IPM

Collider Phenomenology @ Top Sector

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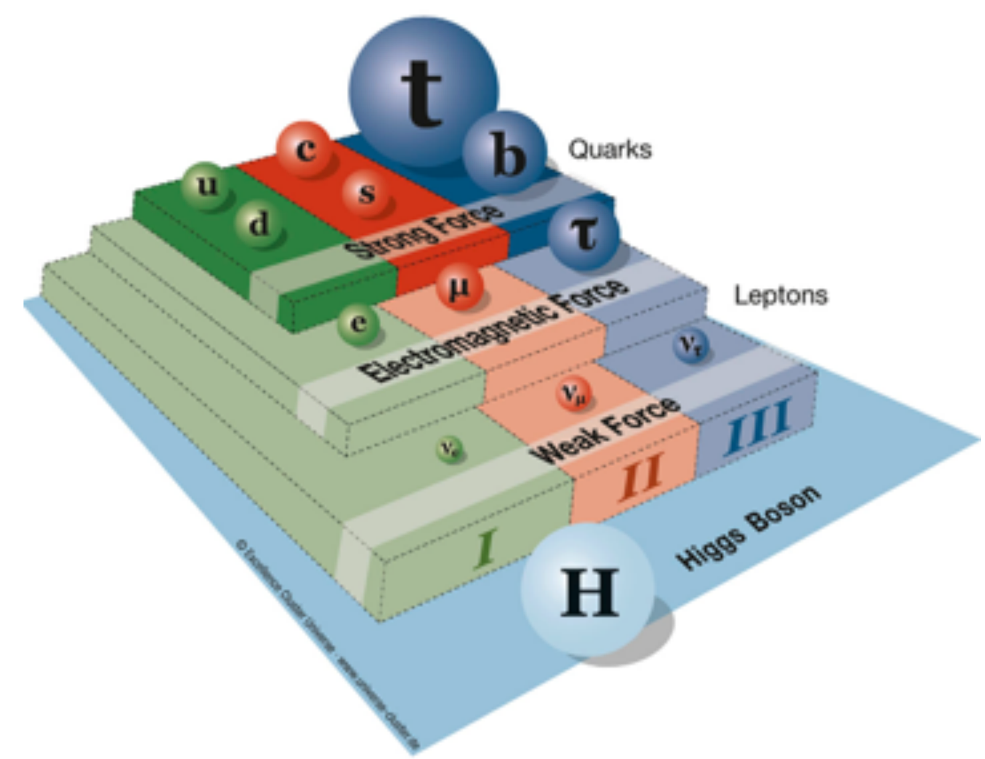
Motivations:
SM and Higgs @ LHC Run I

- *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]

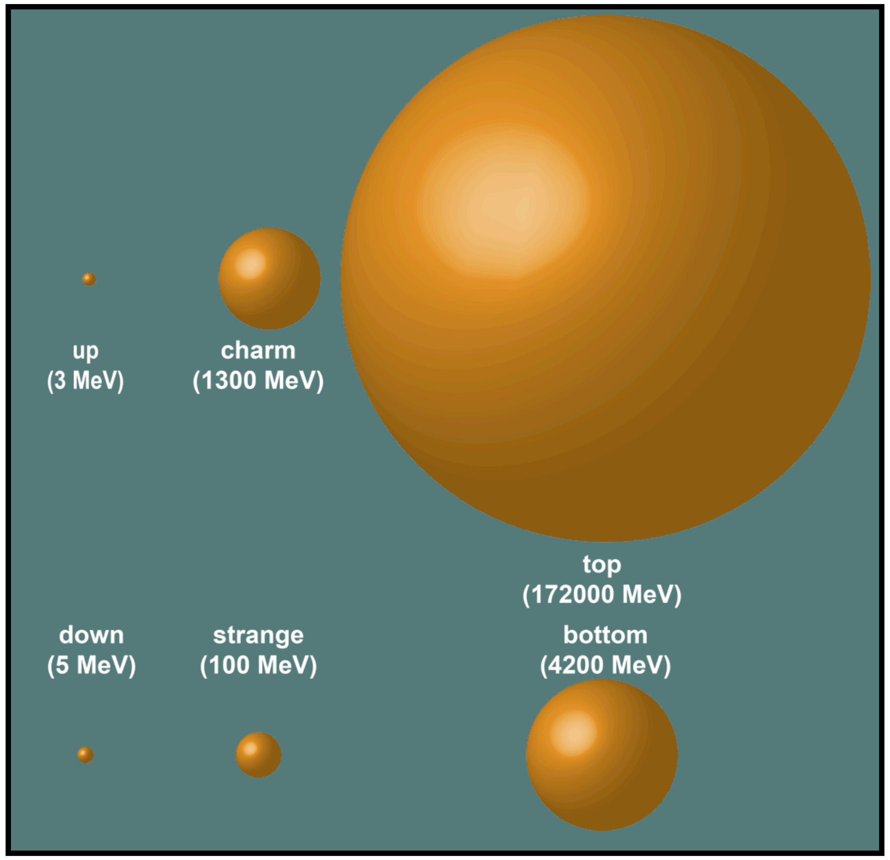
- 1980ies
Search for light top (mt < mW–mb)
in decays W → tb

- 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.*



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

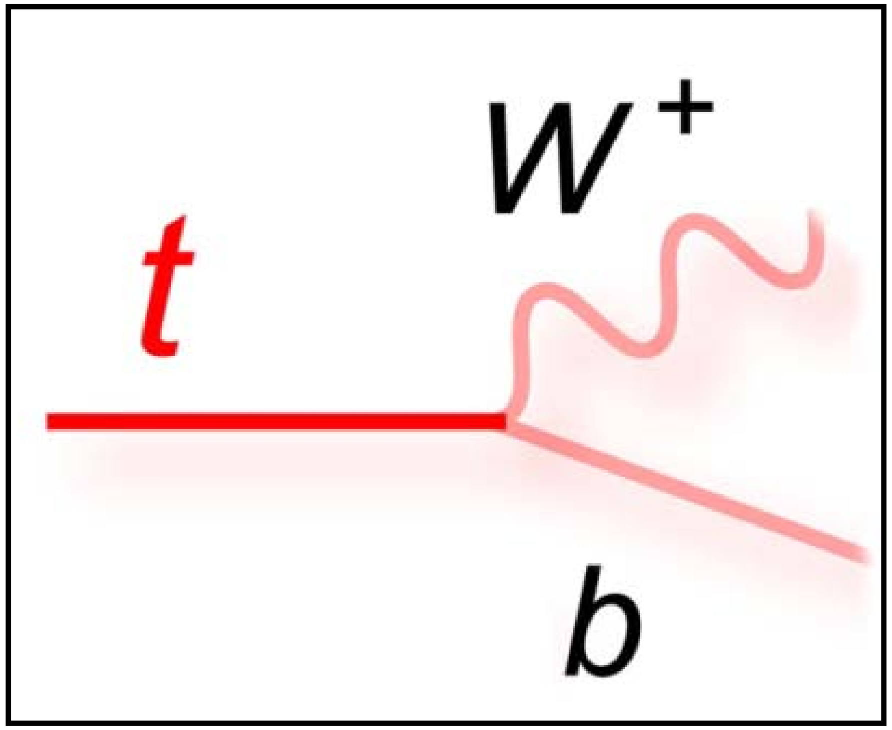
- *Special role in EWSB?*

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

Motivation: Top quark as bare quark

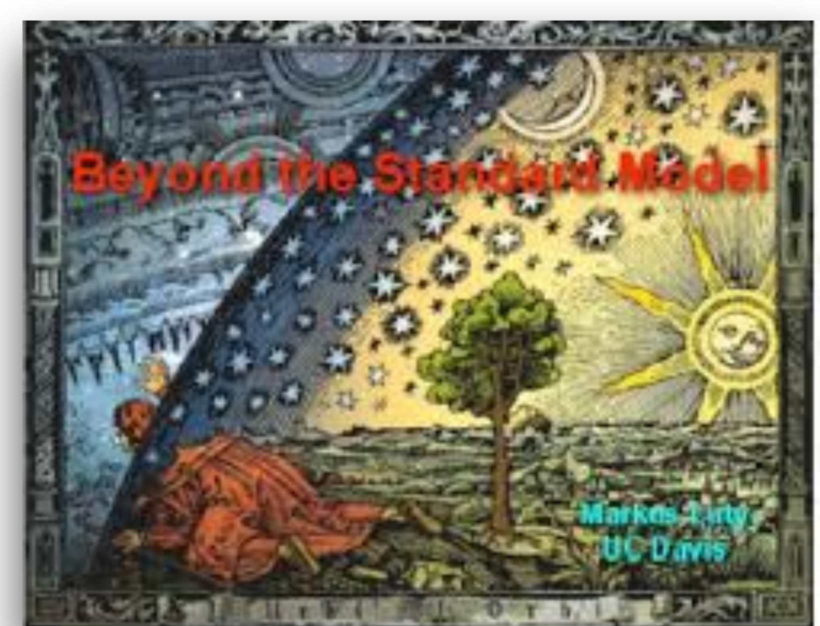
- *Top quark is short lived! (Decays almost exclusively to W b)*
- *Lifetime < hadronization*

