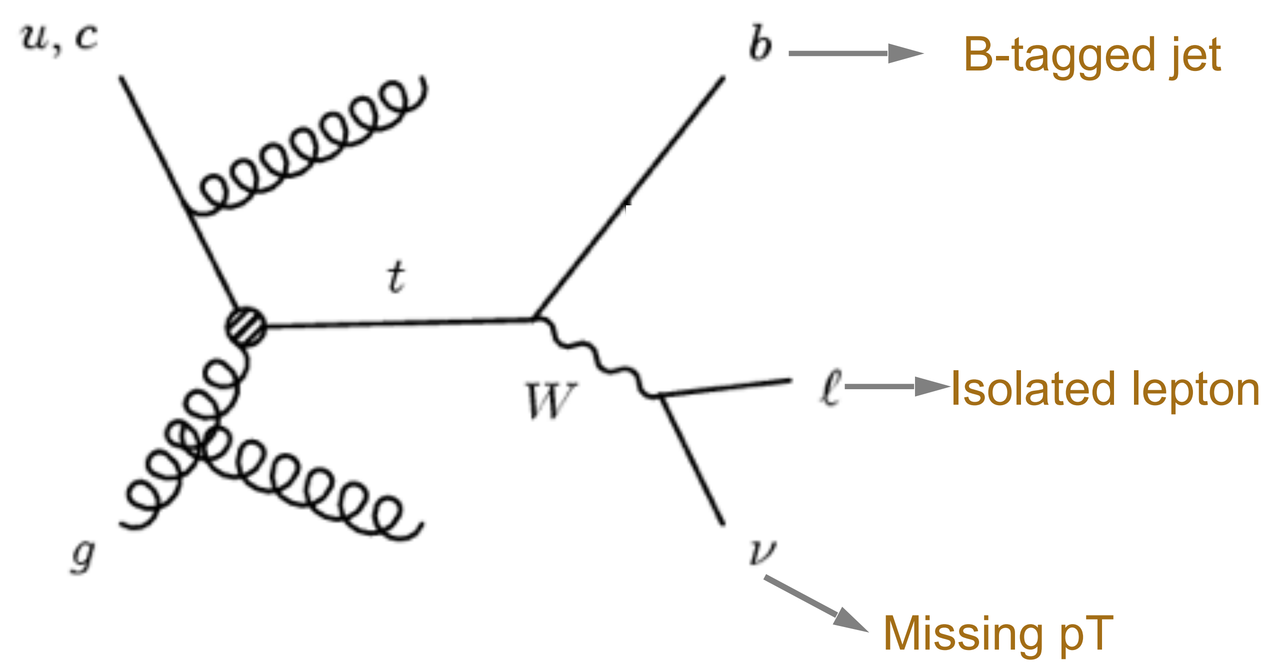
$$qg \to t \to W(\to \ell\nu)\, b$$

ATLAS:

$$\mathcal{B}(t \to ug) < 4.0 \times 10^{-5}$$

$$\mathcal{B}(t \to cg) < 17 \times 10^{-5}$$

using 20.3 fb^{-1} of data collected at $\sqrt{s}$ = 8 Te



$t \to Zq$

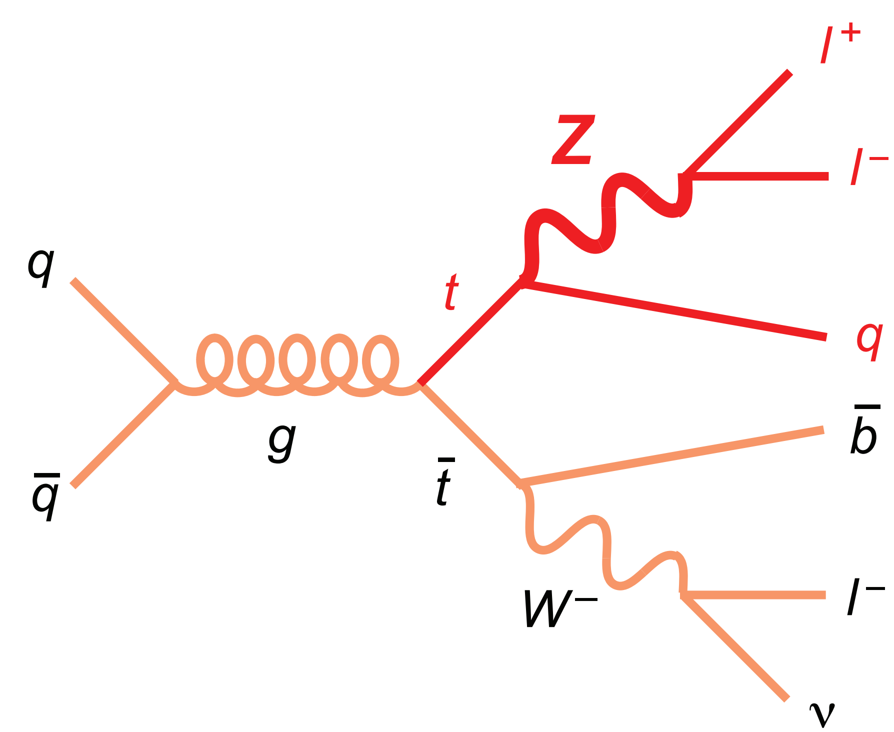
- A search for flavor-changing neutral currents in top-quark decays $t \to Zq$ is performed in events produced from the decay chain $tt \to Zq + Wb$, where both vector bosons decay leptonically, producing a final state with three leptons (electrons or muons).

CMS: $$BR(t \to qZ) < 5 \times 10^{-4}$$

using 25 fb^{-1} of data collected at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV

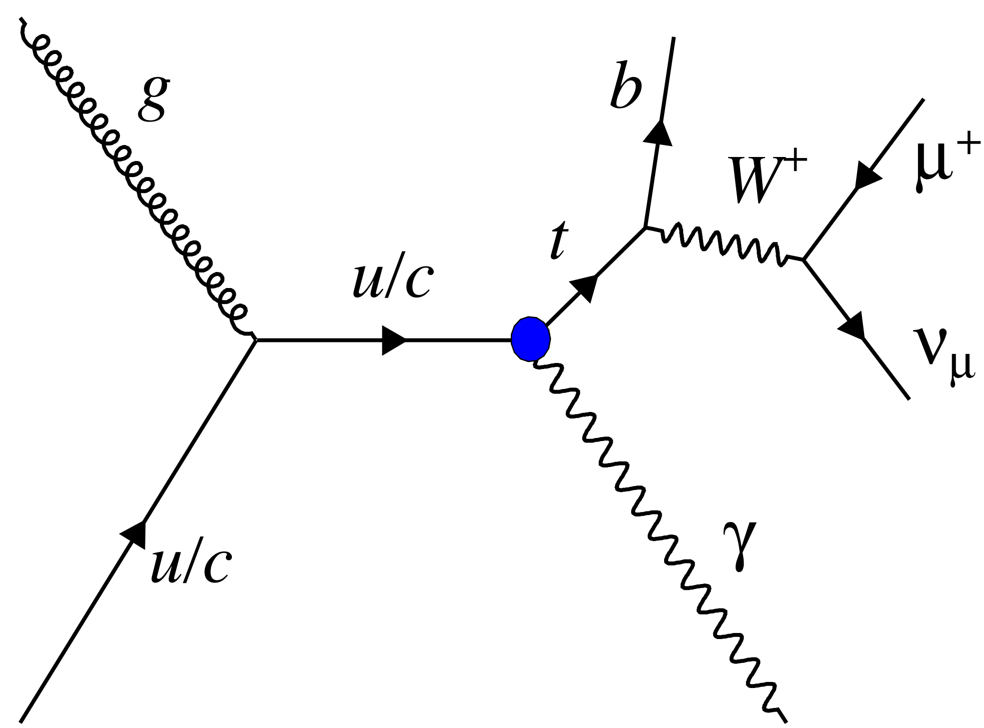
ATLAS: $$BR(t \to qZ) < 7 \times 10^{-4}$$

using 20.3 fb^{-1} of data collected at $\sqrt{s}$ = 8 TeV



$t \rightarrow \gamma q$

Upper limits at the 95% confidence level are set on the tuγ and tcγ anomalous couplings and translated into upper limits on the branching fraction of the FCNC top quark decays:



CMS: $\mathcal{B}(\mathrm{t} \rightarrow \mathrm{u}\gamma) < 1.3 \times 10^{-4}$

$$\mathcal{B}(\mathrm{t} \rightarrow \mathrm{c}\gamma) < 1.7 \times 10^{-3}$$

using 19.8 fb^{-1} of data collected at $\sqrt{s}$ = 8 TeV

$t \to hq$

CMS: $t\bar{t} \to (bW)(ch)$

$h \to WW^*$

$h \to ZZ^*$ — multilepton final states

$h \to \tau\tau$

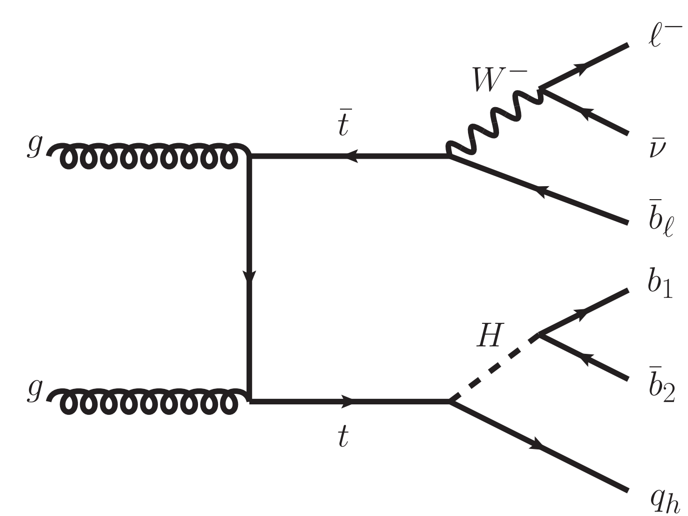
using 19.8 fb^{-1} of data collected at $\sqrt{s}$ = 8 TeV

$h \to \gamma\gamma$ — lepton+diphoton final state

an upper limit of 0.56% on $\mathcal{B}(t \to ch)$

ATLAS: $t\bar{t} \to WbHq$

using 20.3 fb^{-1} of data collected at $\sqrt{s}$ = 8 TeV



95% CL combined upper limits:

B($t \to Hc$) —> 0.46%

B($t \to Hu$) —> 0.45%

tqH and tqg FCNC Couplings

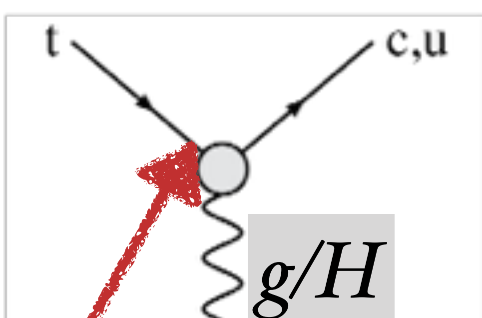
Effective Lagrangian for tqH and tqg FCNC Couplings

- The most general effective Lagrangian up to dimension-six operators :

Coupling strength (top, up-type quark and gluon)

$$\mathcal{L} = \sqrt{2}g_s \sum_{q=u,c} \frac{\kappa_{tqg}}{\Lambda} \bar{t}\sigma^{\mu\nu}T_a(f_q^L P_L + f_q^R P_R)qG^a_{\mu\nu}$$

$$+ \frac{g}{2\sqrt{2}} \sum_{q=u,c} g_{tqH}\bar{q}(g^v_{tqH} + g^a_{tqH}\gamma_5)tH + h.c.,$$

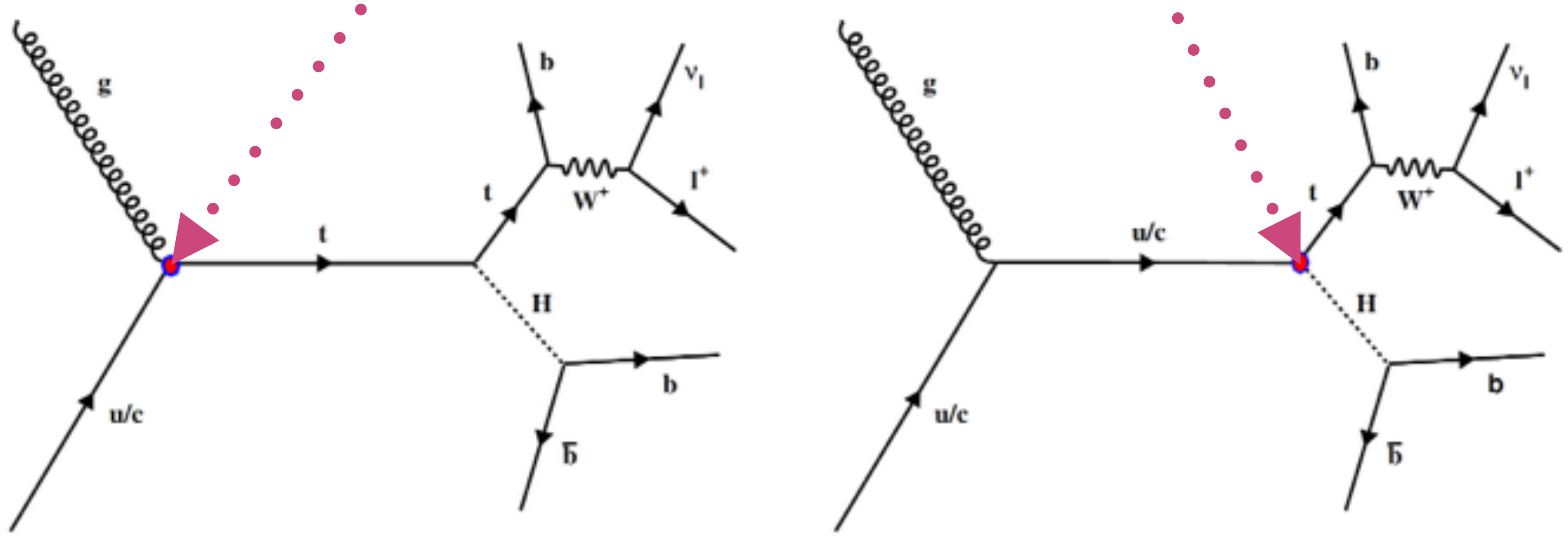


New Physics?