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



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....*

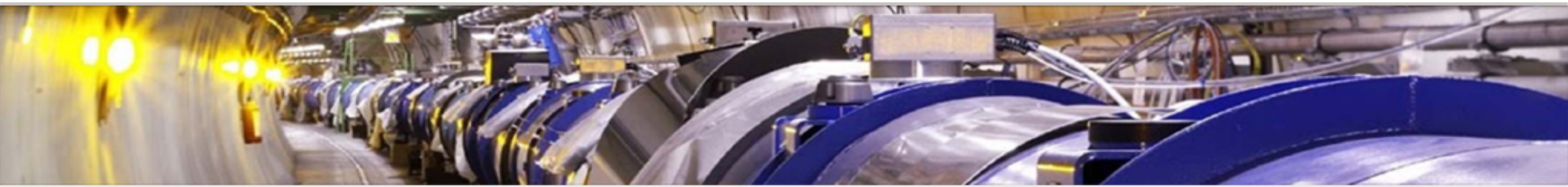


Top Physics @ Colliders

Outline

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

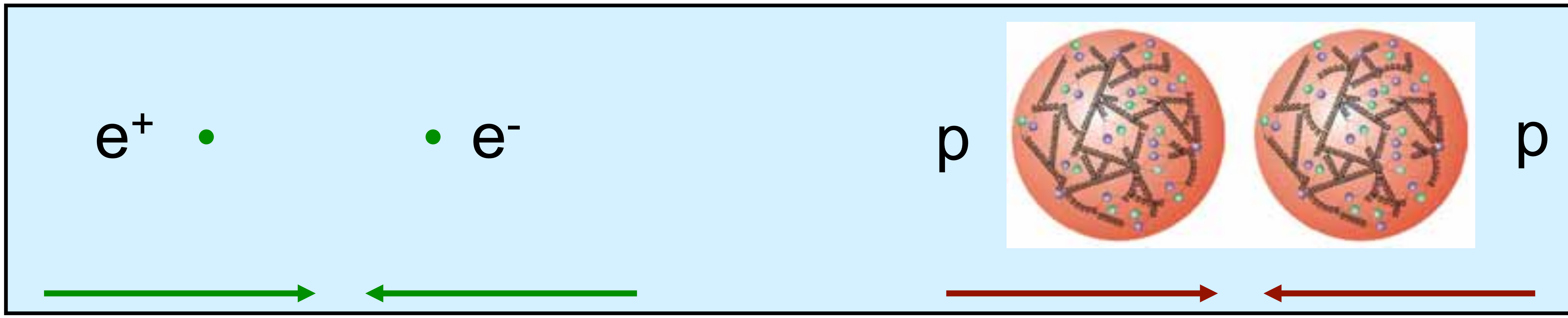
Collider Phenomenology



Colliders

Lepton Collider

Hadron collider



collisions of point-like particles

- Clean environment

collisions of composite particles

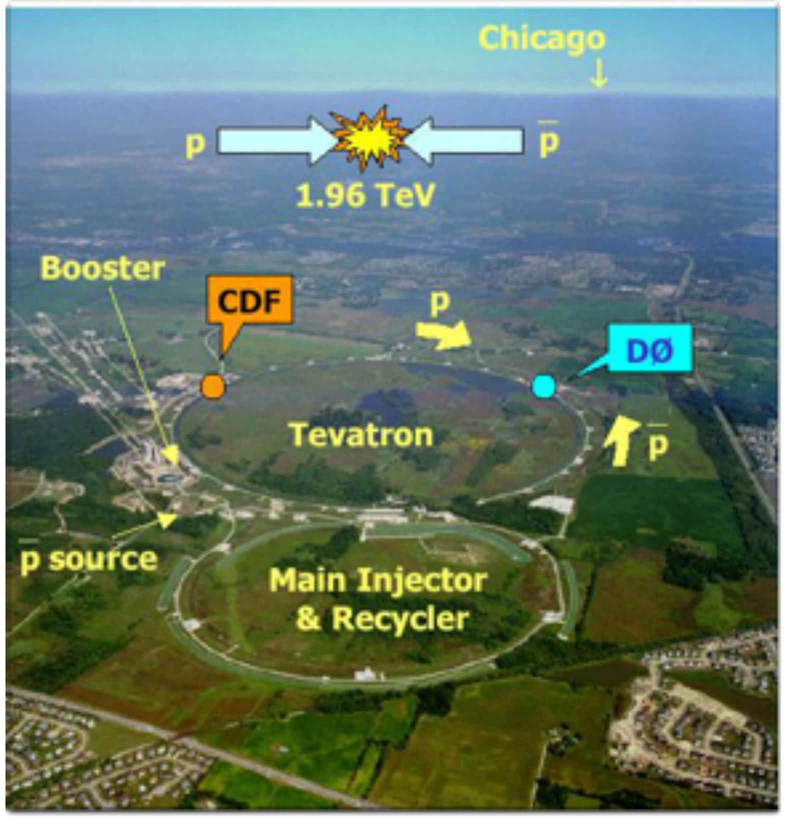
- Can access higher energies

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

Hadron Colliders

TeVatron:

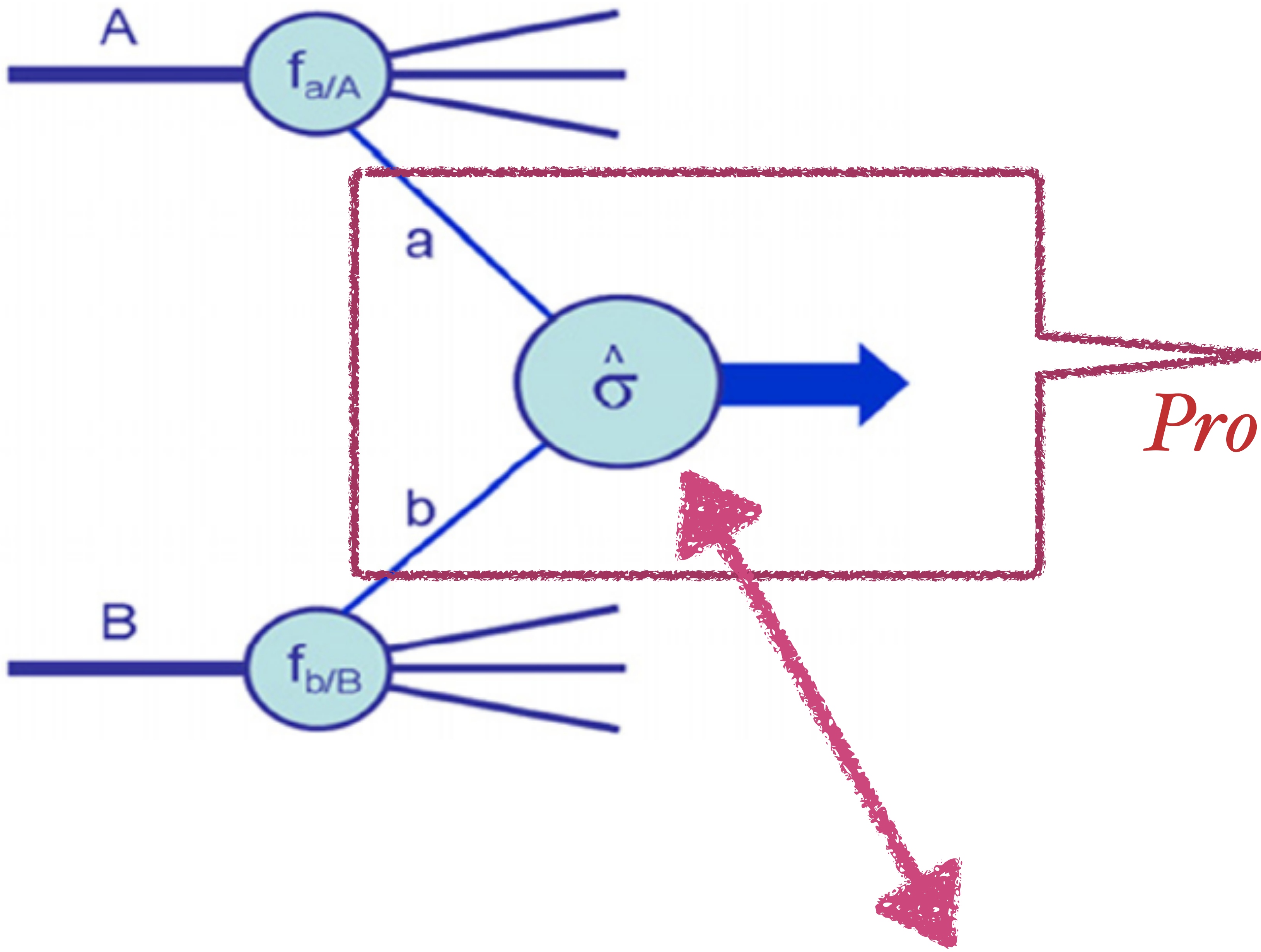
- **P-Pbar collider @ 1.96 TeV**
- *Detectors : CDF and D0*
- *Shut down in 2011*



LHC:

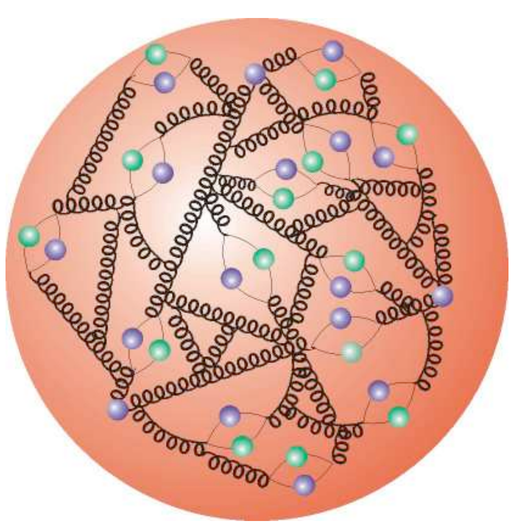
- **P-P collider @ 7,8,13 TeV**
- *Detectors : ATLAS and CMS*

Hard Scattering Process @ the Hadron Colliders

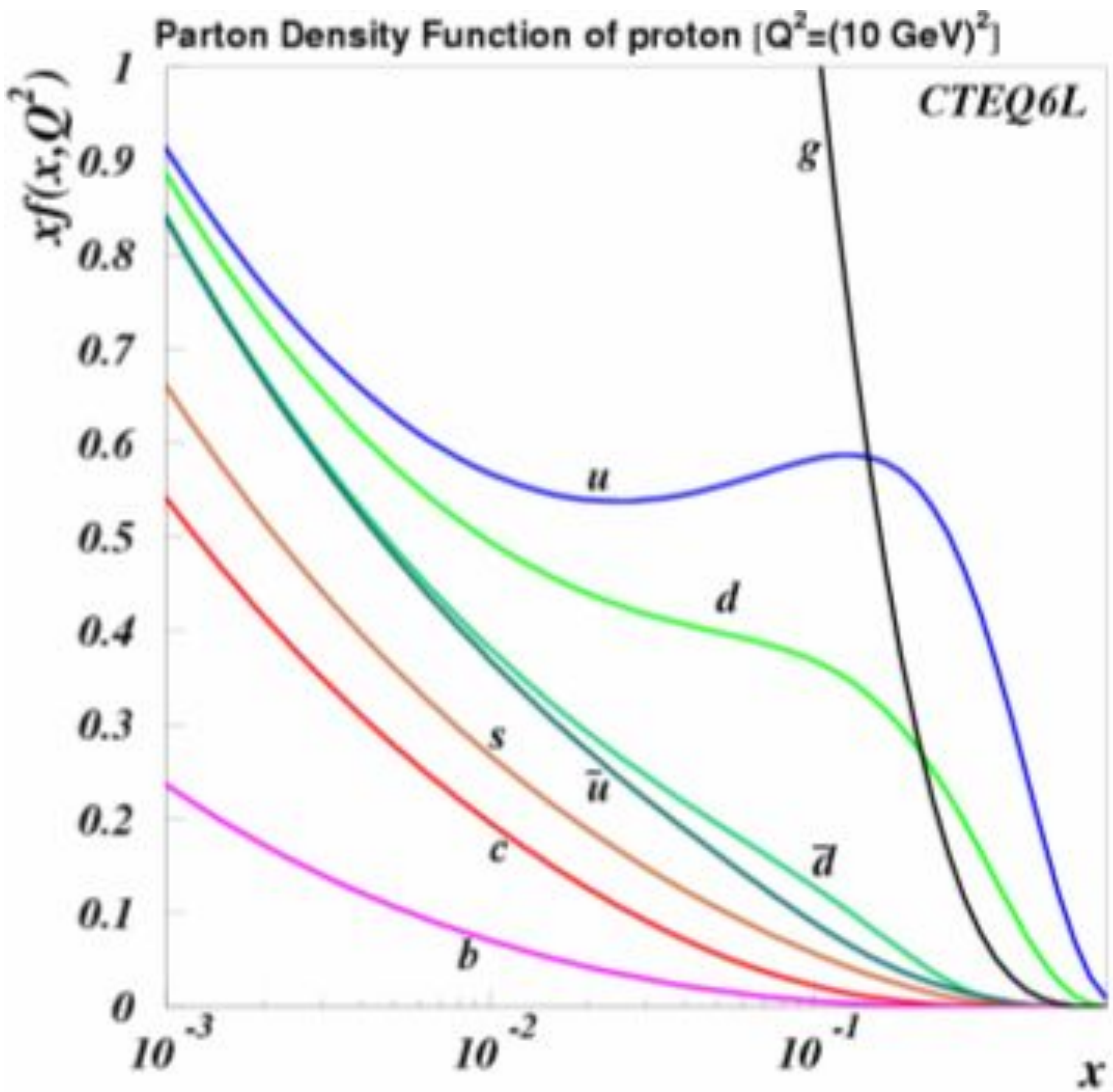


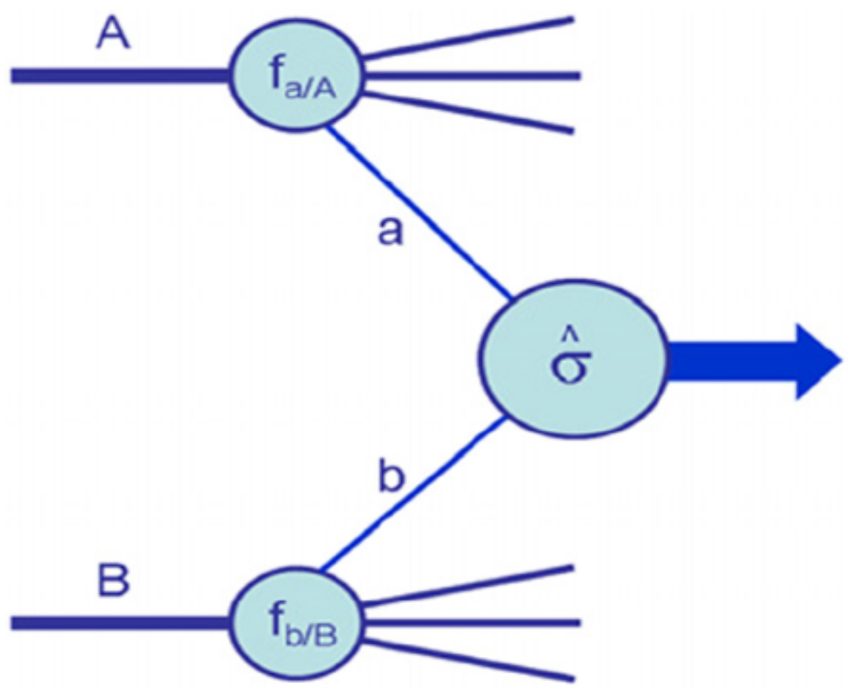
Proton process

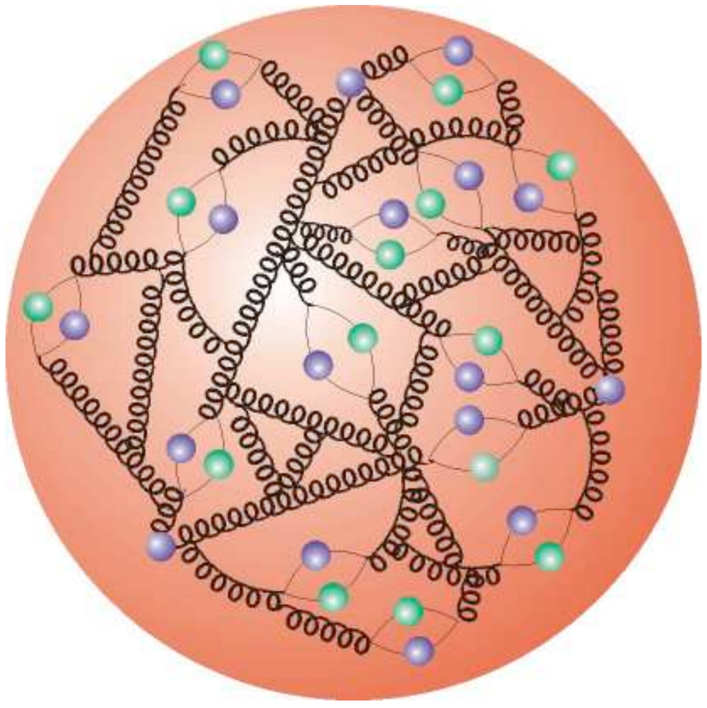
Protonic cross section



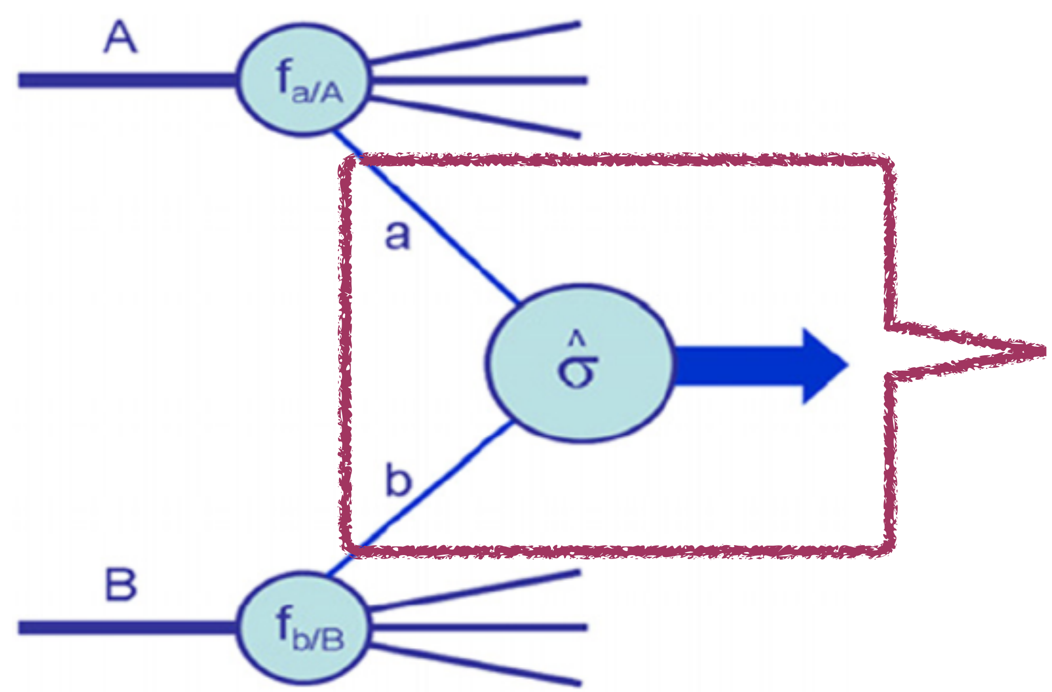
Proton Parton Distribution Function(PDF)







Hard Scattering Process @ the Hadron Colliders



Proton process

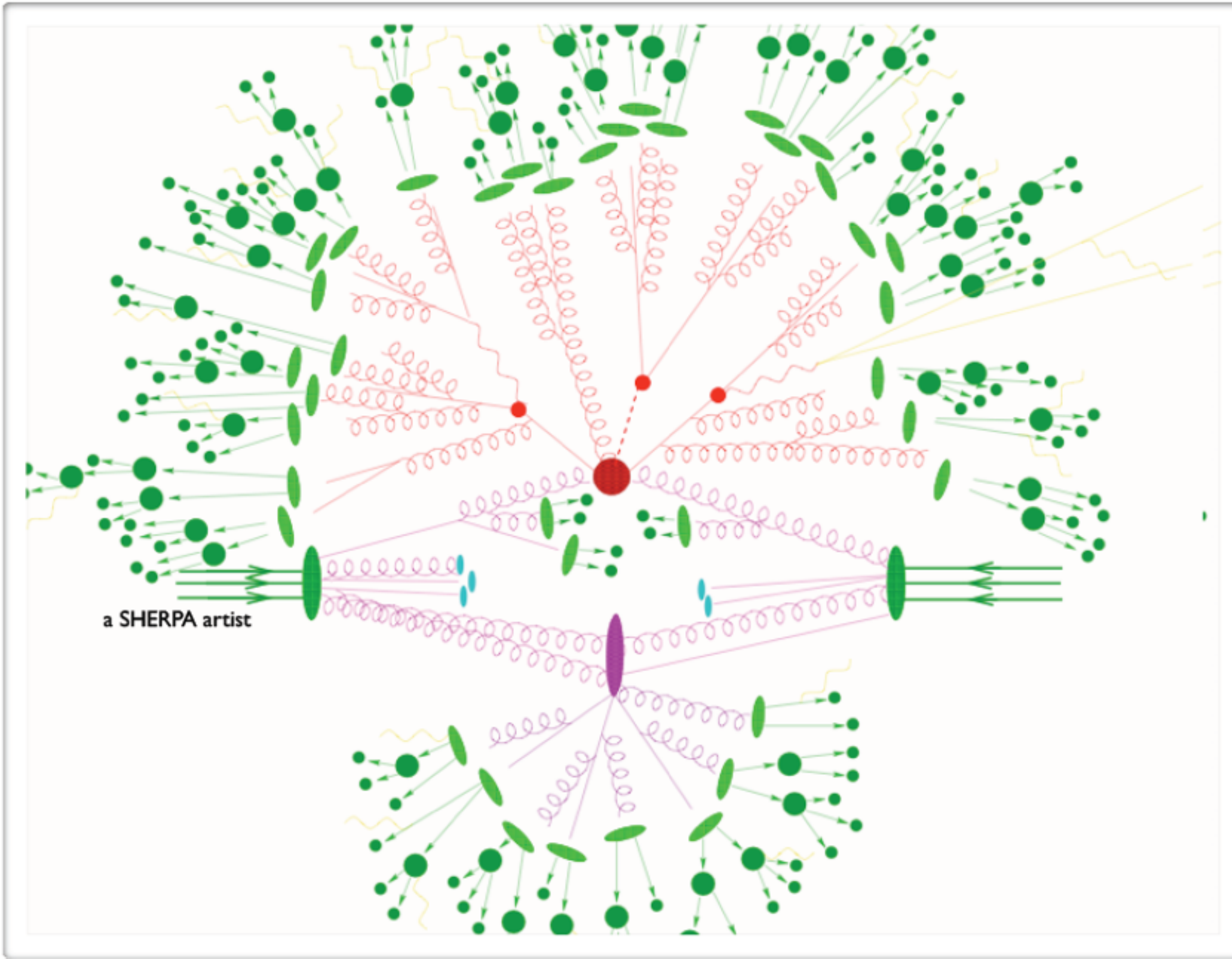
$$\sigma_{AB} = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, \mu_F^2) f_{b/B}(x_b, \mu_F^2) \hat{\sigma}_{ab}(x_a, x_b, \alpha_s(\mu_R^2)).$$