Coupling strength (top, up-type quark and Higgs)

Single top + Higgs due to FCNC Couplings at the LHC

$$\mathcal{L} = \sqrt{2} g_s \sum_{q=u,c} \frac{\kappa_{tqg}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q G^a_{\mu\nu} + \frac{g}{2\sqrt{2}} \sum_{q=u,c} g_{tqH} \bar{q} (g^v_{tqH} + g^a_{tqH} \gamma_5) t H + h.c.,$$

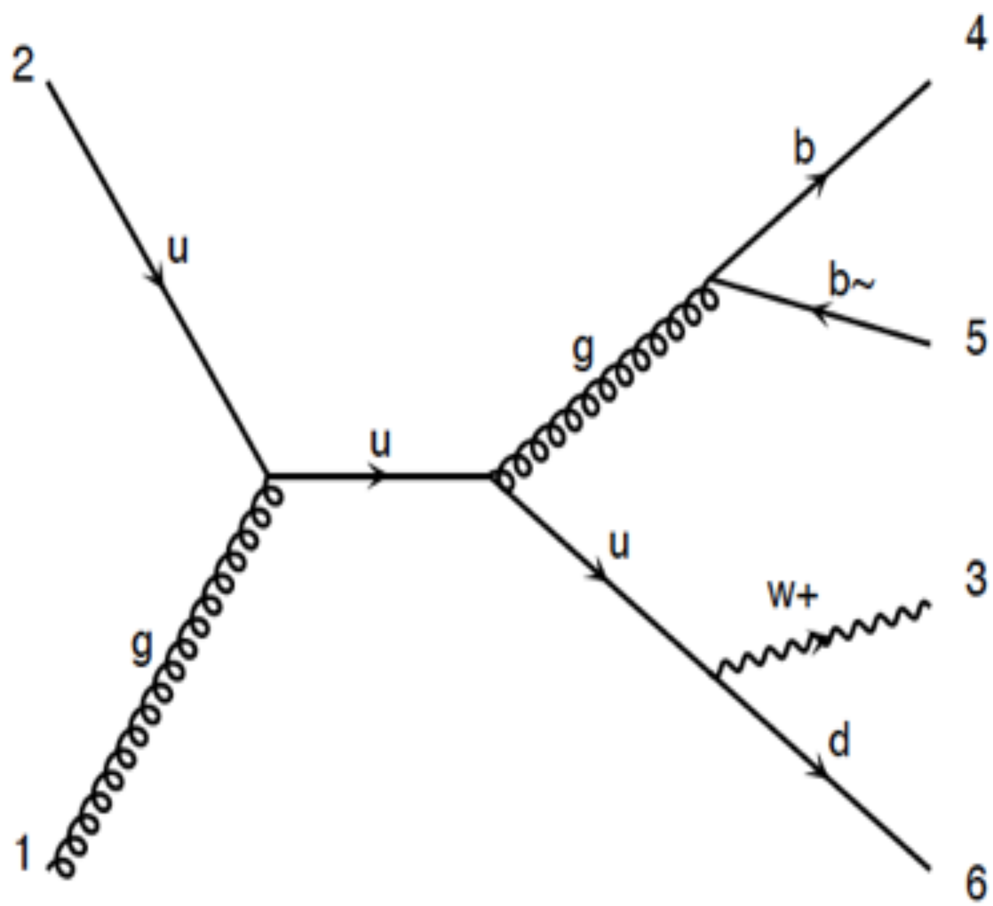


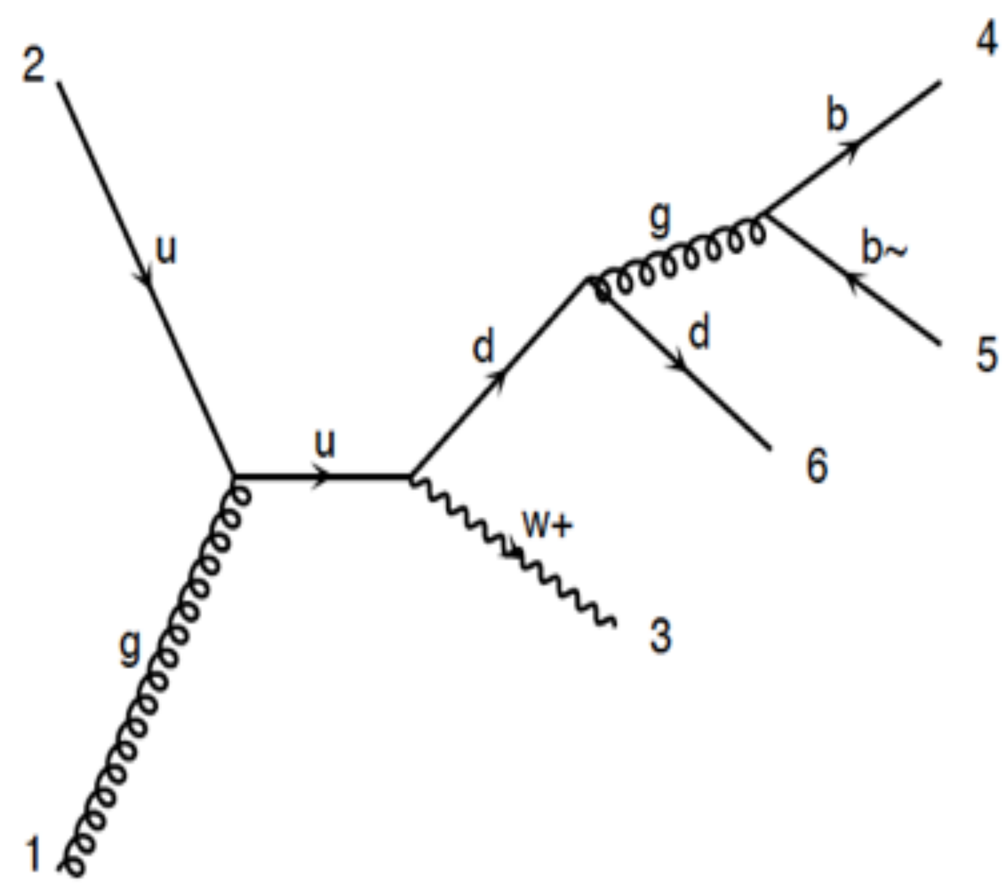
- **Final state:**
  - 3 b-jets
  - One charged lepton
  - Missing energy (Neutrino)

Backgrounds and detector simulations

The main background processes are Wbbj, Wjjj, WZj and top pair.

No TOP and No Higgs but the same final state





b-tagging efficiency = 60 % mis-tagging rate=10 %

Event Generation and Simulation

- FeynRules Package → Implementing the model
- MadGraph → Generating the hard processes
- PYTHIA → Hadronization and showering
- FastJet → Reconstructing Jets

Preliminary Cuts

- Based on the detector resolutions and acceptance, following cuts have been applied:

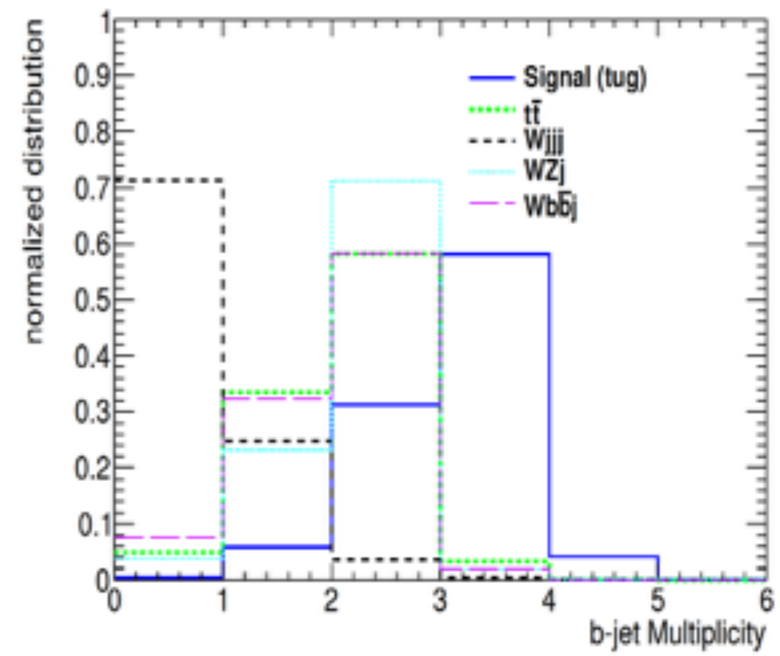
- Lepton and jets → $p_T > 25GeV \quad |\eta| < 2.5$

- Distance between two object → $\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} > 0.4$

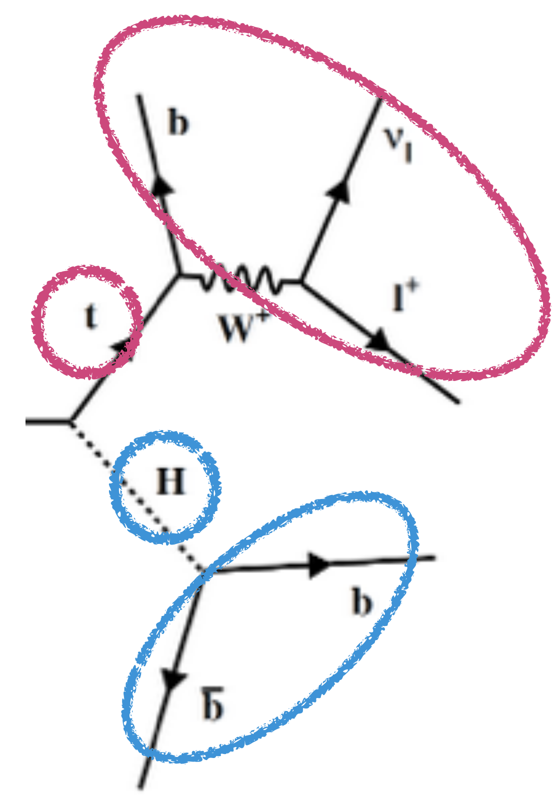
- Missing Transverse Energy → $\not{E}_T > 25GeV$

Object Selection & Reconstruction

- We require to have only three b-tagged jets.



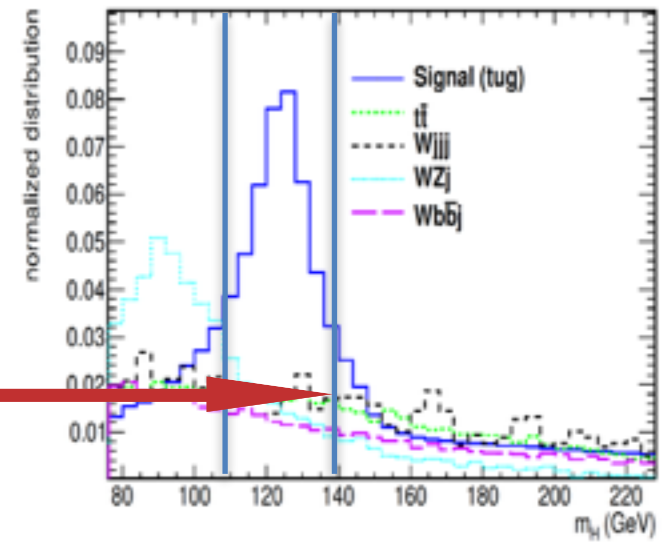
- The combination which gives the closest mass to the top quark is selected as top.

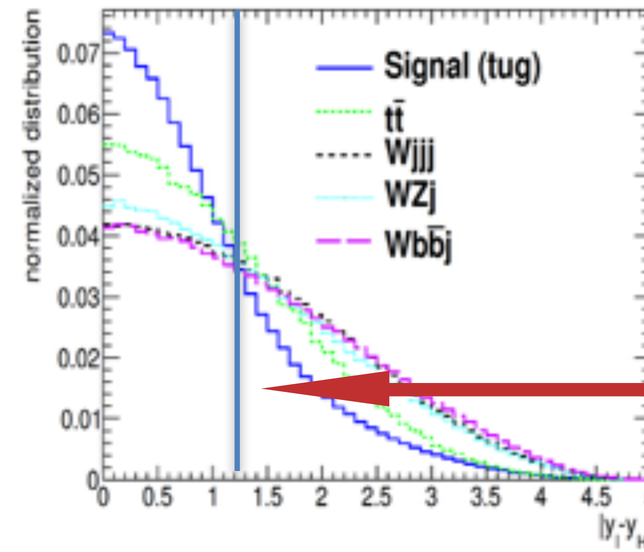


- The other remaining two b-jets are combined to reconstruct the Higgs boson.

Looking at different kinematic distributions for suppressing Backgrounds.

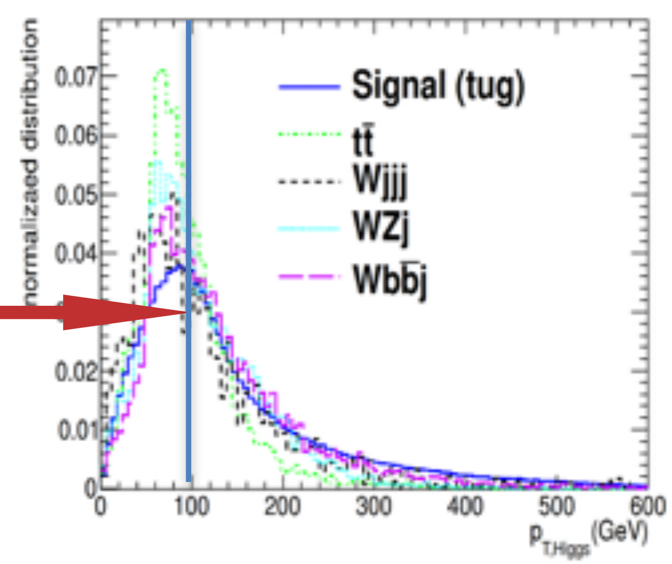
$|m_{H,rec} - 125| > 15\,GeV$

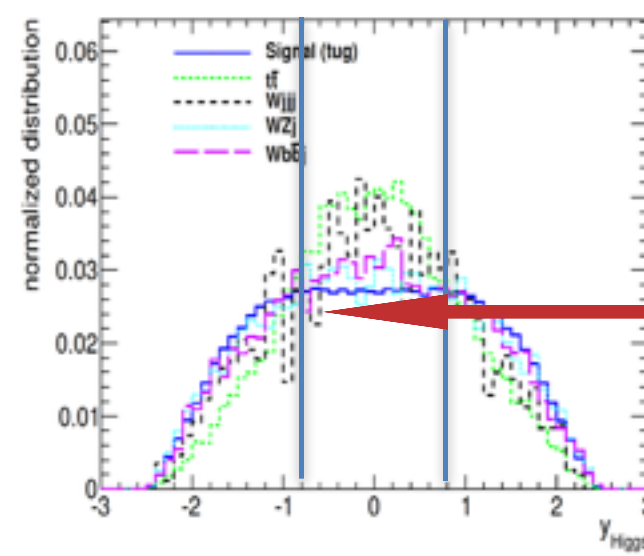




$|y_l - y_H| < 1.2$

$p_{T,Higgs} > 100\,GeV$

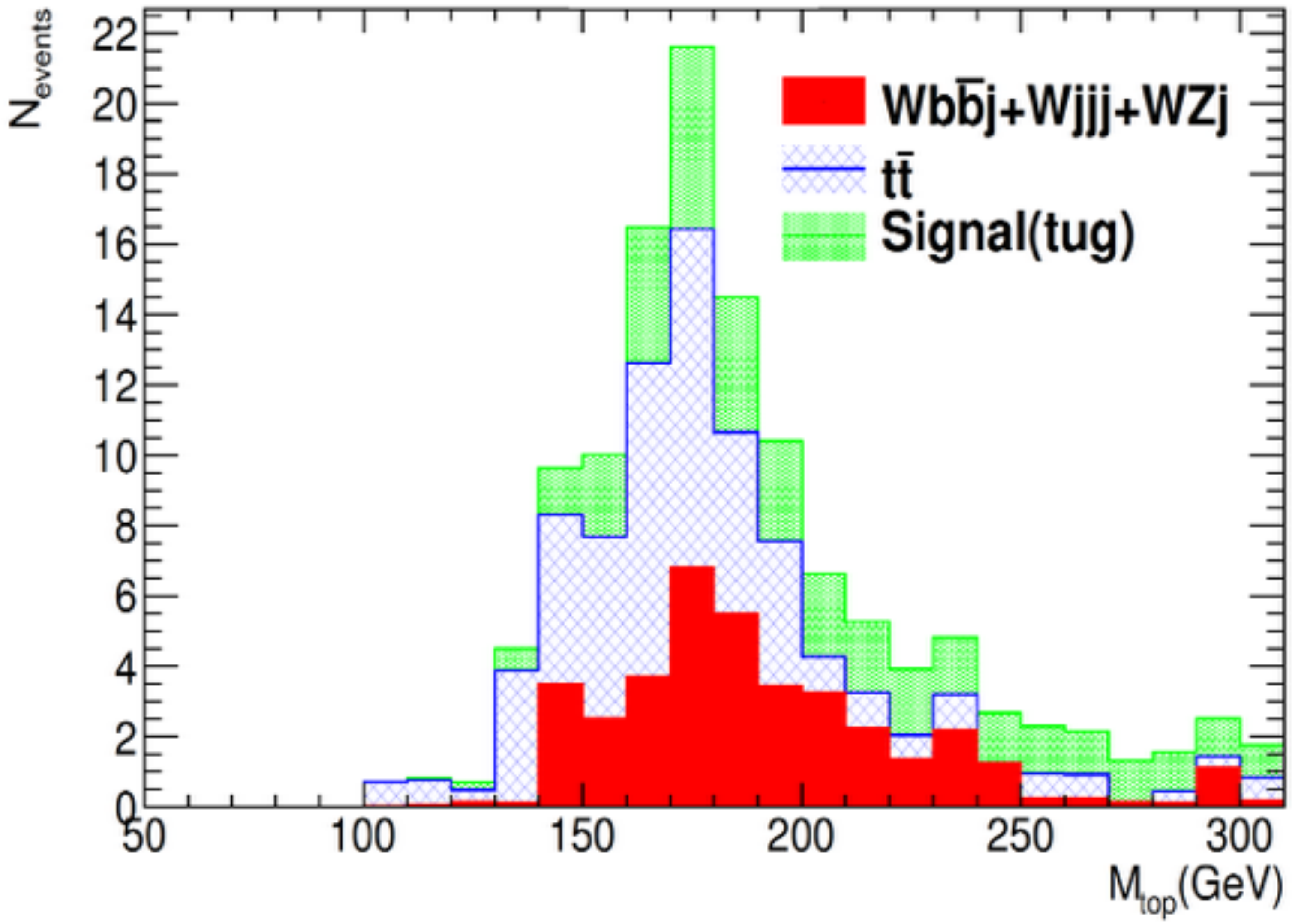




$|y_H| > 0.8$

S.Kh, M.M.Najafabadi , Phys.Rev.D 89 (2014) 5, 054011

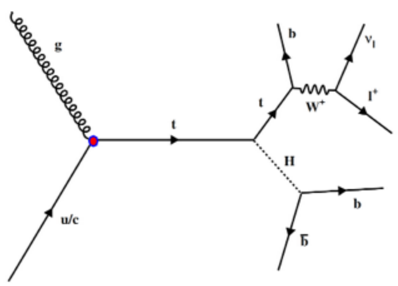
Reconstructed top quark mass after all cuts for signal and backgrounds:

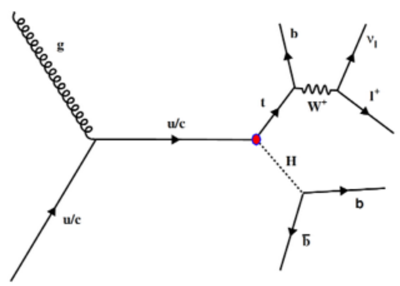


Top quark has been reconstructed well!

S.Kh, M.M.Najafabadi , Phys.Rev.D 89 (2014) 5, 054011

Results for FCNC t-q-gluon Couplings



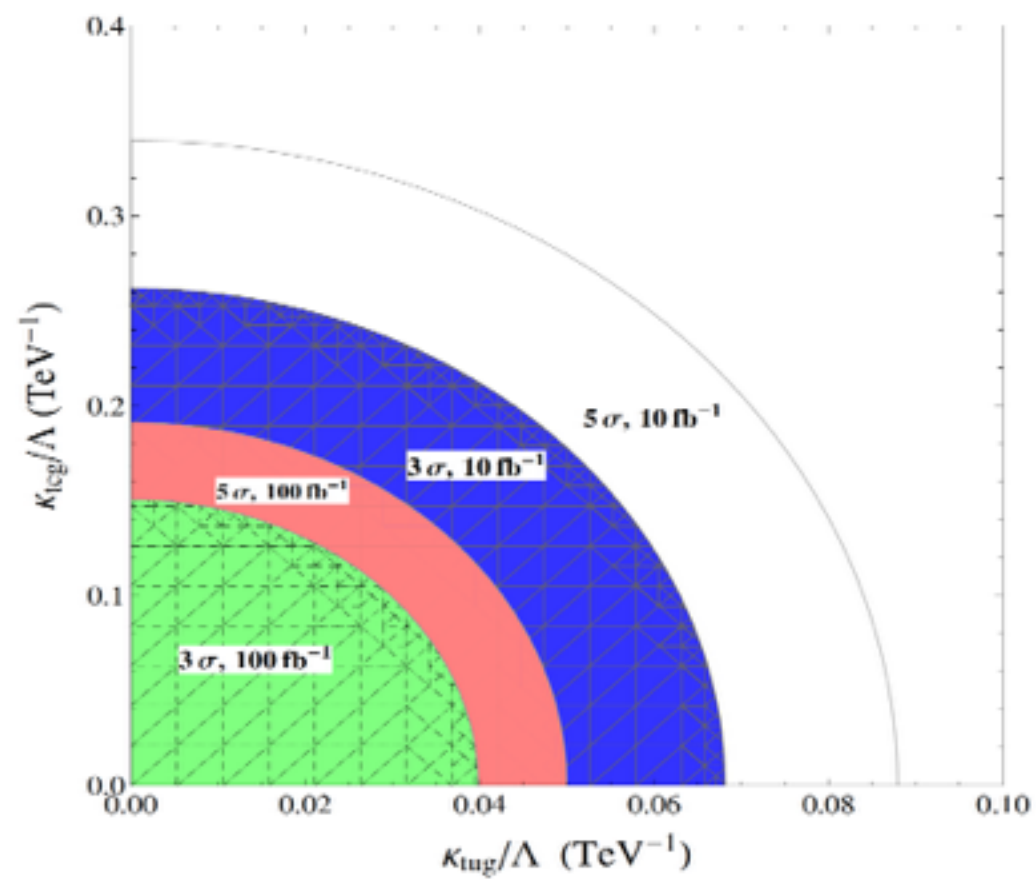


- *Now we find the values of new physics model parameters, κ_{tqg} , at which the observation of new physics can be claimed. To do so, a statistical significance is defined as the difference of number of signal distribution from the background:*

$$Significane = S/\sigma_B = S/\sqrt{B}$$

Requiring significance > 3(5) leads to :

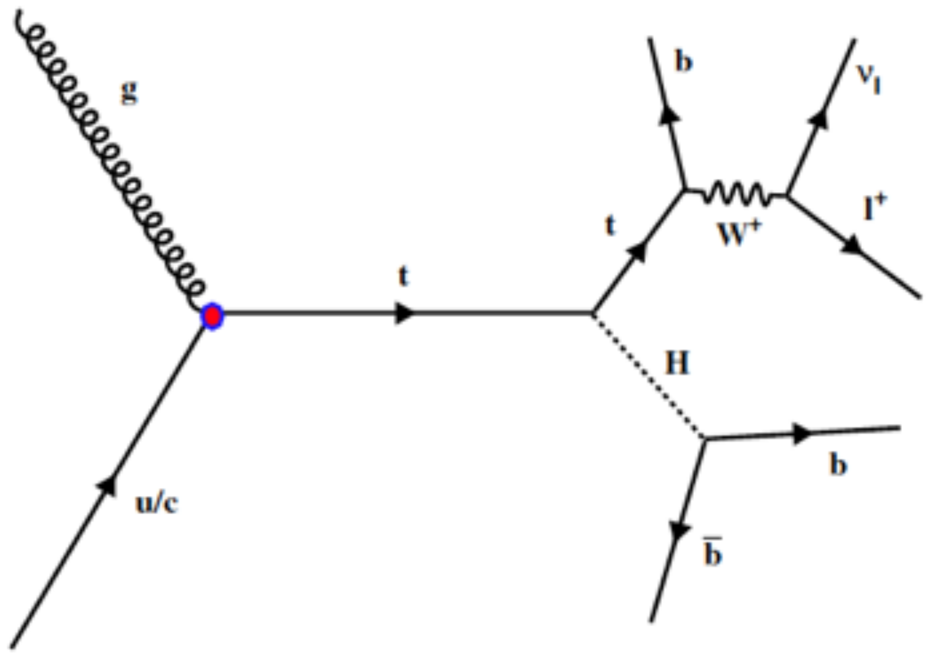
$$\frac{\kappa_{tug}}{\Lambda} \geq 0.069\ (0.088)\ TeV^{-1},$$
$$\frac{\kappa_{tcg}}{\Lambda} \geq 0.26\ (0.34)\ TeV^{-1}.$$

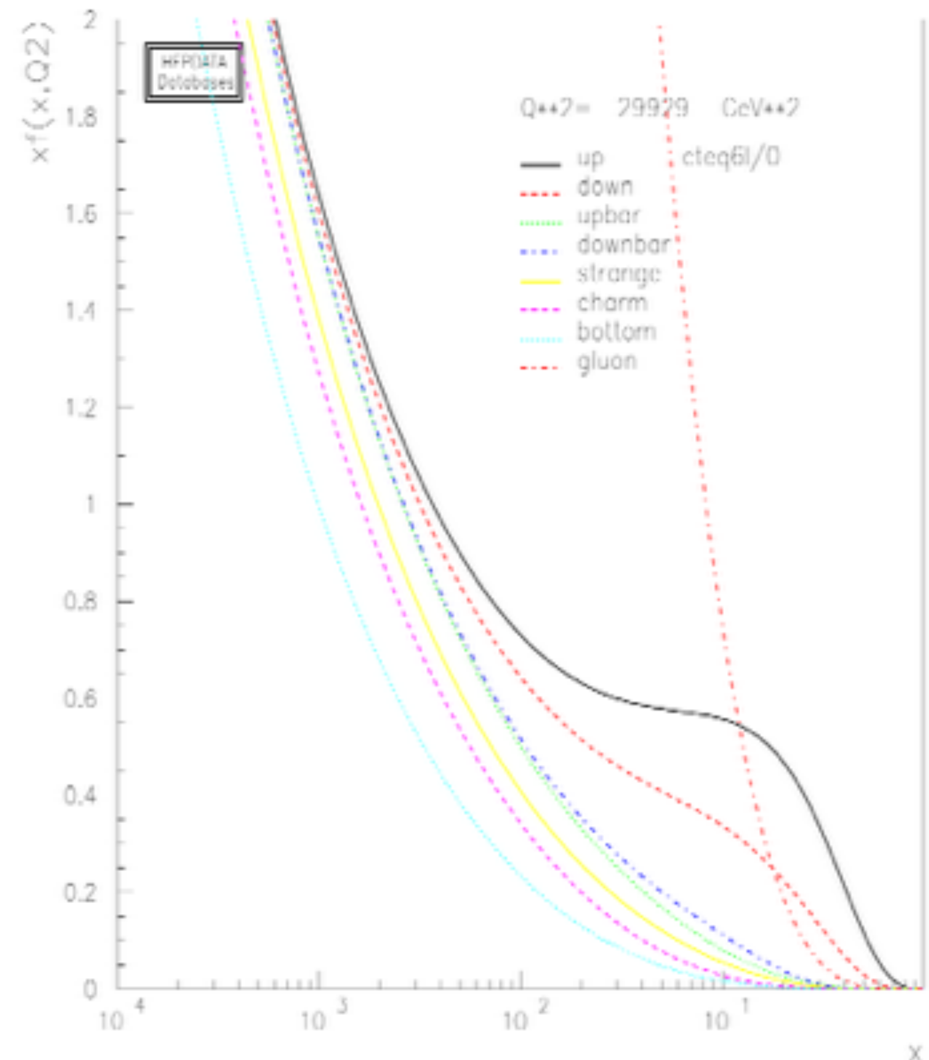


S.Kh, M.M.Najafabadi , Phys.Rev.D 89 (2014) 5, 054011

Charge Ratio

$$g + u(\bar{u}) \rightarrow t(\bar{t}) + H$$





The number of events with positive charged lepton to the number of events with negative charge :

$$R = \frac{\sigma(t+H)}{\sigma(\bar{t}+H)} = N(l^+)/N(l^-)$$

This observable can Discriminate between signal and backgrounds. In case of discovery, it can distinguish between tug and tcg couplings.

Charge Ratio

Inclusive values g+u > t+H :