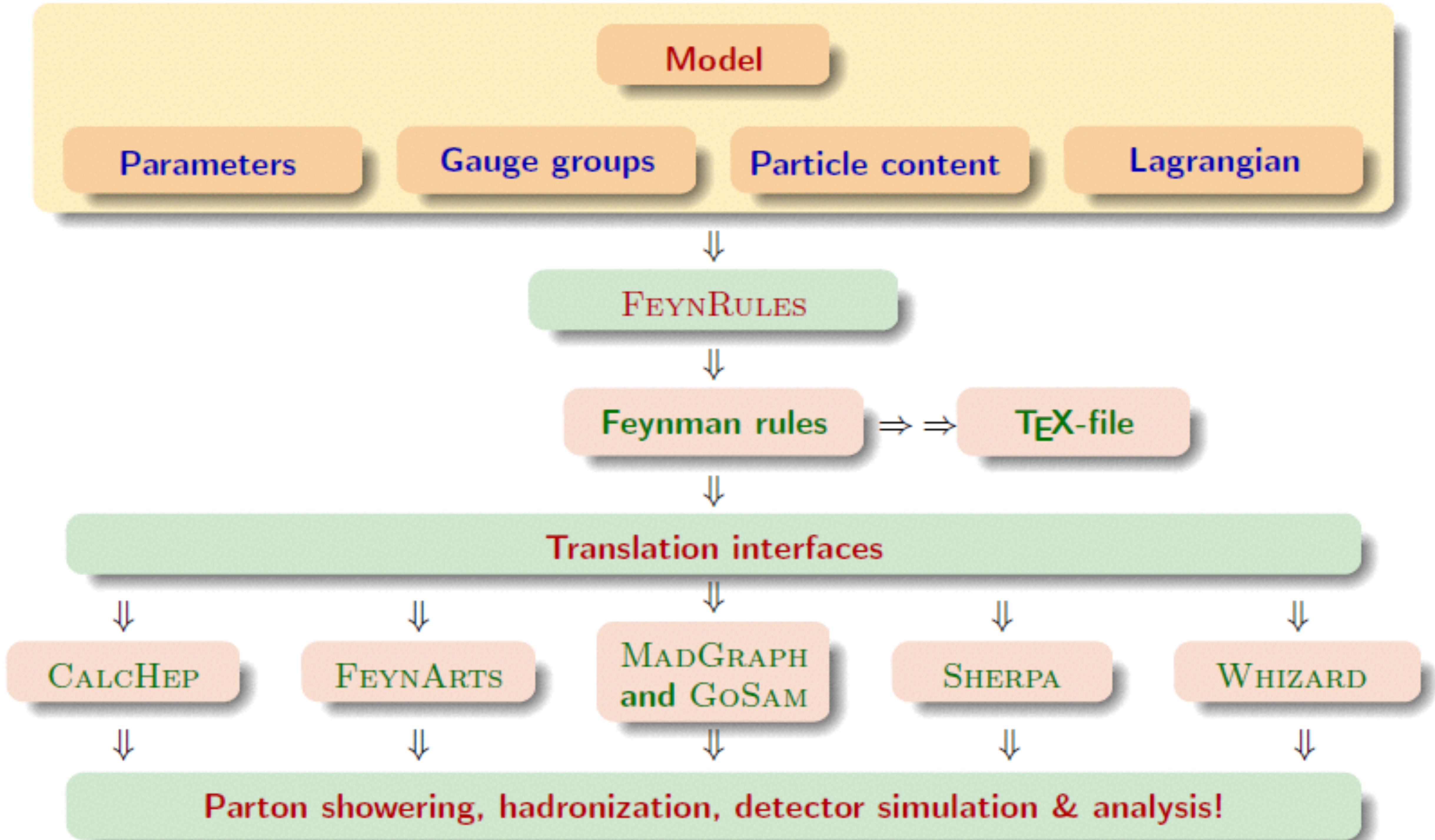
Momentum fraction of the parton

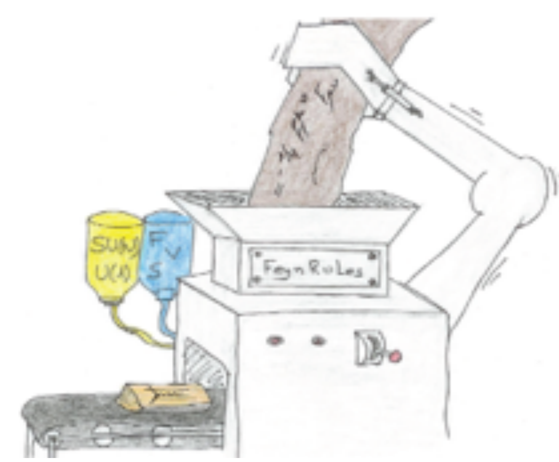
Protonic cross section

Sum over incoming partons

Proton Parton Distribution Function(PDF)

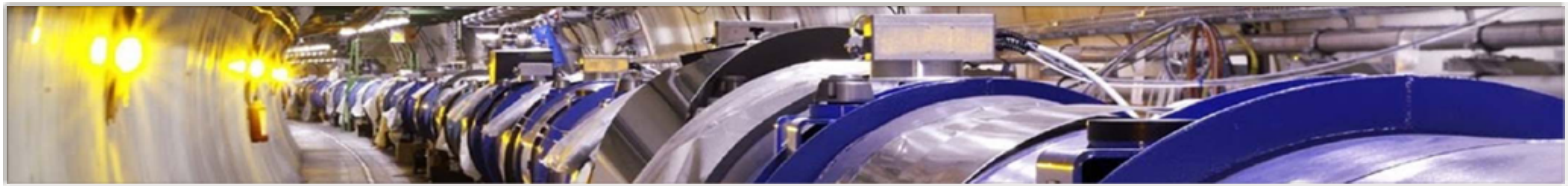

a SHERPA artist





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

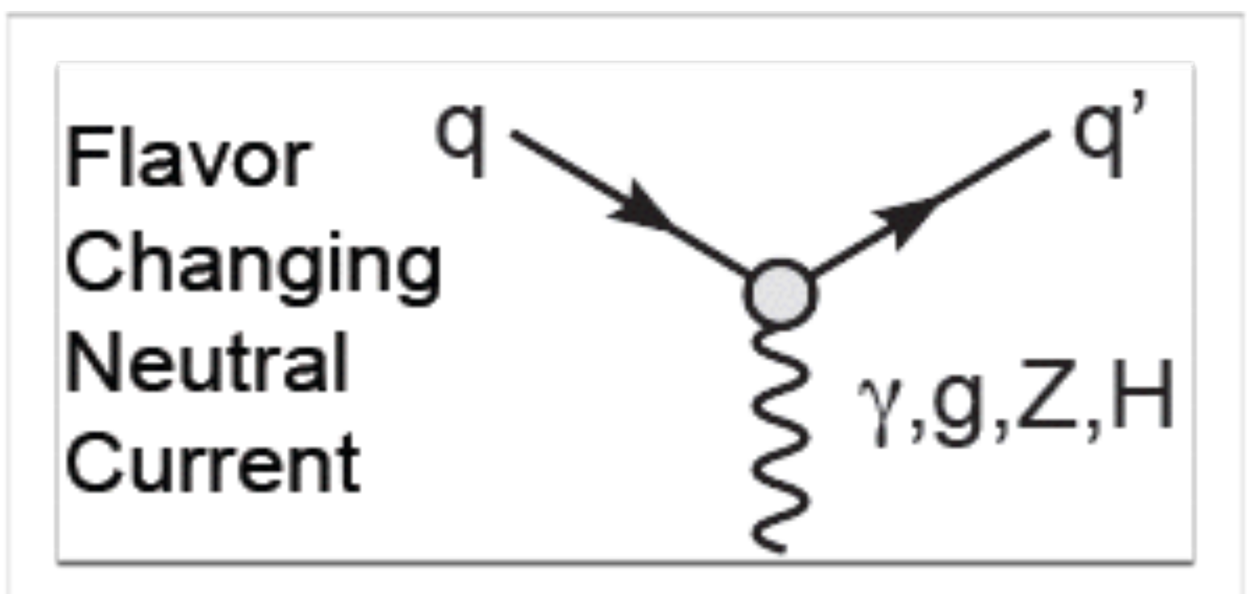
4+n

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

New Physics Scale

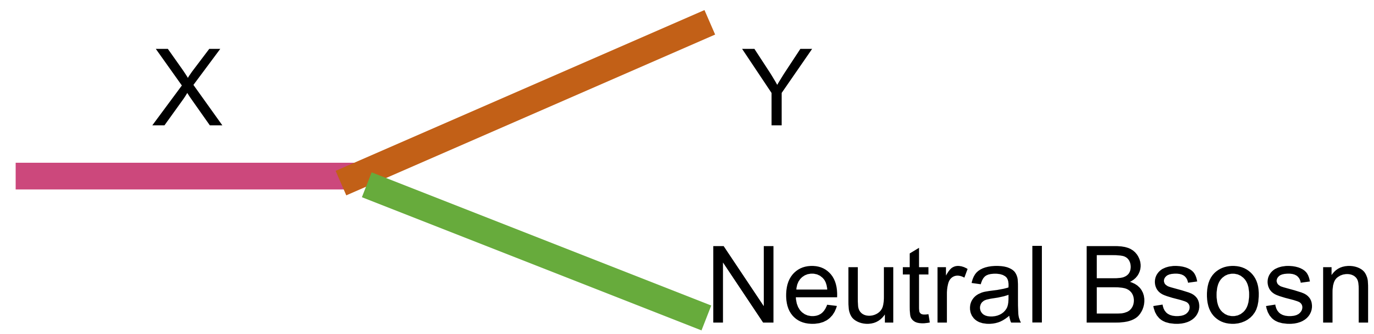
*The effective Lagrangian should be **invariant** under **SM gauge** transformation.*

Top Flavor Changing Neutral Current Processes

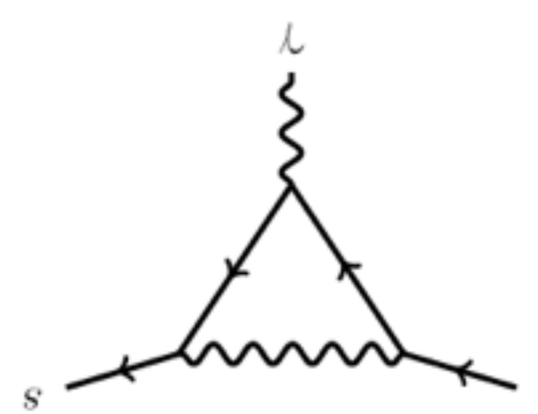


Flavor-Changing Neutral Current (FCNC)

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

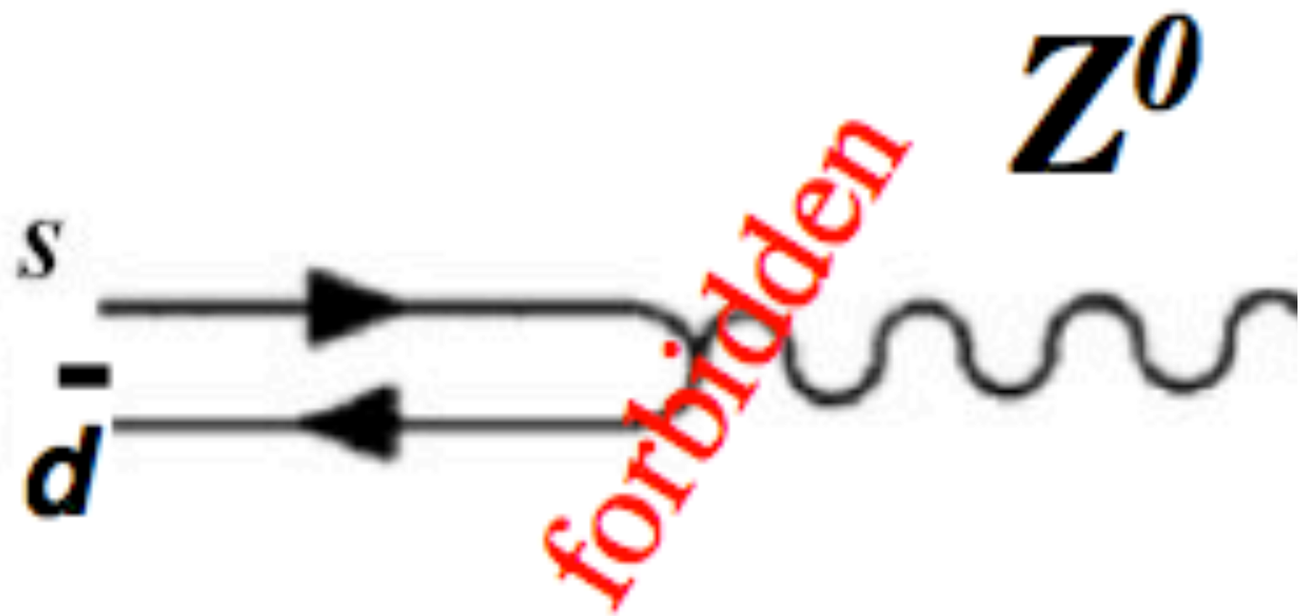


- For example: $b \rightarrow s\gamma$, $t \rightarrow u\gamma$, $t \rightarrow uZ$, …

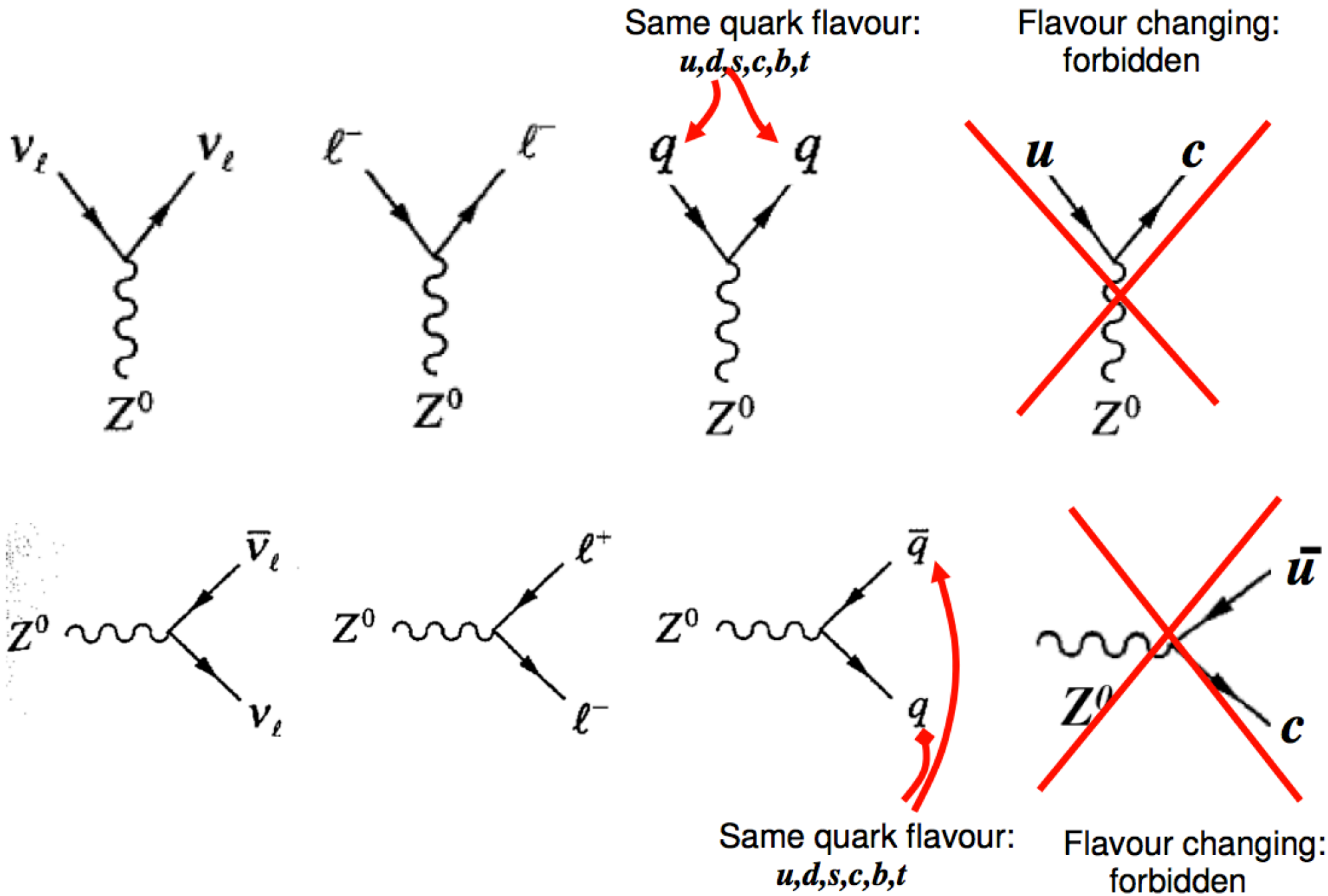


Charged Current

Neutral Current

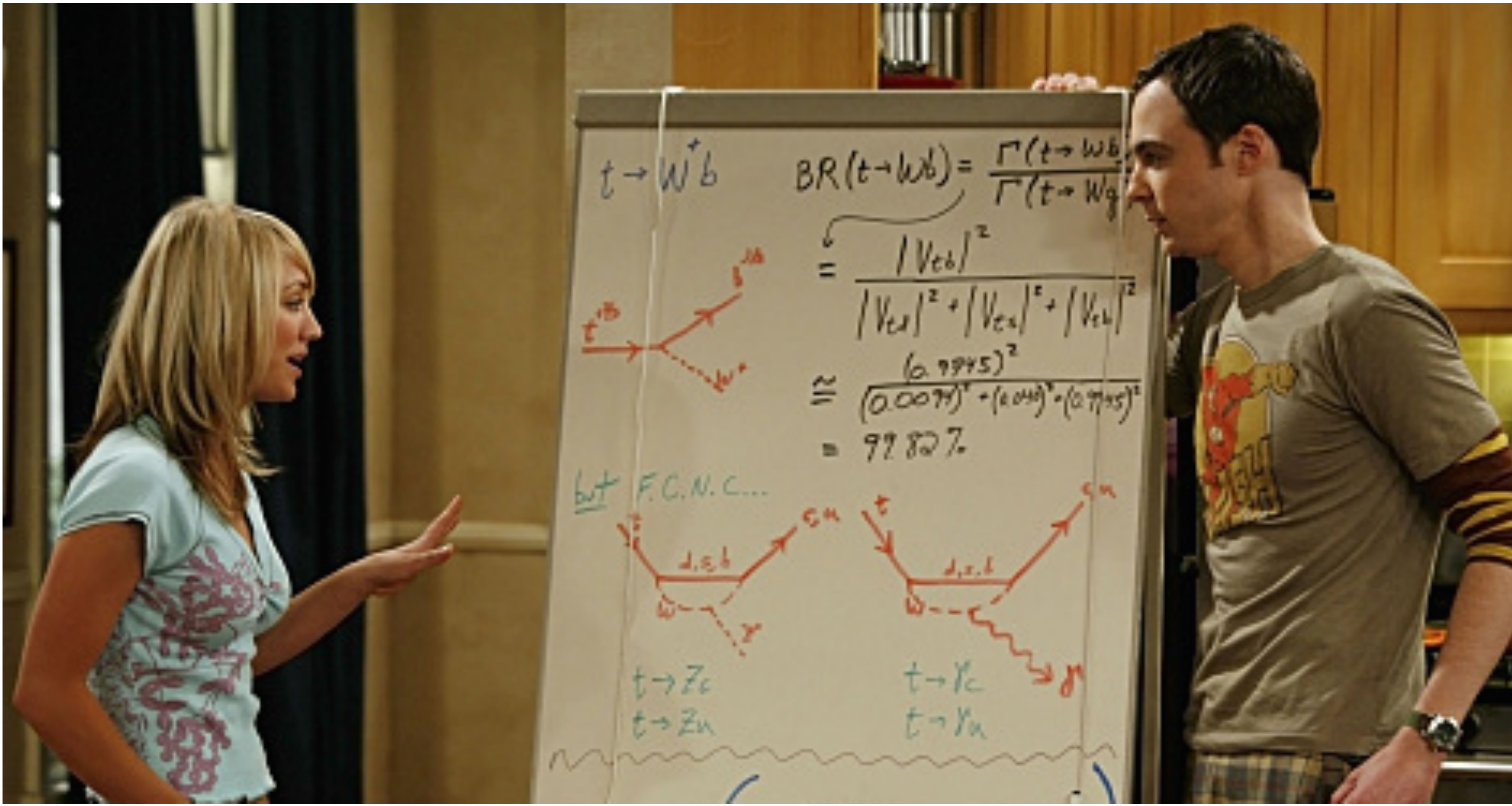


Weak Neutral Current



- 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).

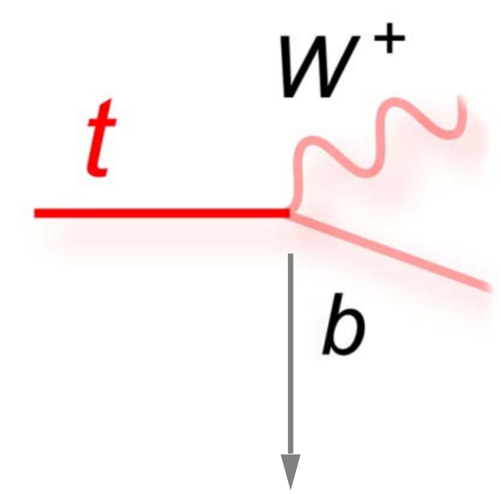
Top FCNC decays



SM prediction For Top decays

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

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



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

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

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

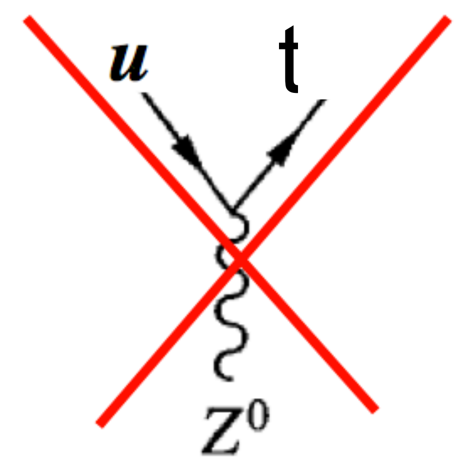
$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$$

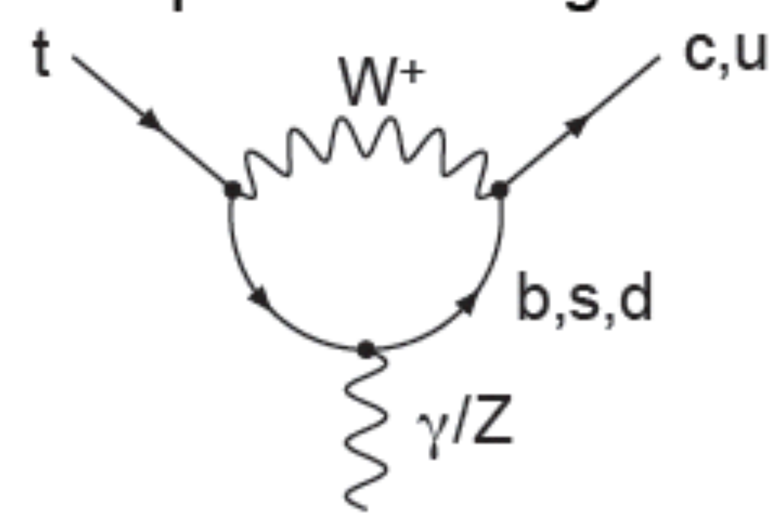
$$|V_{tb}| = \begin{cases} 1.05^{+0.10}_{-0.09} & \text{(CDF)} \\ 1.01^{+0.09}_{-0.09} & \text{(D0)} \end{cases}$$

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

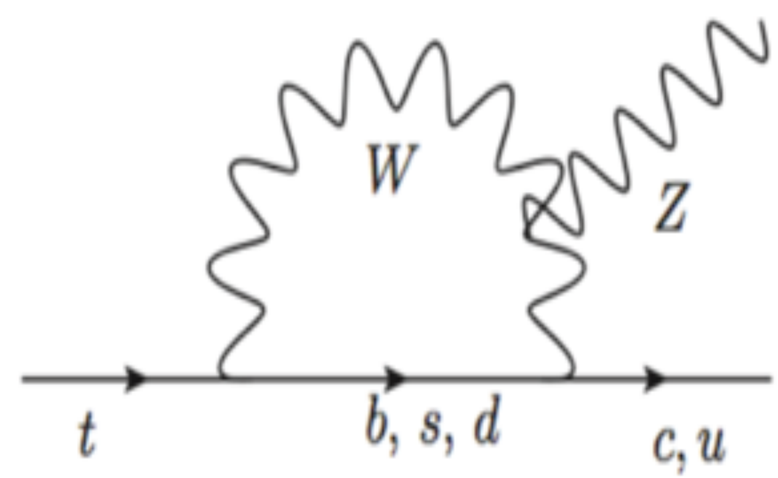
Branching Ratio Definition: $Br(t \to cV) \equiv \frac{\Gamma(t \to cV)}{\Gamma(t \to bW^+)}$,