$$R_{\text{signal}} = 4.35 \pm 0.02,$$

$$R_{W+jets} = 1.57 \pm 0.03,$$

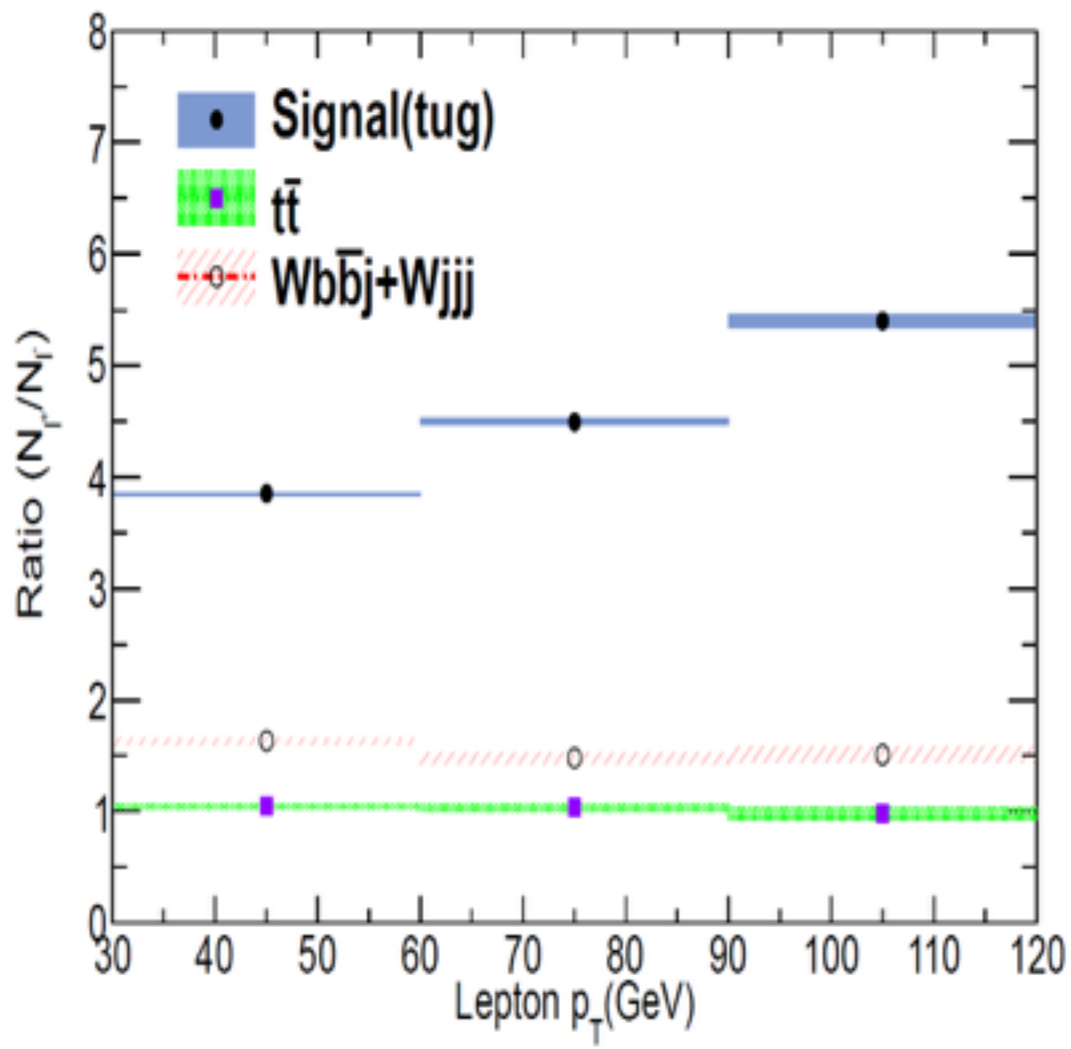
$$R_{t\bar{t}} = 1.04 \pm 0.03,$$

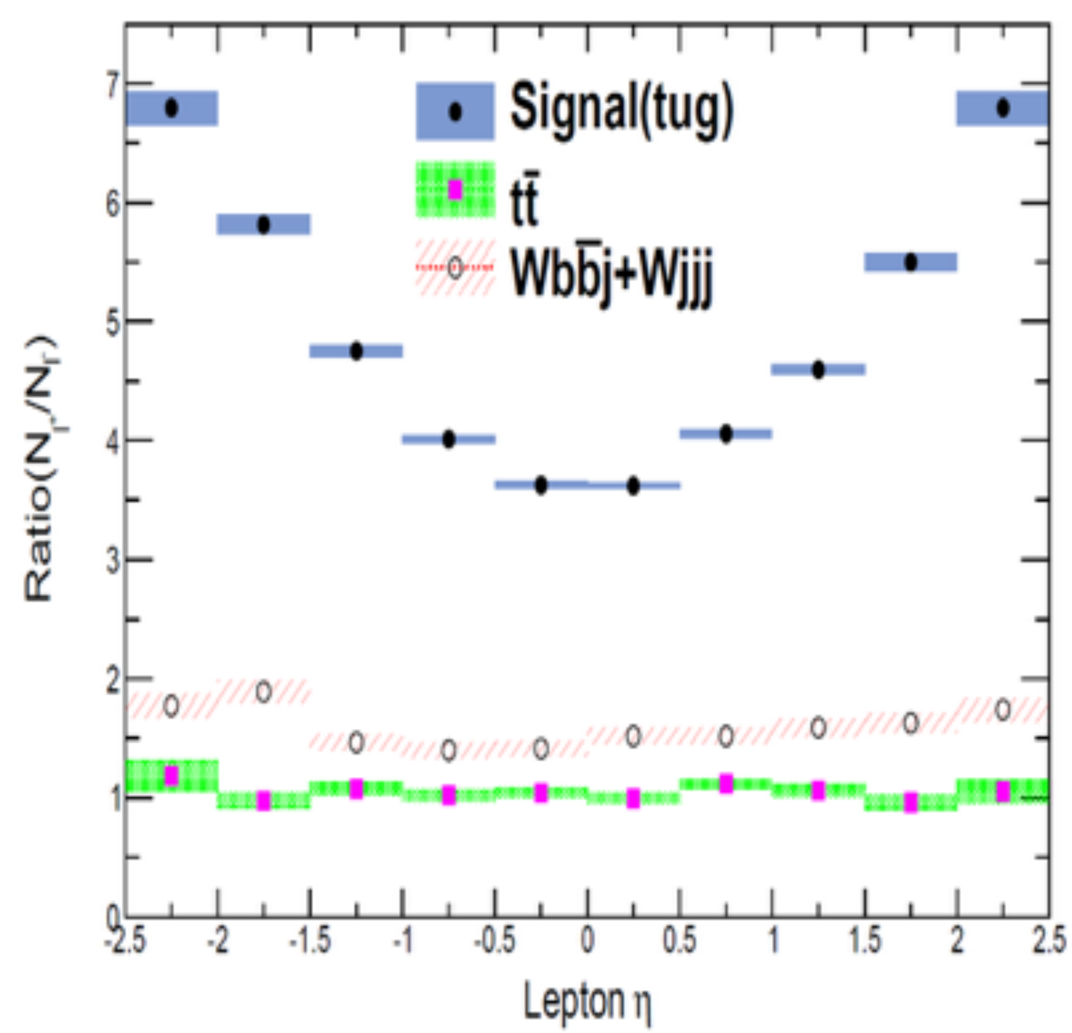
Since the c-quark and cbar-quark PDFs are similar, because both of them are sea quark:

For g + c > t+ H:
R = 1

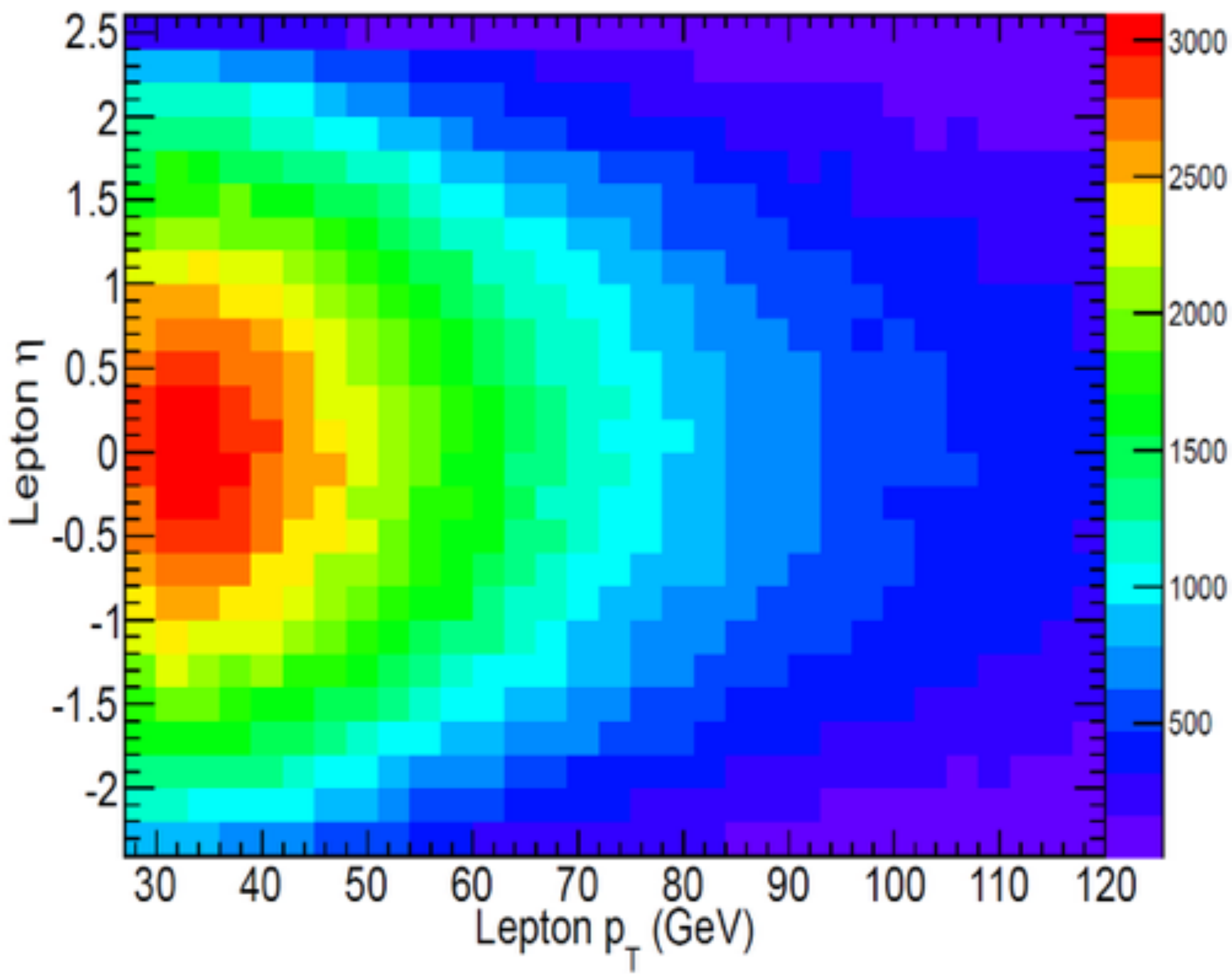
Charge Ratio

Dependence of the charge ratio on the transverse momentum and pseudorapidity of the charged lepton.





The correlation between the transverse momentum and pseudorapidity of the charged lepton for signal events.

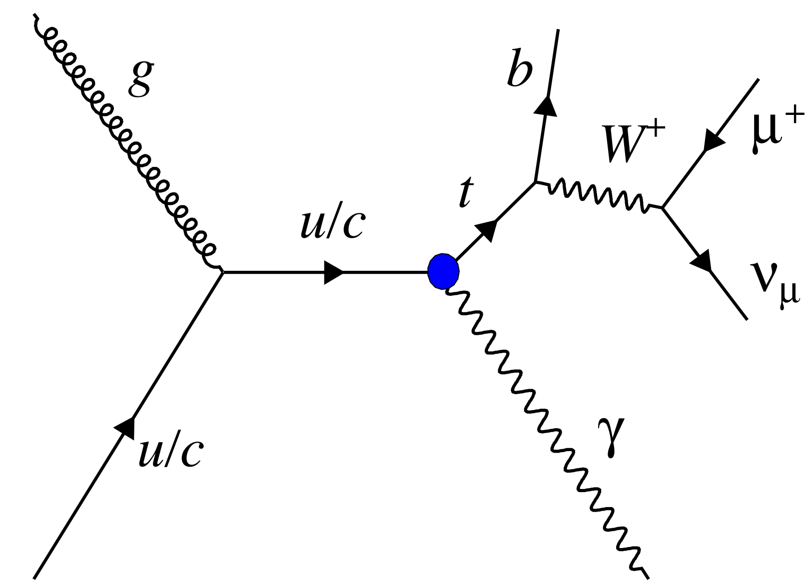


The large charge ratio for very energetic lepton would lead to the large charge ratio in the forward/backward region.

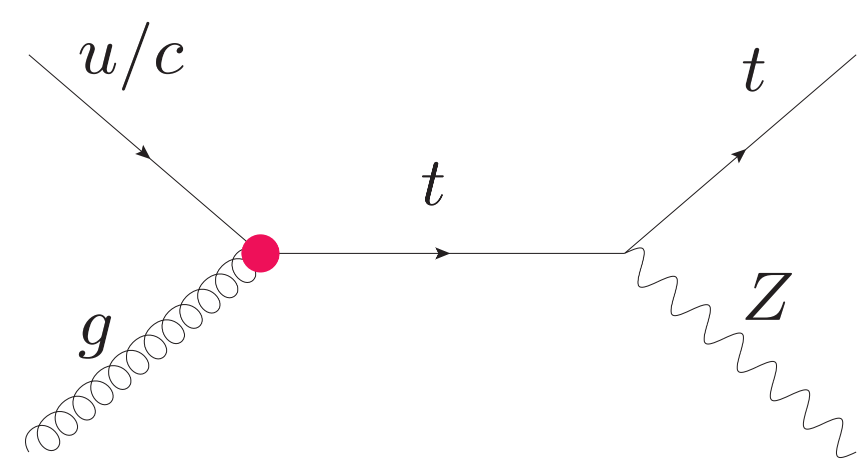
Charge Ratio

- It is notable that similar charge ratio properties as are applicable in the oth channels of anomalous single top production in association with a vector boson gamma or Z-boson.

$$q + g \rightarrow t + \gamma$$



$$q + g \rightarrow t + Z$$



CP-Violating in Top-Higgs Coupling

General Lagrangian for top-Higgs

- *We can parametrize the top-Higgs Lagrangian as,*

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)tH + h.c.$$

- *The coupling κ_t is CP-conserving .*
- *The coupling $\tilde{\kappa}_t$ is CP-violating .*
- *In the SM at leading order:* $\kappa_t = 1$ and $\tilde{\kappa}_t = 0$
- *CP-violating component can arise from loops at higher order in SM.*
- *They may arise from several new physics.*

Saavedra Nucl.phys.B 821(2009)215-227

Constraints ⇒ *Direct , Indirect*

- *Low Energy Experiments: Electric Dipole Moment(EDM), B meson rare decay, ...*
- *High Energy Experiments: Collider Observables,...*

Electric Dipole Moment(EDM)

$$T: E \rightarrow E, S \rightarrow -S$$

$$P: E \rightarrow -E, S \rightarrow S$$

$$H = -d\vec{S}.\vec{E}$$

$$P(H) = -(d\vec{S}.(-\vec{E})) \neq H$$

$$T(H) = -(d(-\vec{S}).\vec{E}) \neq H$$

- ***A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP.***
- *EDM is known to a good probe to CP violation in particle physics models.*
- *EDM of fermions first arises at the three loop level @ SM.*

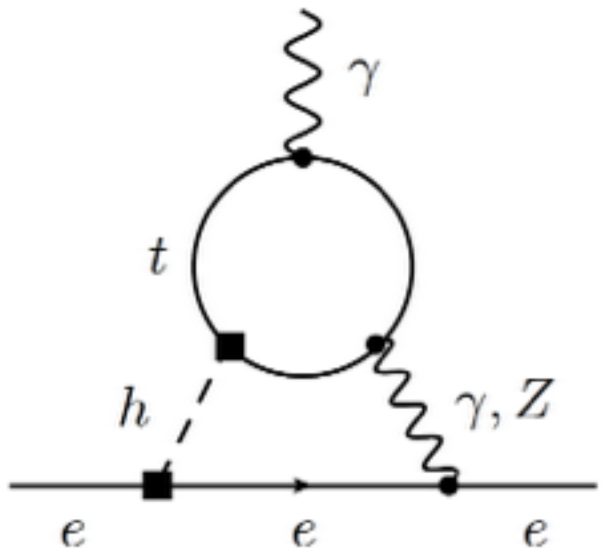
No one has ever found the EDM of any elementary particle.

Top-Higgs probe (I): EDM of the electron

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)tH + h.c.$$

$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F m_e \left[\kappa_e\tilde{\kappa}_t f_1(x_{t/h}) + \tilde{\kappa}_e\kappa_t f_2(x_{t/h})\right]$$

$$x_{t/h} \equiv \frac{m_t^2}{m_h^2}$$



Barr-Zee type digram

The 90% confidence level limit from AMCE collaboration:

$$\left|\frac{d_e}{e}\right| < 8.7 \cdot 10^{-29}\ \mathrm{cm} \quad \Rightarrow \quad |\tilde{\kappa}_t| < 0.01$$

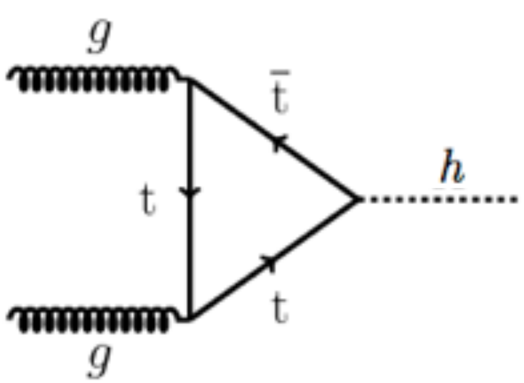
Zupan, et al. JHEP 1311, 180 (2013)

Science 343(6168):269-289

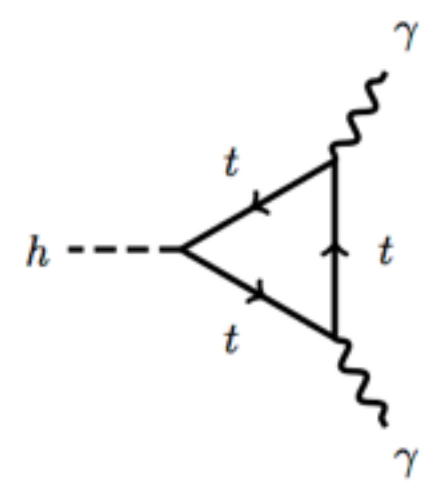
Top-Higgs probe (II): Higg Energy Constraints

- *The CP-violating Higgs couplings affect the production cross sections and decay branching ratios of the Higgs at loop level.*

- *Modifications of the Higgs-top couplings affect both the* $gg \to h$ *as well as the* $h \to \gamma\gamma$ *vertex, which are generated at one loop in the SM.*



$$\mu_{gg} = \frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}}$$



$$\mu_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}}$$

$$\mu_{gg} \simeq \kappa_t^2 + 2.6\tilde{\kappa}_t^2 + 0.11\kappa_t\,(\kappa_t - 1)\ ,$$