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

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

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

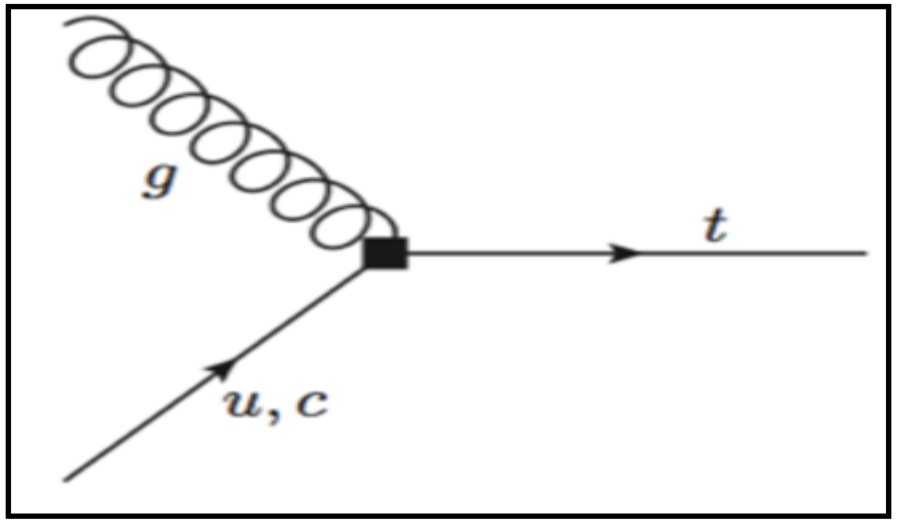
$$Br(t \to ug) \simeq 4 \times 10^{-14} \qquad Br(t \to cg) \simeq 5 \times 10^{-12}$$

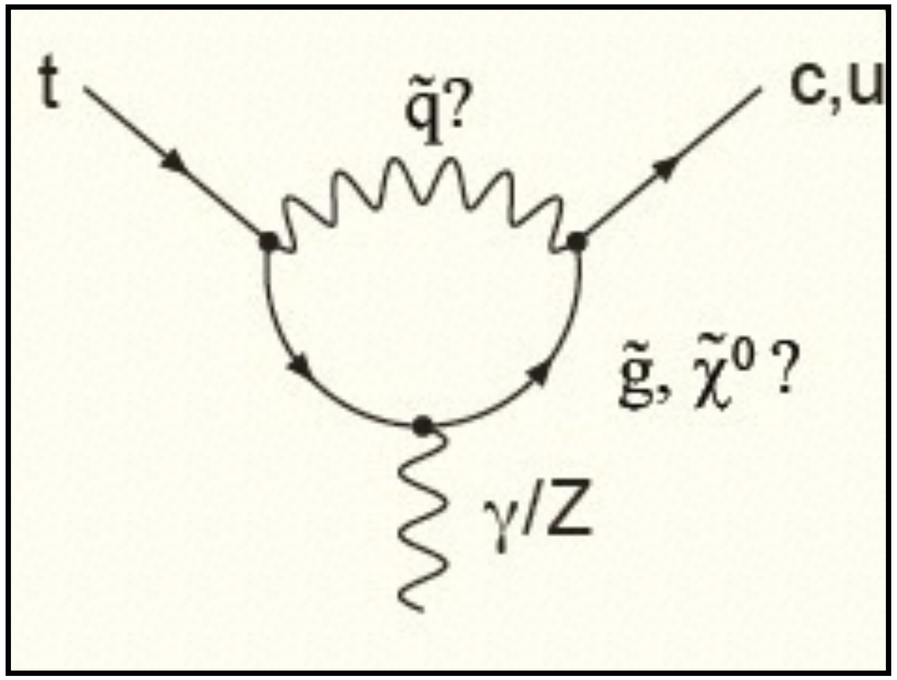


Aguilar-Saavedra, hep-ph/0409342

FCNC @ New Physics

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





FCNC @ New Physics

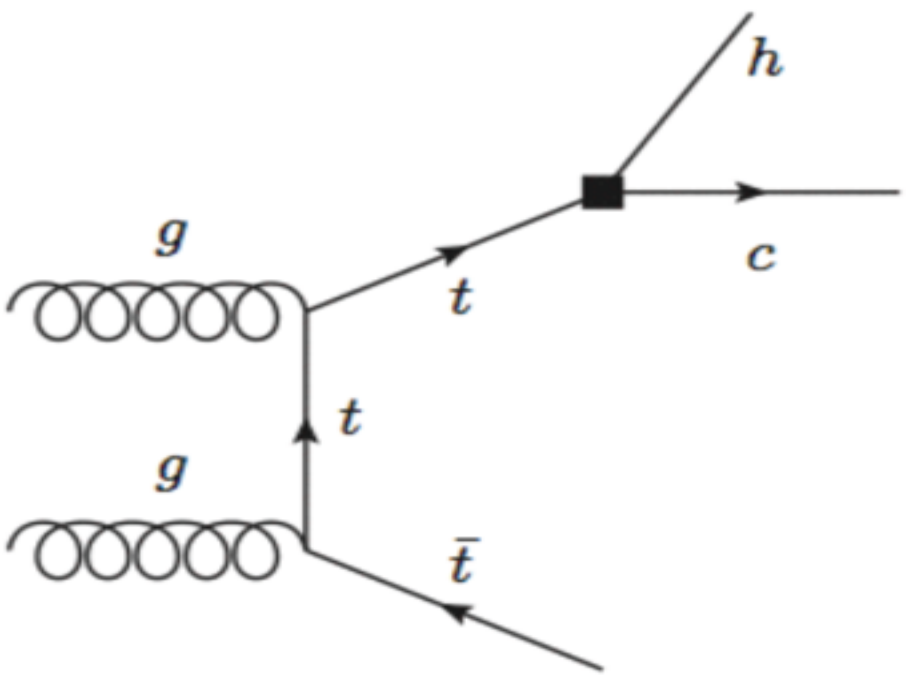
- Experimental tests of FCNC interactions : sensitive probes of new physics
- Any signal above SM expectations would indicate new physics.
- Measurements of FCNC branching ratios allows to constrain new physics models.

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}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

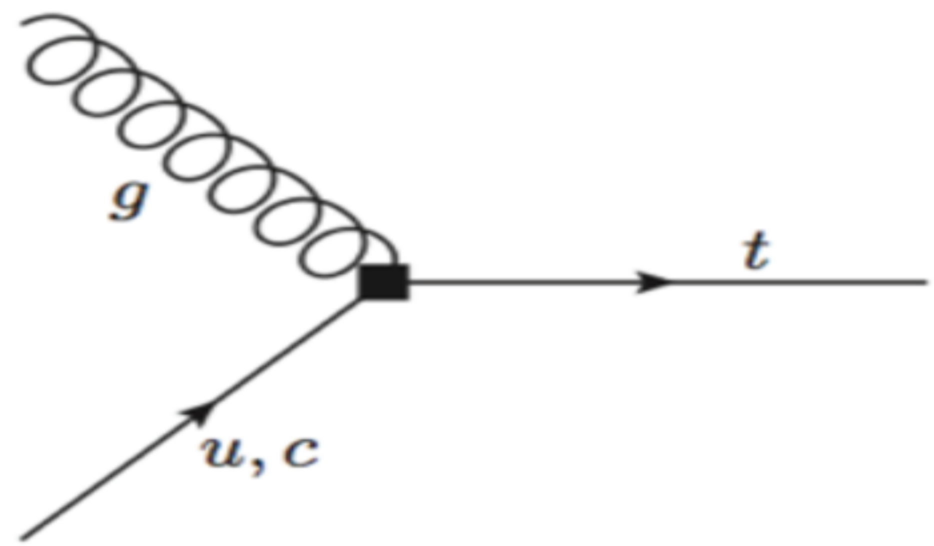
Snowmass 2013 Top quark WG report, 1311.2028

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 ($qg \to t$)

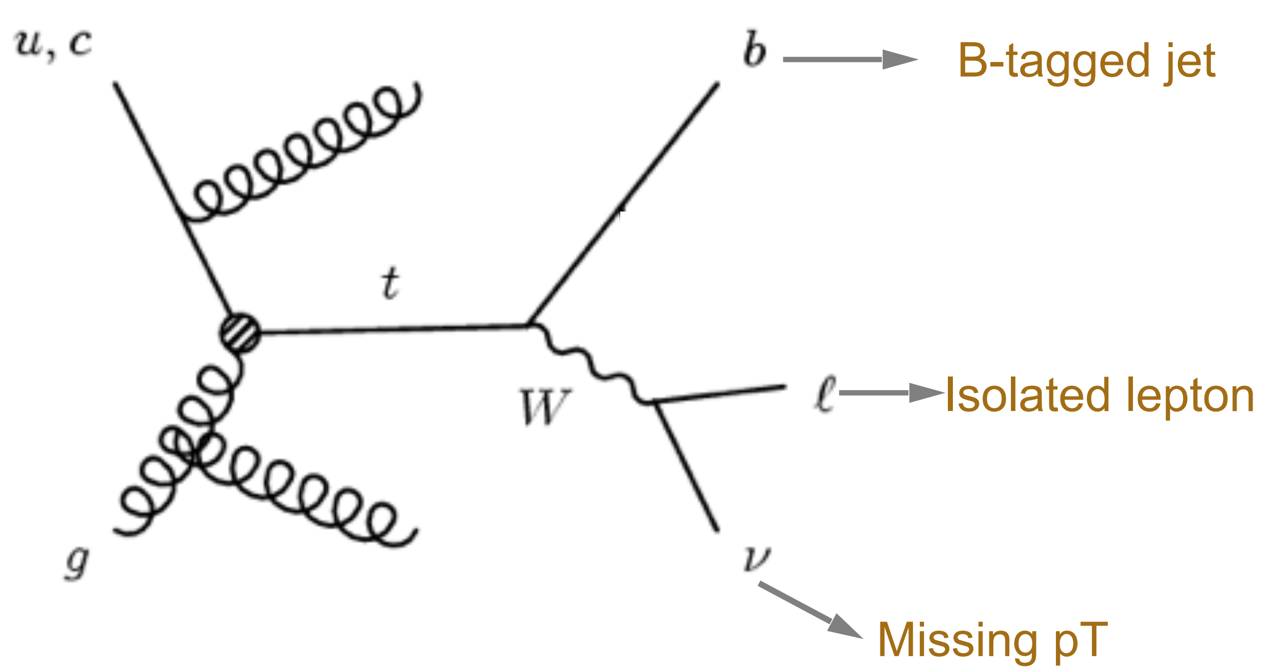
$$qg \to t \to W(\to \ell\nu)\, b$$

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'



$t \to Zq$

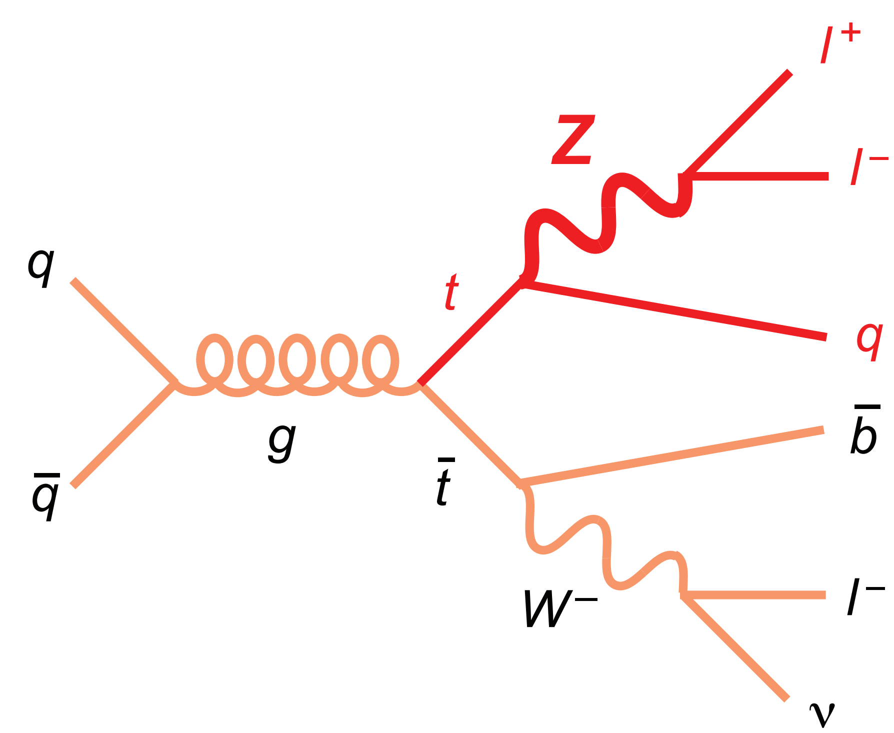
- A search for flavor-changing neutral currents in top-quark decays $t \to Zq$ is performed in events produced from the decay chain $tt \to Zq + Wb$, where both vector bosons decay leptonically, producing a final state with three leptons (electrons or muons).

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

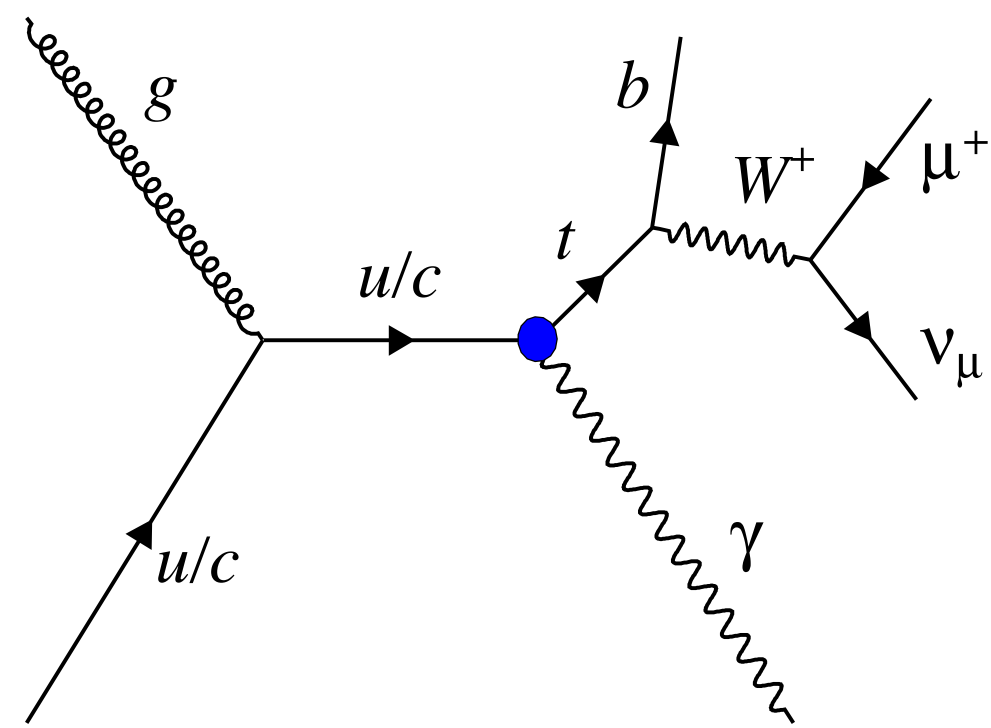
ATLAS: $BR(t \to qZ) < 7 \times 10^{-4}$

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:

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

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

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

$t \rightarrow hq$

CMS: $t\bar{t} \rightarrow (bW)(ch)$ $\begin{cases} h \rightarrow WW^* \\ h \rightarrow ZZ^* \\ h \rightarrow \tau\tau \end{cases}$ multilepton final states

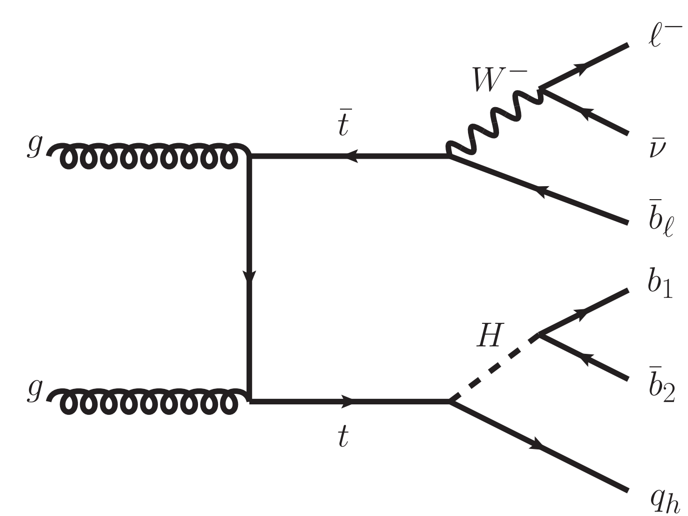
using 19.8 fb^{-1} of data collected at $\sqrt{s}$ = 8 TeV

$h \rightarrow \gamma\gamma$ lepton+diphoton final state

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

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

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



95% CL combined upper limits:

$B(t \rightarrow Hc)$ —> 0.46%

$B(t \rightarrow Hu)$ —> 0.45%

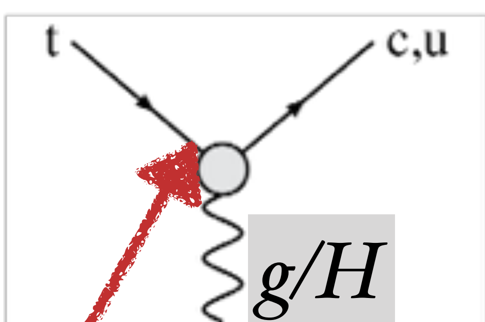
tqH and tqg FCNC Couplings

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?

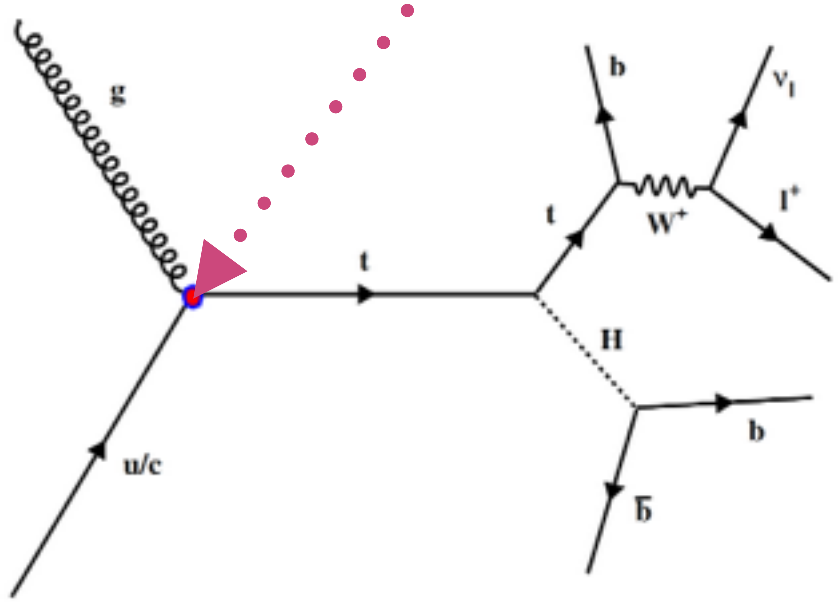
Coupling strength (top, up-type quark and Higgs)