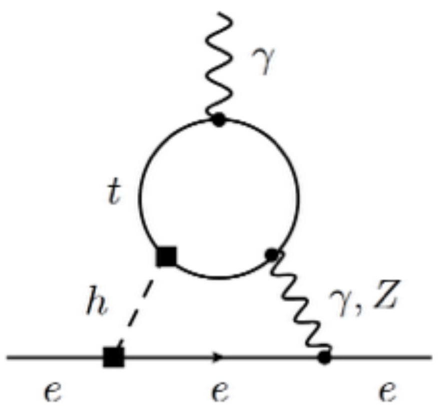
$$\mu_{\gamma\gamma} \simeq 0.078\kappa_t^2 - 0.71\kappa_t + 0.18\tilde{\kappa}_t{}^2 + 1.6,$$

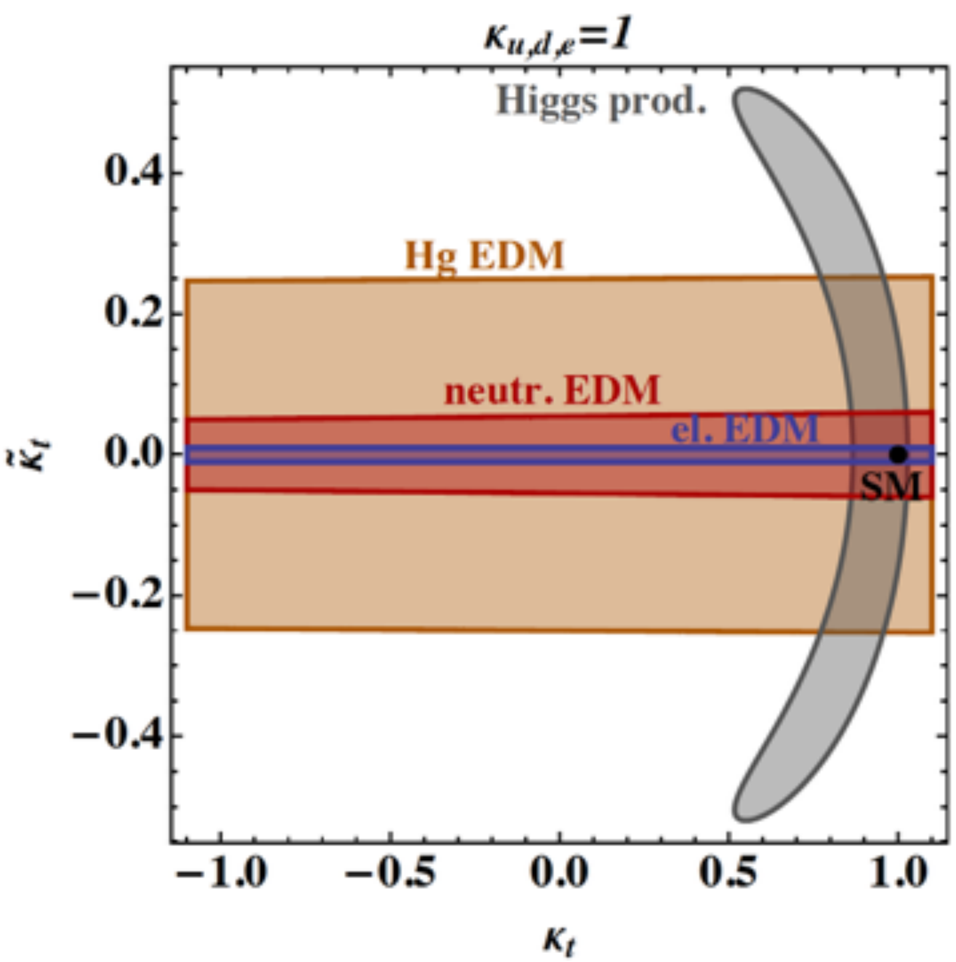
Zupan, et al. JHEP 1311, 180 (2013)

Indirect Constraints

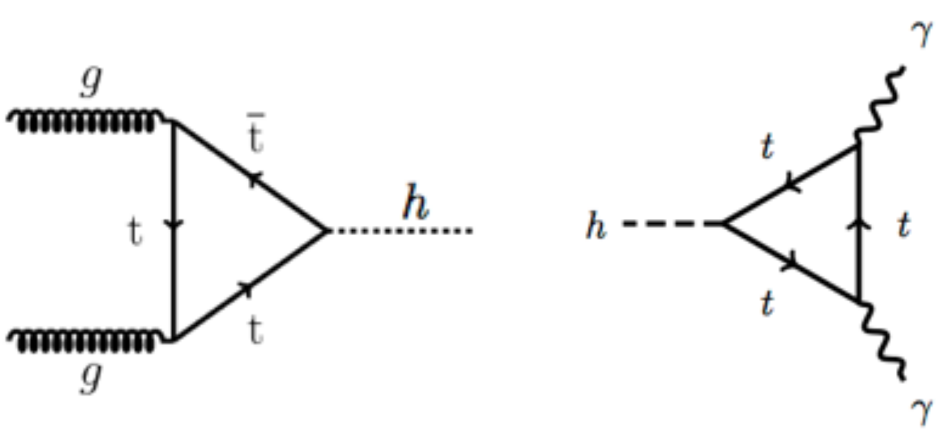
- *electron EDM*

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)tH + h.c.$$





- *Higgs production and Decay*

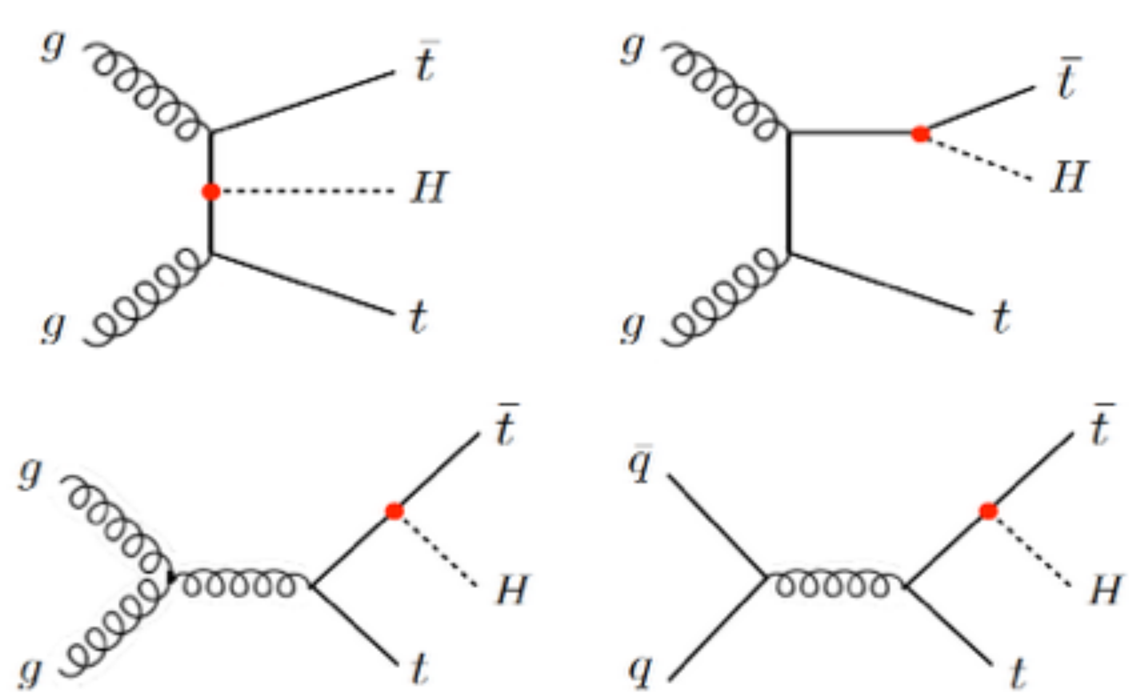


Zupan, et al. JHEP 1311, 180 (2013)

Top-Higgs couplings (III): Direct searches

- *We investigate the LHC potential to distinguish the scalar and pseudoscalar top-Higgs couplings.*
- *This process offers many observable to determine CP-violating and CP-conserving component.*

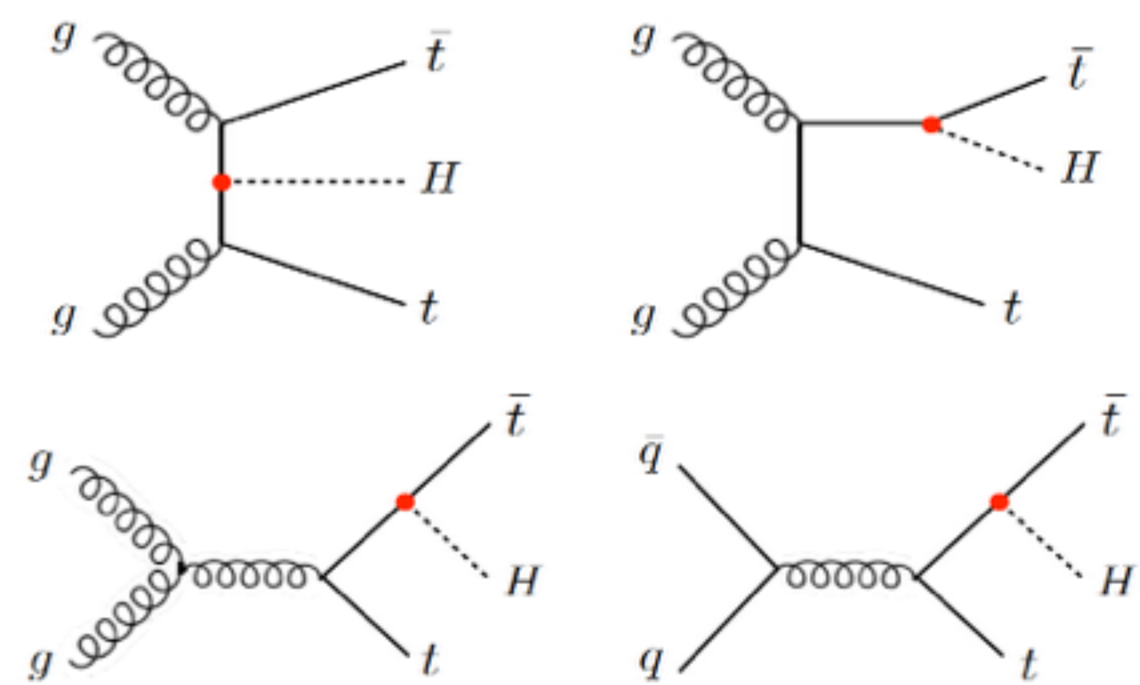
$$\mathcal{L} = -\frac{m_t}{v}\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)tH + h.c.$$



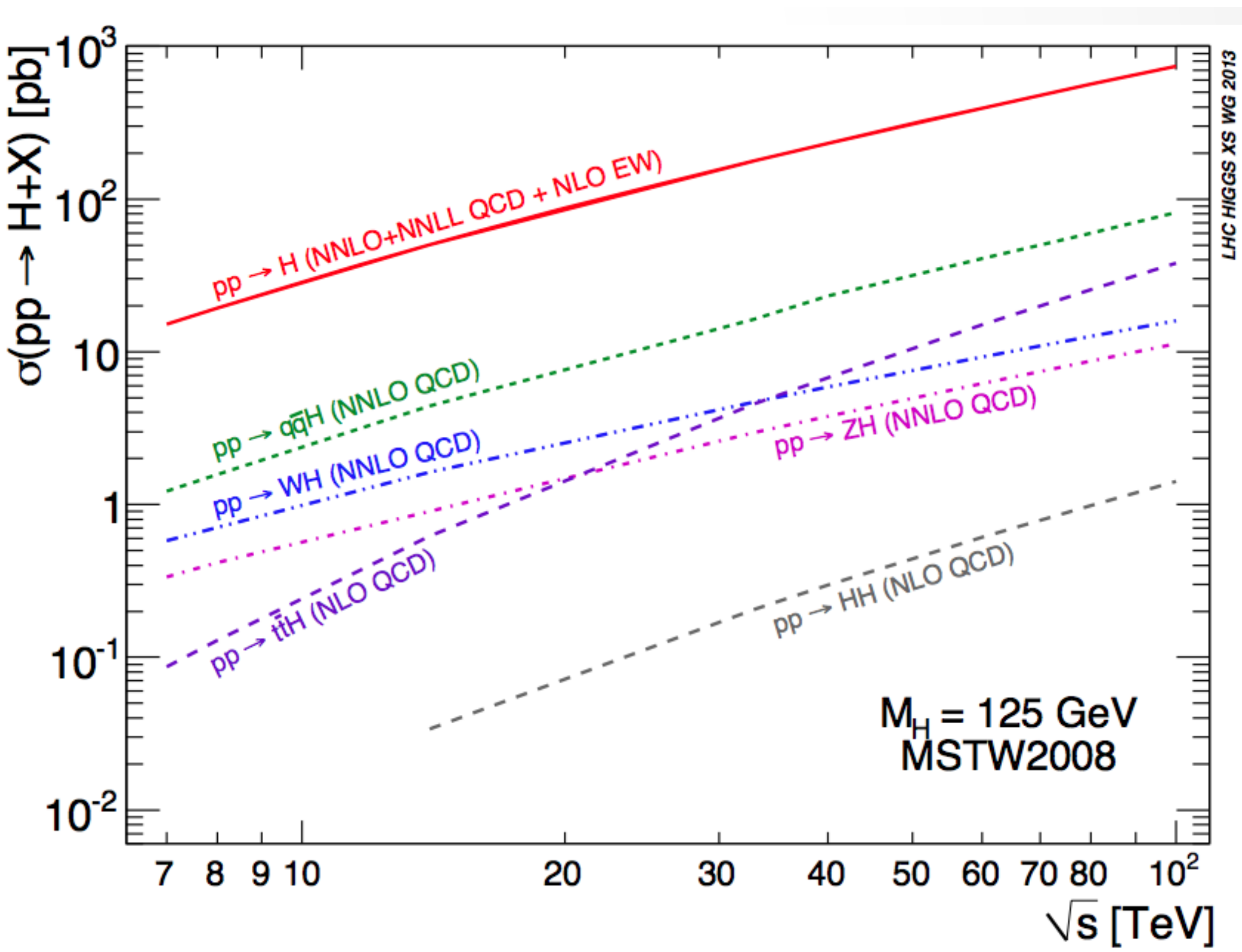
Top-Higgs couplings (III): Direct searches

σ(ttH) known at NLO in QCD
For MH=125 GeV: √s=8 TeV: σ(ttH)=130 fb

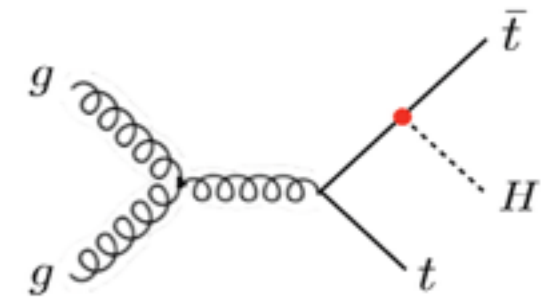
$$\mathcal{L} = -\frac{m_t}{v}\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)tH + h.c.$$



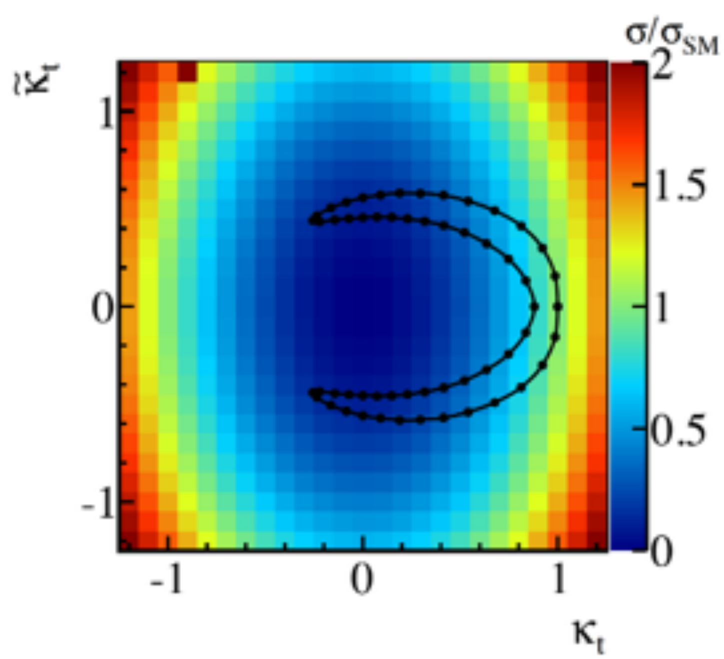
• Interestingly, the phase-space suppression effect is overcome at √s>30-40 TeV, where ttH becomes the 3rd most important production mechanism.



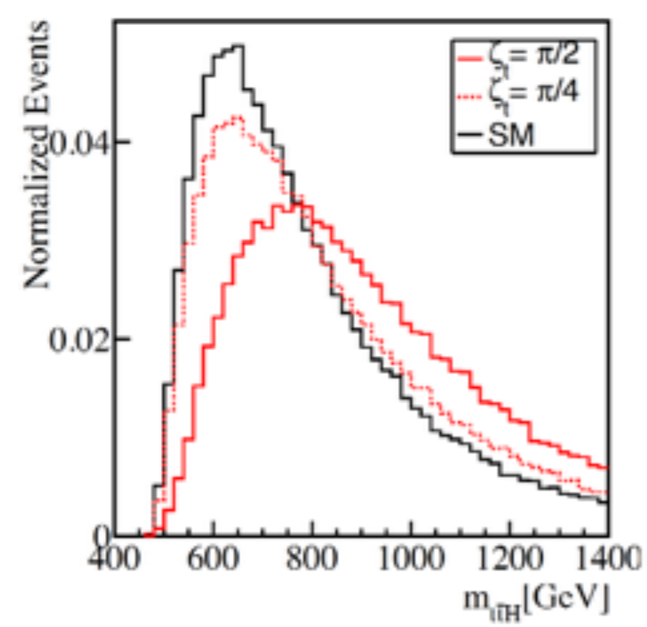
Sensitive Observables in Direct Searches



- *The cross sections and final-state distributions in ttH production are sensitive to the ratio between the scalar and pseudoscalar top-Higgs couplings*
- *The invariant mass distributions for the three-body combinations ttH are sensitive to the ratio between the scalar and pseudoscalar top-Higgs couplings*



$$\mathcal{L} = -\frac{m_t}{v}\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)tH + h.c.$$

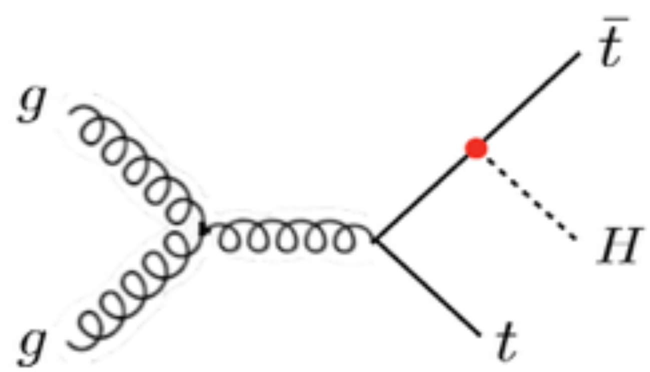


John Ellis , et al. JHEP 1404 (2014) 004

Azimutal Angular Observable

- *We define an asymmetry-like observable in PP > ttH, with respect to the azimutal angle differences :*

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)tH + h.c.$$



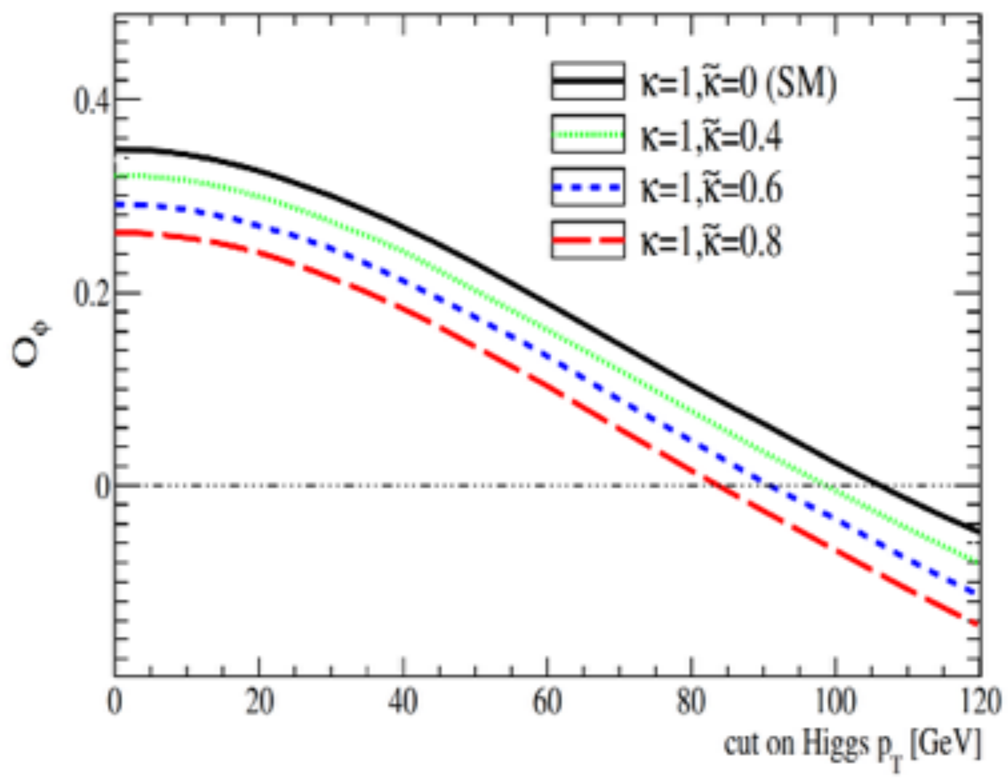
$$O_\phi = \frac{N(|\Delta\phi(t\bar{t})| > |\Delta\phi(tH)|) - N(|\Delta\phi(t\bar{t})| < |\Delta\phi(tH)|)}{N(|\Delta\phi(t\bar{t})| > |\Delta\phi(tH)|) + N(|\Delta\phi(t\bar{t})| < |\Delta\phi(tH)|)}$$

$$\Delta\phi_{t\bar{t}} = \phi_t - \phi_{\bar{t}} \text{ and } \Delta\phi_{tH} = \phi_t - \phi_H$$

- *The observable as a function of the cut on Higgs boson pT:*

SM →

cut on Higgs-p_T (GeV)	0.0	50.0	100.0	200.0	300.0
$O_\phi(\kappa_t = 1, \tilde{\kappa}_t = 0)$	0.356	0.229	0.021	-0.265	-0.411
$O_\phi(\kappa_t = 1, \tilde{\kappa}_t = 0.4)$	0.317	0.191	-0.006	-0.299	-0.441

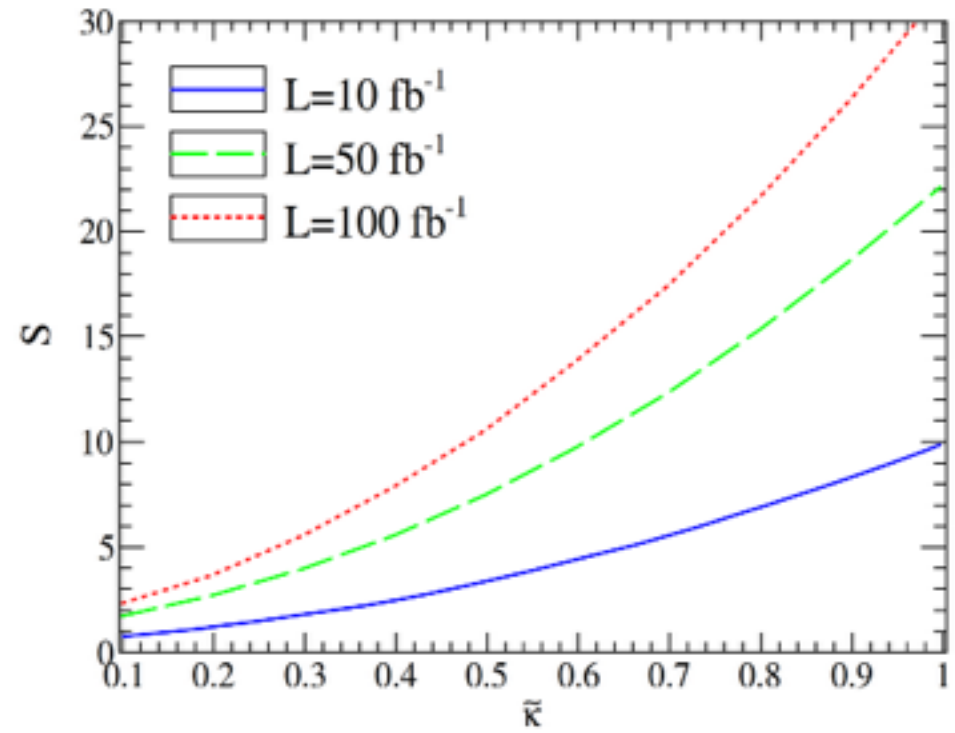


- *The presence of a CP-violating coupling in ttH interaction reduces the amount of O at any value of the cut on Higgs boson pT .*

Statistical Significance

The significance of the observable O is defined as the number of standard deviations σ of which O differs from zero:

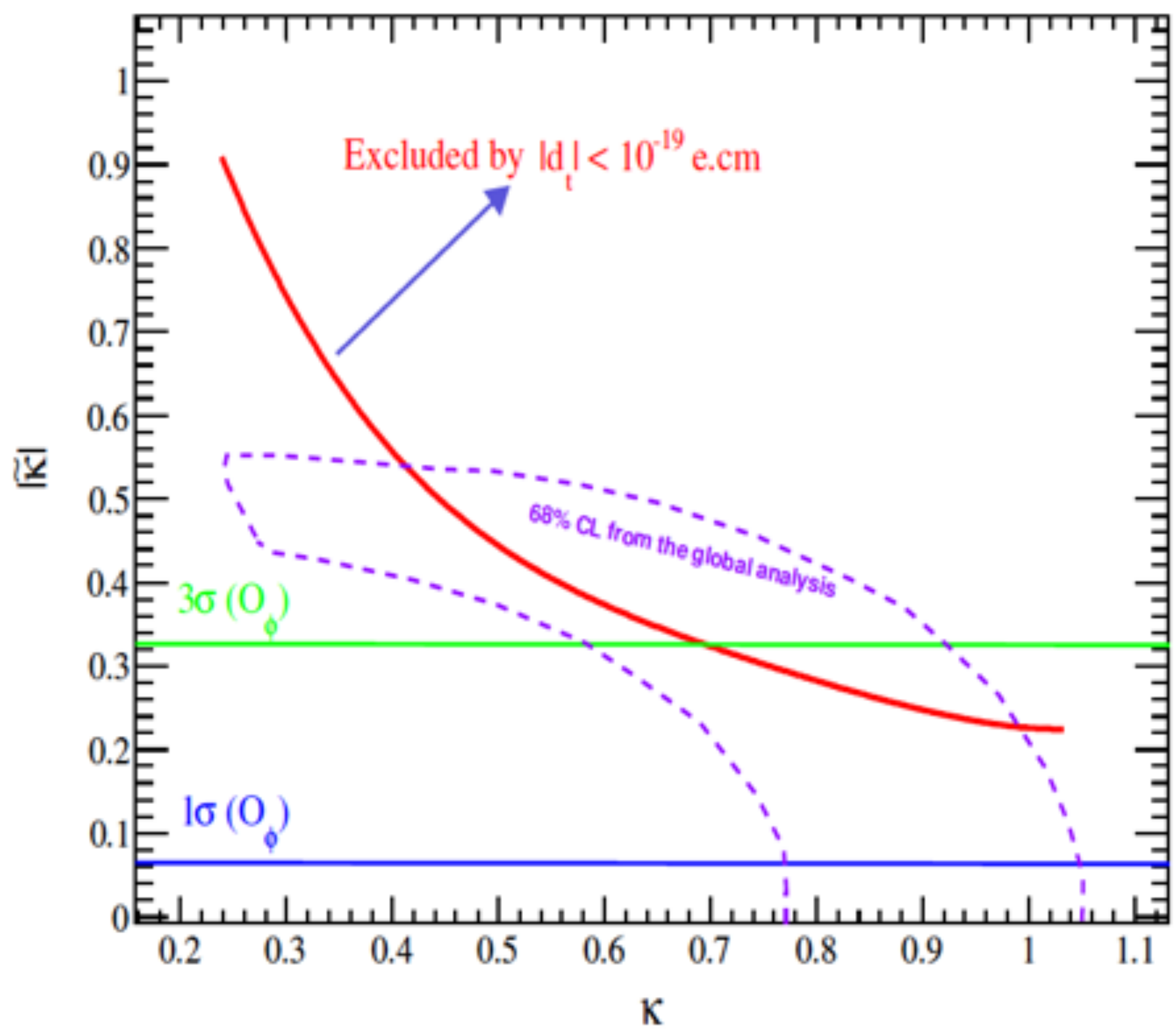
$$S(\kappa_t, \tilde{\kappa}_t) = \frac{O_\phi(\kappa_t, \tilde{\kappa}_t) - O_\phi^{SM}}{\sqrt{1 - (O_\phi^{SM})^2}} \sqrt{\sigma^{SM}_{pp \to t\bar{t}H} \mathcal{L}}$$



The left plot shows the statistical significance for the integrated luminosities of 10,50,100 fb-1*. The right plot shows, the* 1,3 *and* 5 *sigma regions.*

Allowed Region

68% CL allowed region from the global analysis(violet dashed-curve), the 1 and 3 sigma allowed region obtained using the observable with 30 fb-1 of the LHC data at 14 TeV. The red solid curve shows the allowed region that could be obtained by the future upper limit on the top quark EDM .

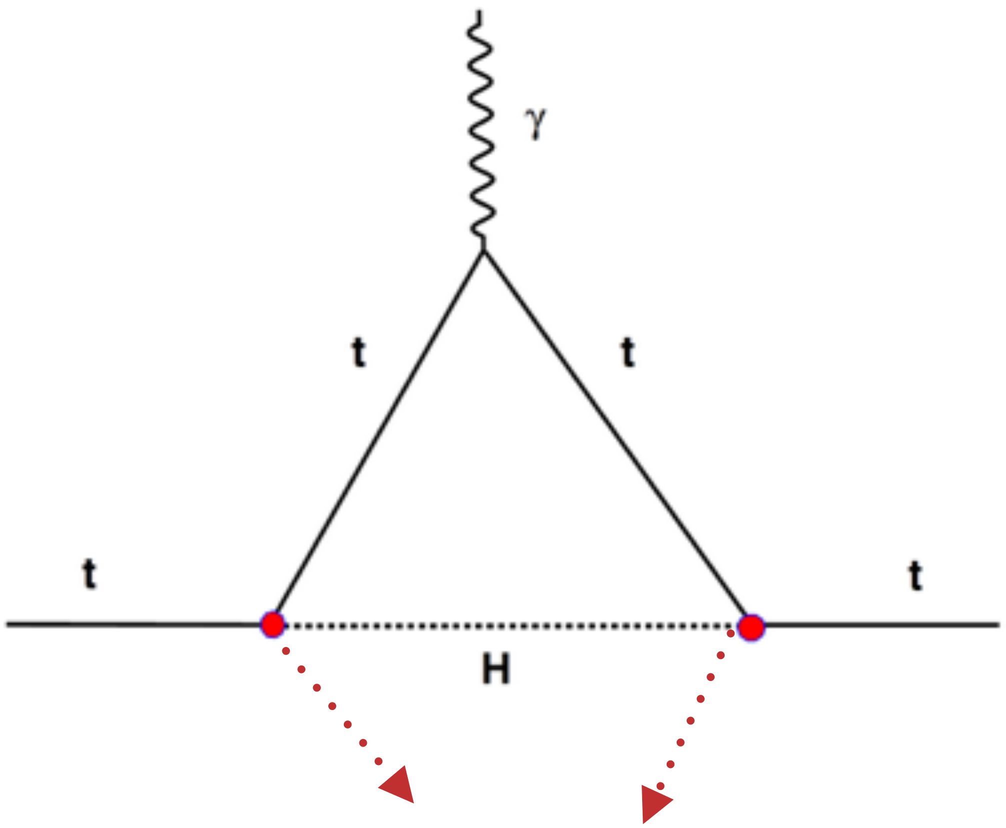


Top Electric Dipole Moment(EDM) Analysis

$$|d_t| = \frac{1}{8\pi^2}\frac{2e}{3m_t}\kappa_t\tilde{\kappa}_t f(x)$$

$$x = \frac{m_H^2}{m_t^2}$$

$$|d_t| < 10^{-19}\, e.cm$$



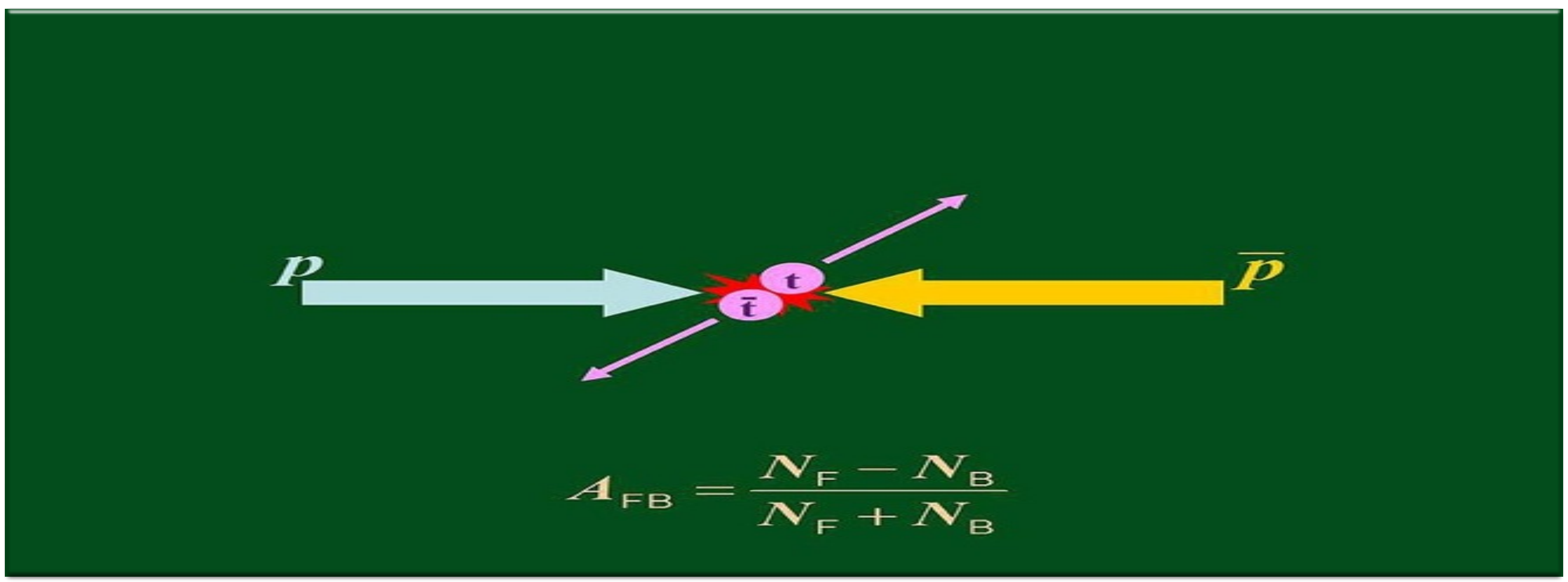
$$\mathcal{L} = -\frac{m_t}{v}\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)tH + h.c.$$

Summary

- Top quark has important rule to search for new physics.
- Top FCNC interactions can be important to search for New Physics.
- Top-Higgs Coupling is important to search for new physics as well by using low energy and high energy experiments.
- It must be explored indirectly by flavor physics and directly by collider physics in as many as possible channels.

“Backup Slides”

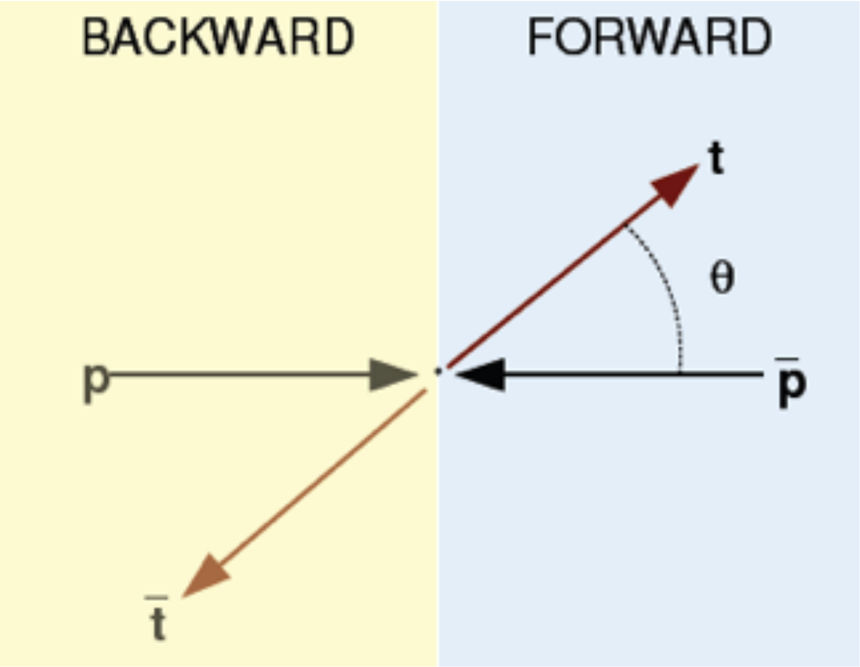
Top Asymmetries



Top Forward-Backward Asymmetry

- *Well-known Tevatron Forward-Backward Asymmetry in ttbar events*

$$A_{t\bar{t}} = \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)}.$$

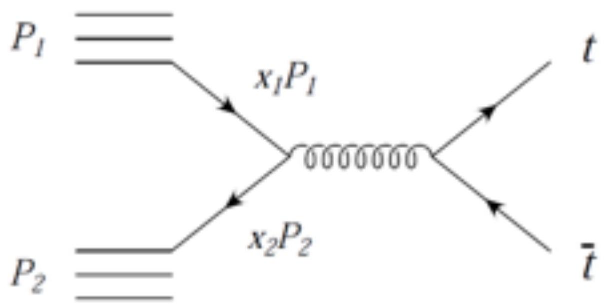


❖*Kuhn & Rodrigo* [PRL **81 (1998) 49**]

❖*First experimental result:*
DO paper [PRL: 100 (2008) 142002]
Quickly followed by CDF paper [PRL: 100 (2008) 202001]

❖*Both experiments found higher values than the SM expectations.*

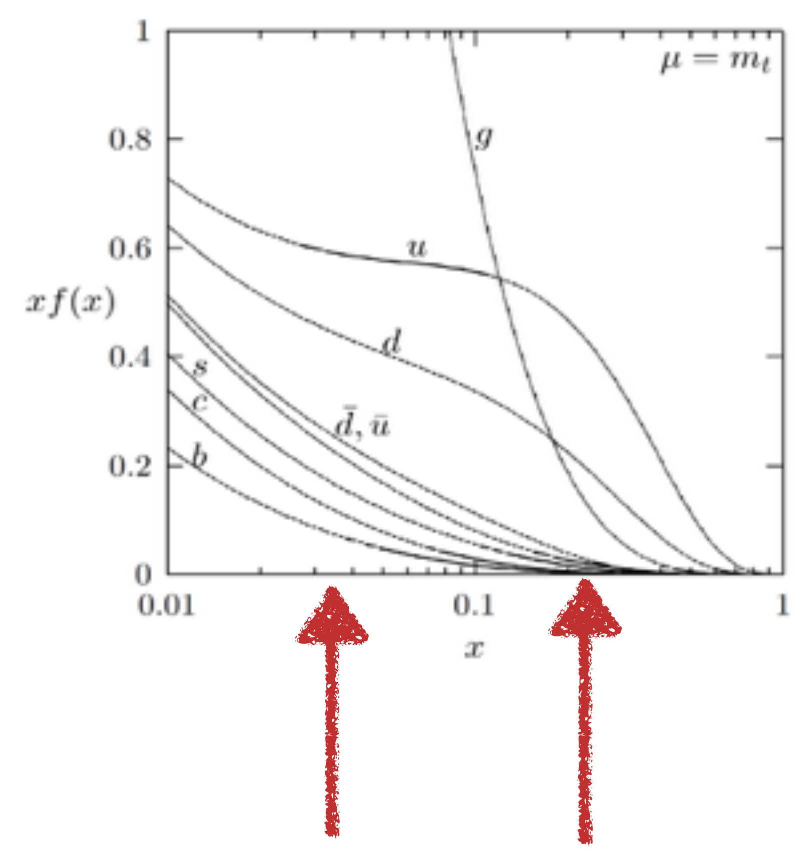
❖*For* $m_{t\bar{t}} \geq 450 GeV \Rightarrow A^{\exp}{}_{t\bar{t}} = 0.475 \pm 0.114, A^{SM}{}_{t\bar{t}} = 0.13 \pm 0.01$ *there were* 3.4 *discrepancy.*



Top Pair production @ hadron colliders

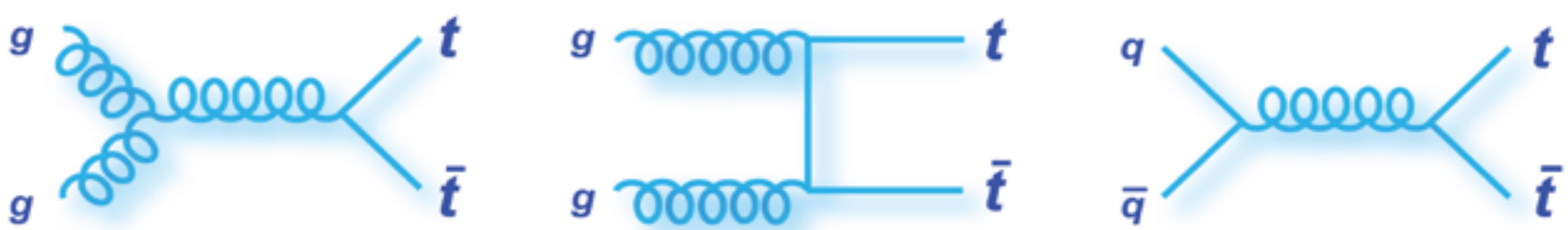
$$x_1 x_2 = \frac{\hat{s}}{S} \geq \frac{4m_t^2}{S} \quad \Rightarrow \quad x \approx \frac{2m_t}{\sqrt{S}}$$

	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%



LHC *Tevatron*

top-pair strong production

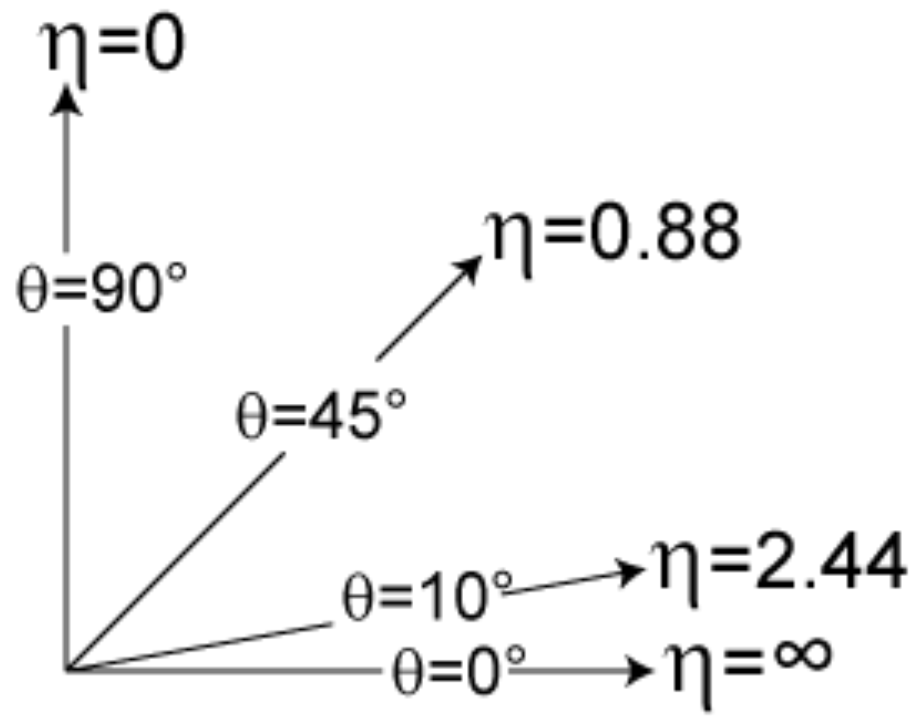


Rapidity

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

In the massless limit:

$$y \rightarrow \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = \ln\cot\frac{\theta}{2} \equiv \eta$$



Top Forward-Backward Asymmetry

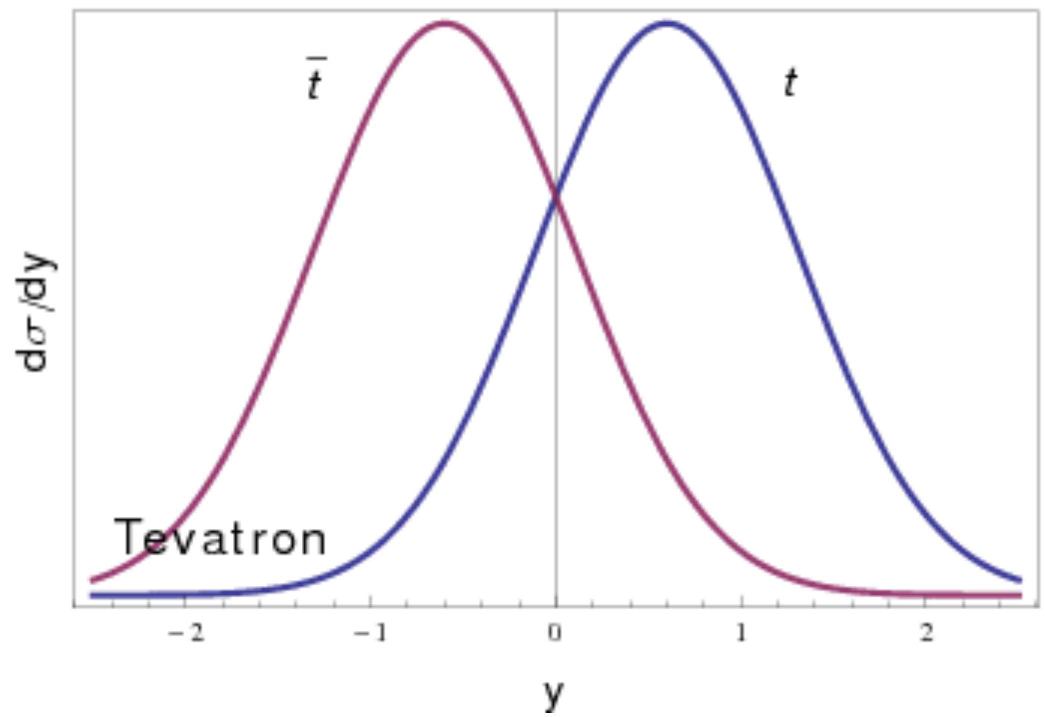
Longitudinal boost independent

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

$$\Delta y^{t\bar{t}} \equiv y_t - y_{\bar{t}}$$

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

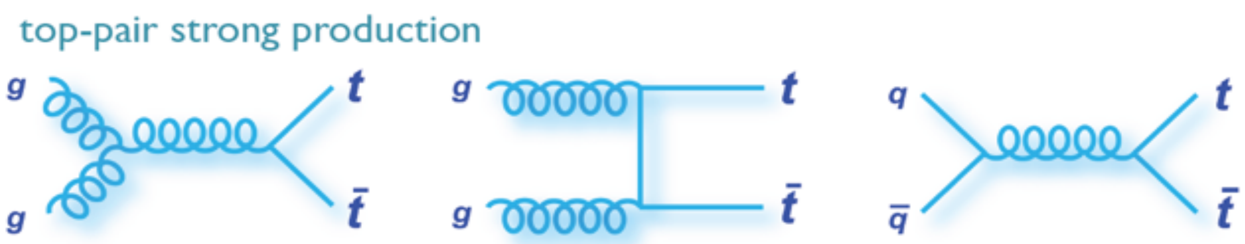
$$y_t - y_{\bar{t}} = 2 \text{ arctanh } \left(\sqrt{1 - \frac{4m_t^2}{\hat{s}}} \cos\theta\right)$$



A_{tt} @ SM

$$A_{t\bar{t}} = \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)}.$$

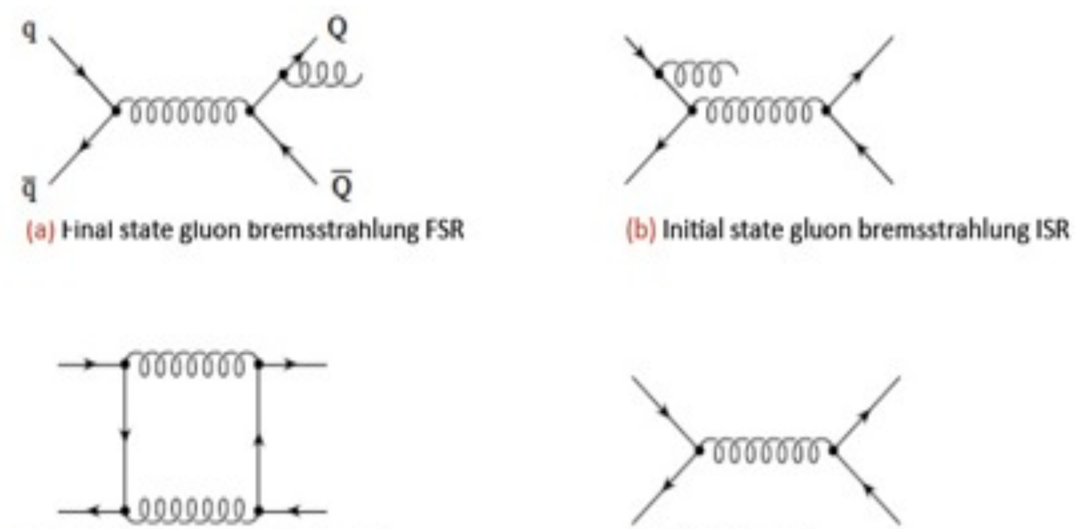
- *Tree level top pair production diagrams can not generate any asymmetry.*



$$LO : N_t = L \times \sigma_{t\bar{t}} \propto a + b(\cos\theta)^2$$

- *Top Asymmetry arise at next to leading order in* ***QCD***.

$$NLO : N_t = L \times \sigma_{t\bar{t}} \propto a' + b'\cos\theta + c'(\cos\theta)^2$$



(a) Final state gluon bremsstrahlung FSR

(b) Initial state gluon bremsstrahlung ISR

(c) double virtual gluon exchange

(d) Born diagram

Order	$A_{t\bar{t}}$
NLO QCD	0.072 ± 0.009

$$A_{t\bar{t}}(\text{CDF}) = 0.164 \pm 0.047,$$

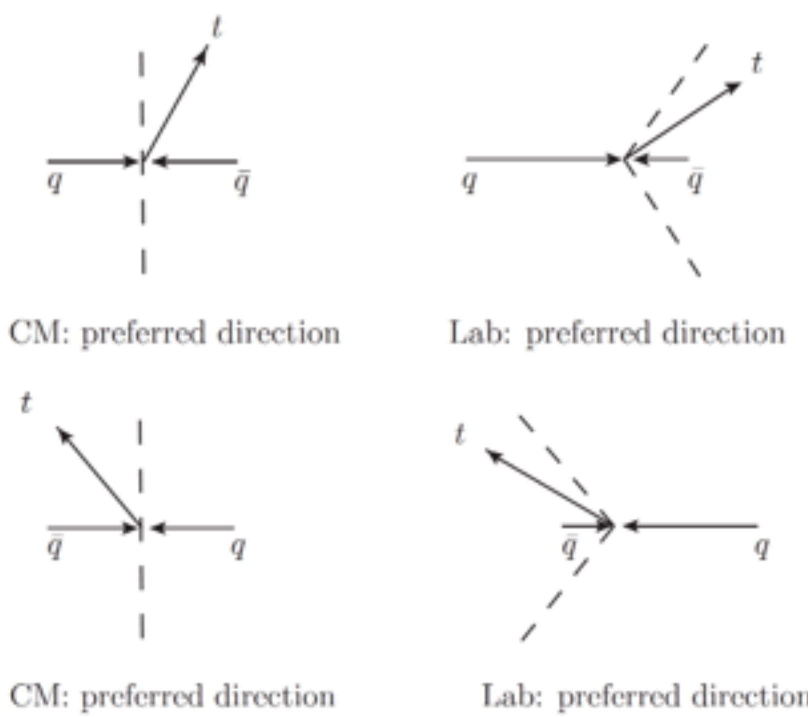
$$A_{t\bar{t}}(\text{DØ}) = 0.106 \pm 0.030,$$

Kuhn & Rodrigo, 2011 *CDF Collaboration, Phys. Rev. D 87, 092002 (2013)* D0 Collaboration, Phys. Rev. D 90, no. 7, 072011(2014)

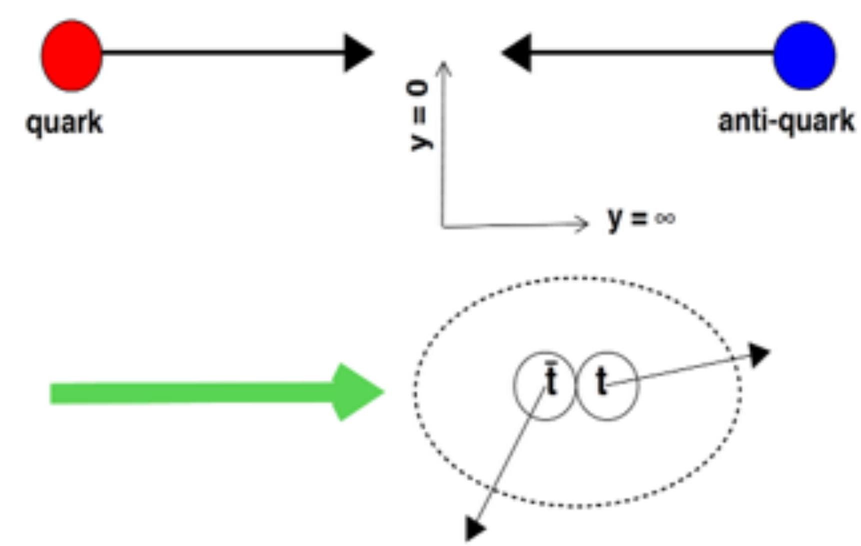
Related Charge Asymmetry @ LHC

LHC is Symmetric ⇨ *No Forward-Backward Asymmetry*

But suppose that there is a charge asymmetry at Parton level(QCD predicts that tops are preferentially emitted in the direction of incoming quark, BSM asymmetry can be positive or negative)



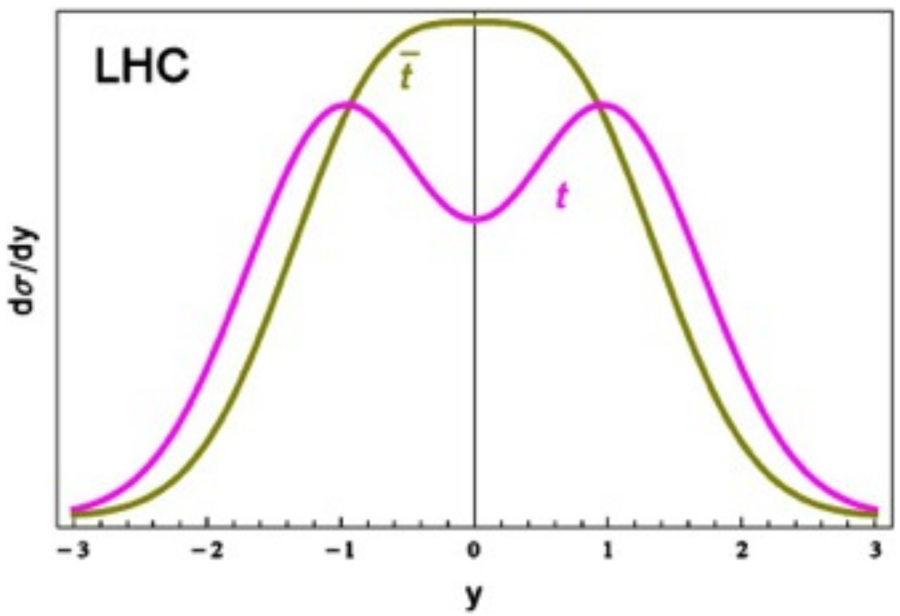
quarks carry more momenta than antiquarks



Related Charge Asymmetry @ LHC

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

$$\Delta|y|^{t\bar{t}} \equiv |y_t| - |y_{\bar{t}}|$$



Due to the dominant symmetric contribution from initial state gluons the SM predicts a small charge asymmetry :

$\sqrt{S}$	$A_C^{t\bar{t}}$
7 TeV	0.0123 ± 0.0005
8 TeV	0.0111 ± 0.0005

$$A_C^{t\bar{t}}(\text{CMS}, 7\ \text{TeV}) = \quad 0.004 \pm 0.010 \pm 0.011$$

$$A_C^{t\bar{t}}(\text{CMS}, 8\ \text{TeV}) = \quad 0.005 \pm 0.007 \pm 0.006,$$

No hint of an excess ... but still some room for new physics

W. Bernreuther and Z. -G. Si, Phys. Rev. D 86, 034026 (2012)

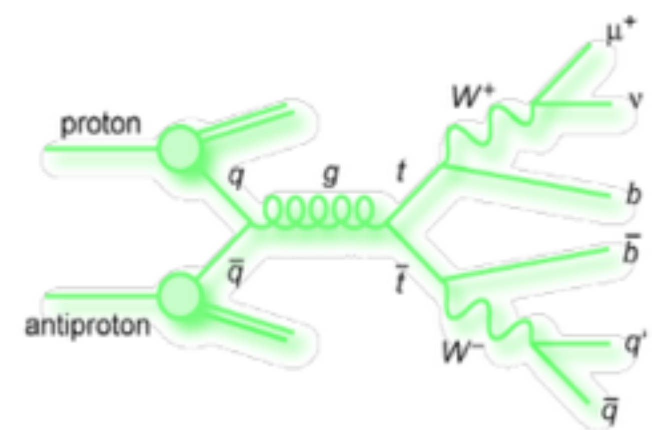
CMS collaboration, Phys. Lett .B.717(2012)129

Lepton-Based Asymmetries

Tevatron:

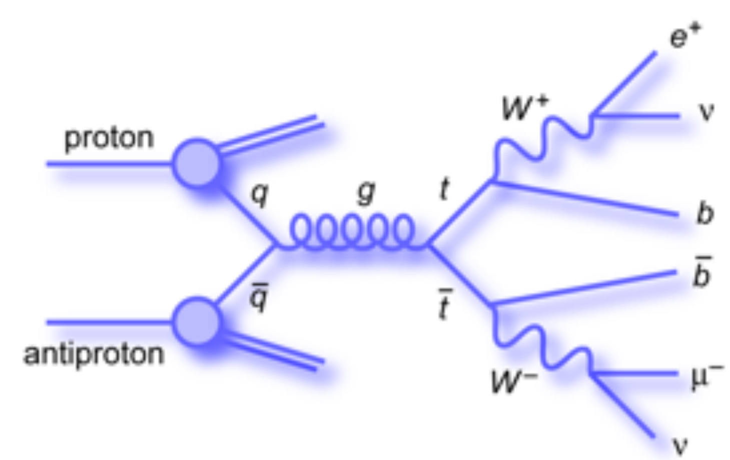
$$A_\ell = \frac{N(q \times \eta > 0) - N(q \times \eta < 0)}{N(q \times \eta > 0) + N(q \times \eta < 0)},$$

$$A_{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) - N(\Delta\eta < 0)}, \qquad \Delta\eta \equiv \eta_{l^+} - \eta_{l^-}$$



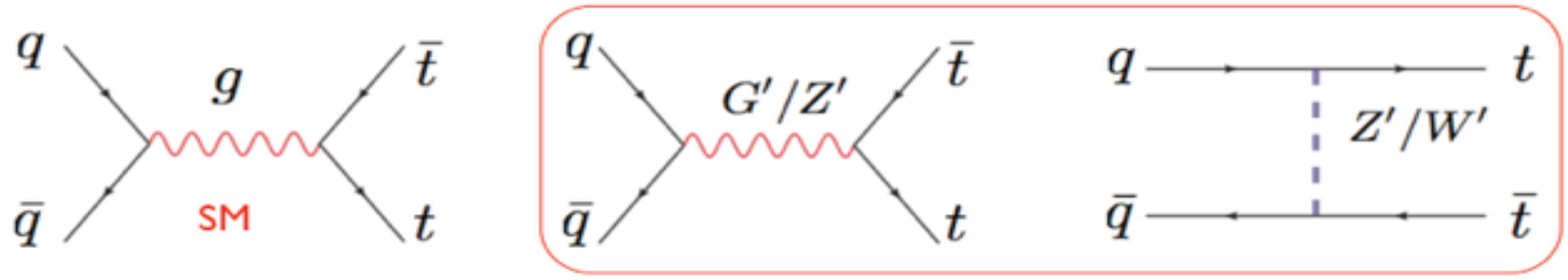
LHC:

$$A_C^{\ell\ell} = \frac{N(\Delta|\eta|^{l^+l^-} > 0) - N(\Delta|\eta|^{l^+l^-} < 0)}{N(\Delta|\eta|^{l^+l^-} > 0) + N(\Delta|\eta|^{l^+l^-} < 0)}, \quad \Delta|\eta|^{l^+l^-} \equiv |\eta_{l^+}| - |\eta_{l^-}|$$



Lepton based asymmetries in t-tbar events are in principle independent observables that can reveal or constrain new physics.

NP models may be divided into Two classes :



s-channel: extra octet-color vector gluon (axigluon).

Frampton andS. L. Glashow, Phys. Lett. B 190, 157

t-channel: flavor changing interaction (W´, Z´).

- A puzzling aspect of the observed excess is that the large value of the measured asymmetries are not accompanied by any sizable deviation in other top observables, such as the total or differential tt production cross sections.
- Furthermore, non-SM dynamics can naturally induce a large deviation for the AFB at the Tevatron without affecting the charge asymmetry at the LHC

These strongly constrains possible explanations of the anomalous AFB.