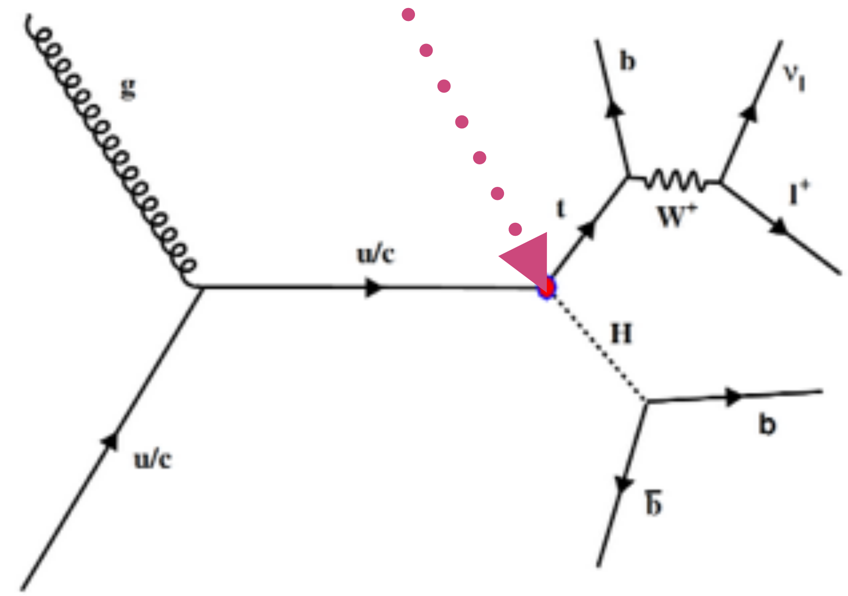
Saavedra Nucl.phys.B 812(2009)181-204

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

Single top + Higgs due to FCNC Couplings at the LHC

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



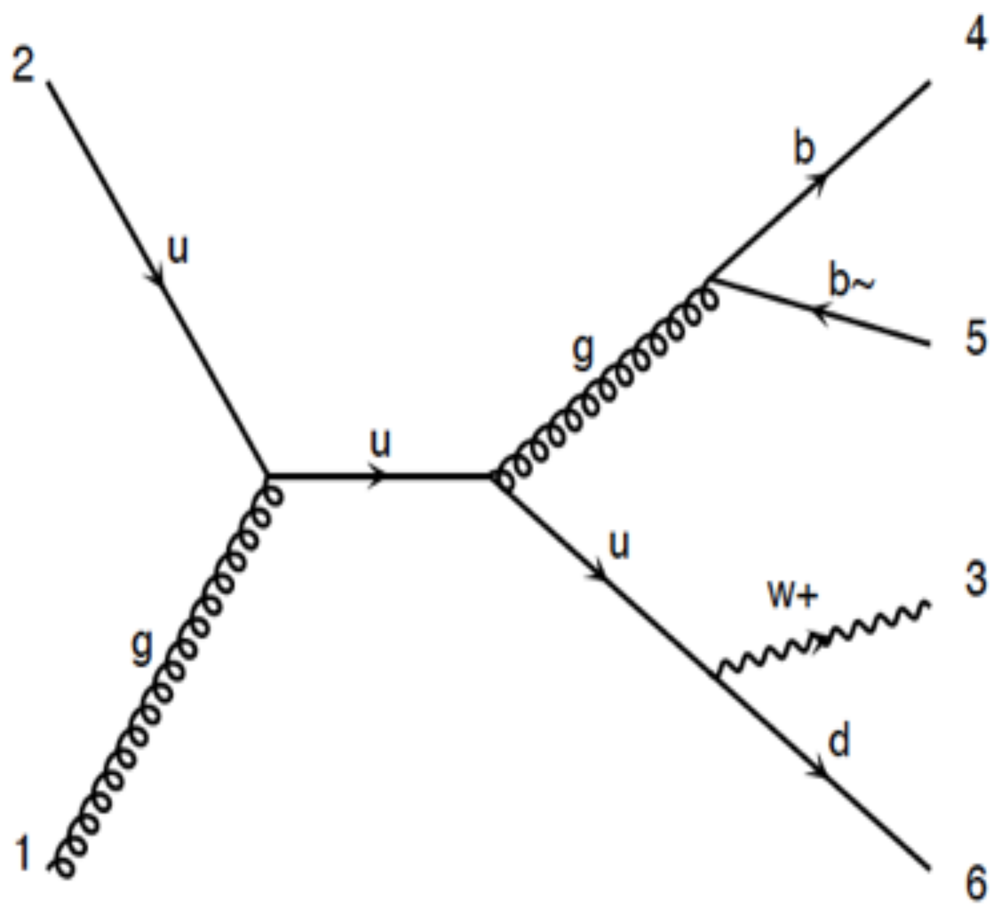


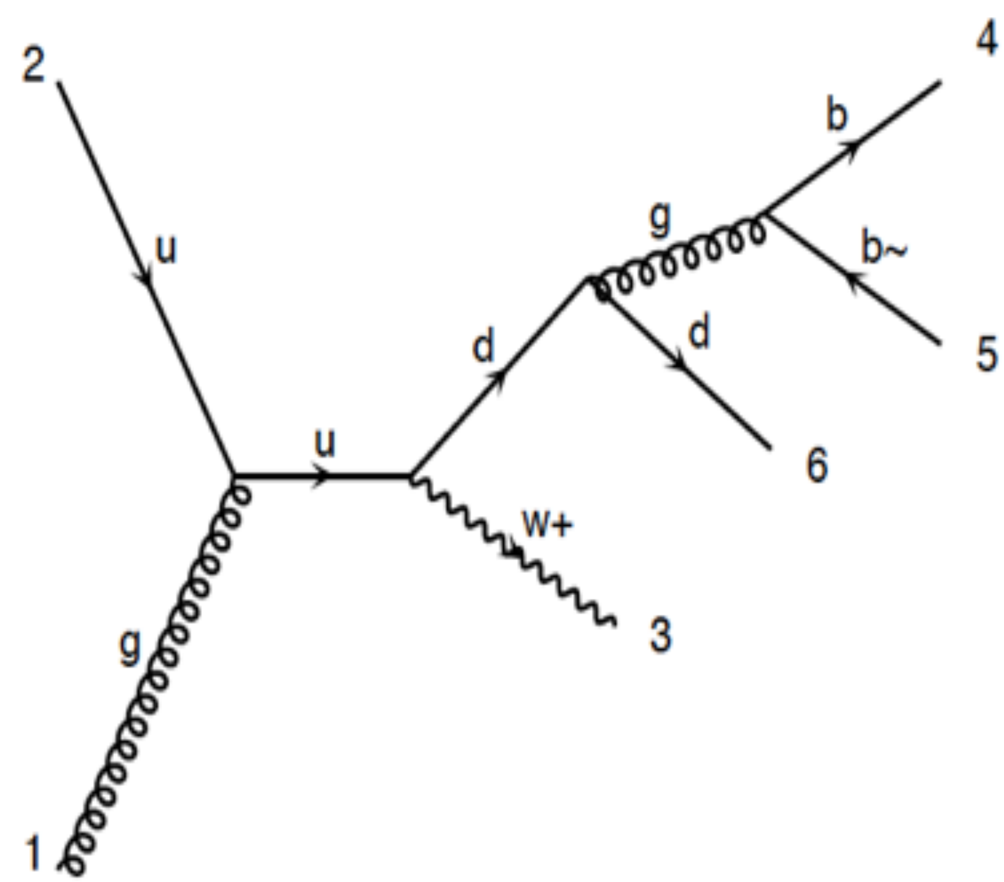
- **Final state:**
  - 3 b-jets
  - One charged lepton
  - Missing energy (Neutrino)

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:

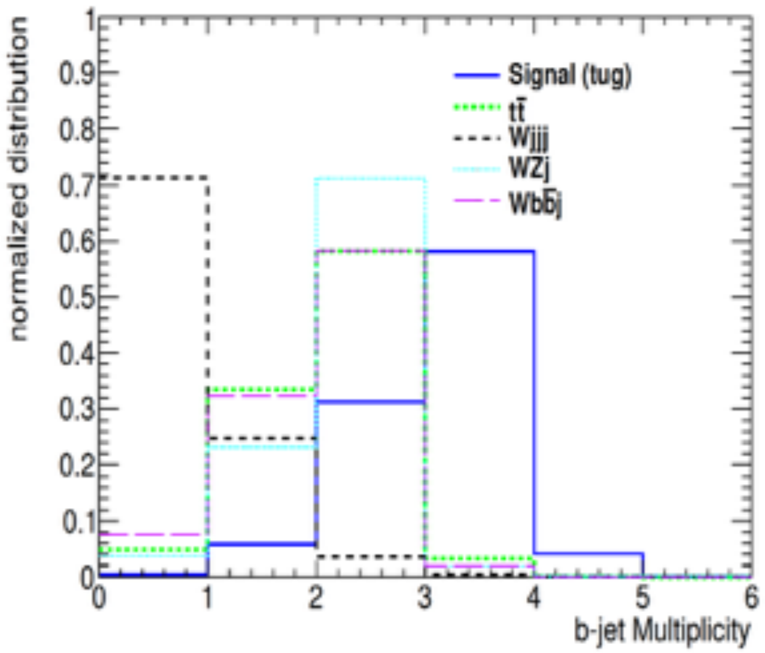
- Lepton and jets → $p_T > 25 GeV$ $|\eta| < 2.5$

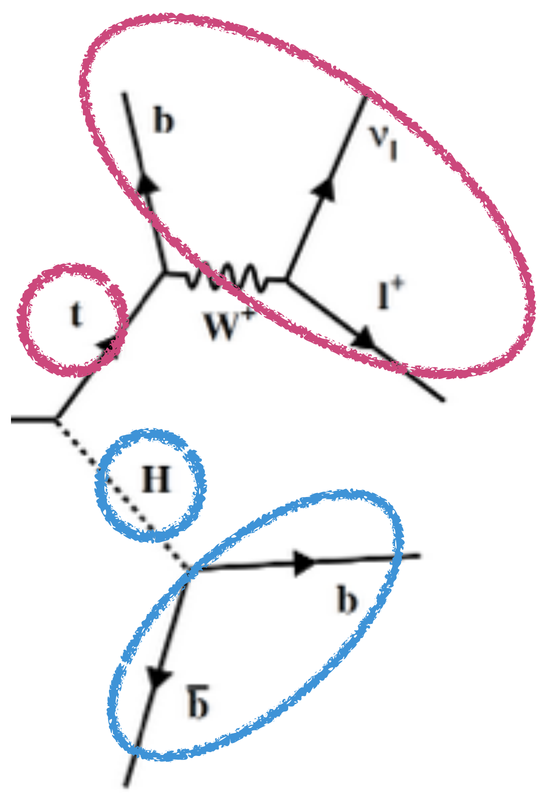
- Distance between two object → $\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} > 0.4$

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

Object Selection & Reconstruction

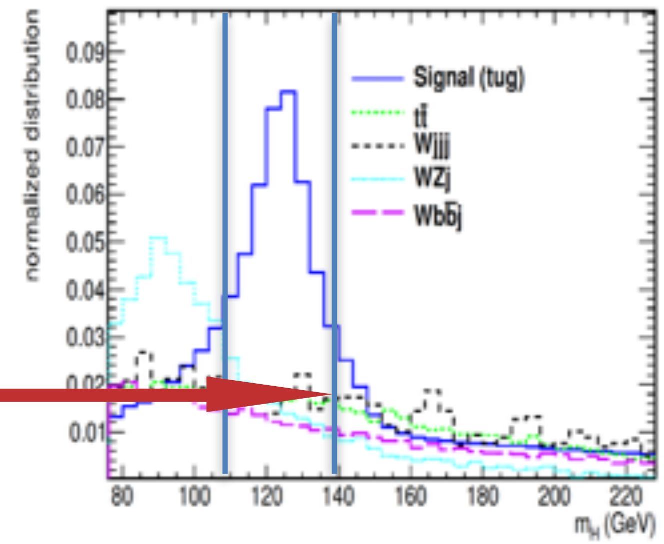
- We require to have only three b-tagged jets.
- The combination which gives the closest mass to the top quark is selected as top.
- The other remaining two b-jets are combined to reconstruct the Higgs boson.

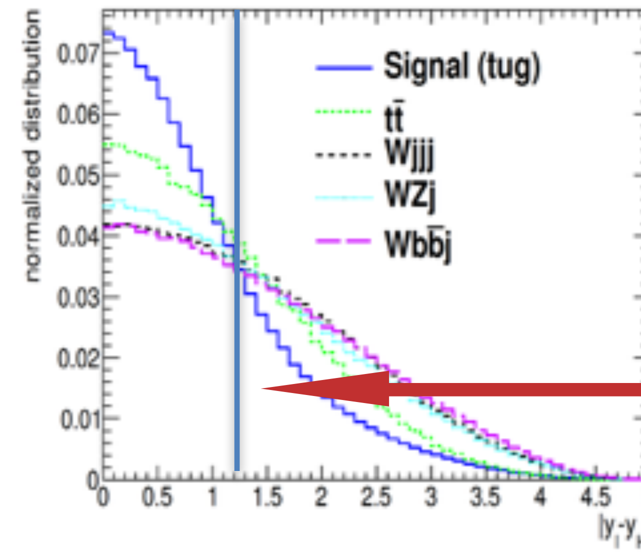




Looking at different kinematic distributions for suppressing Backgrounds.

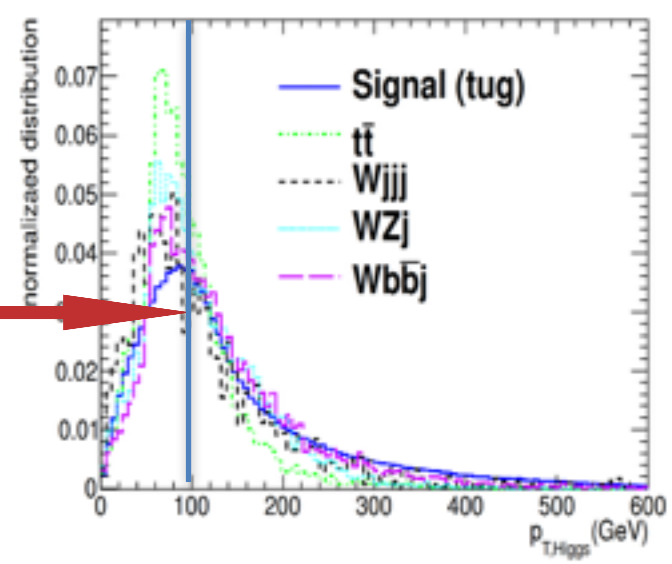
$|m_{H,rec} - 125| > 15GeV$

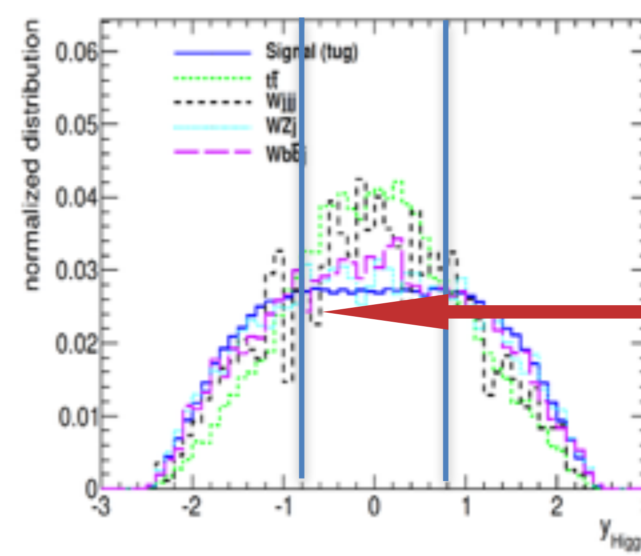




$|y_l - y_H| < 1.2$

$p_{T,Higgs} > 100GeV$





$|y_H| > 0.8$

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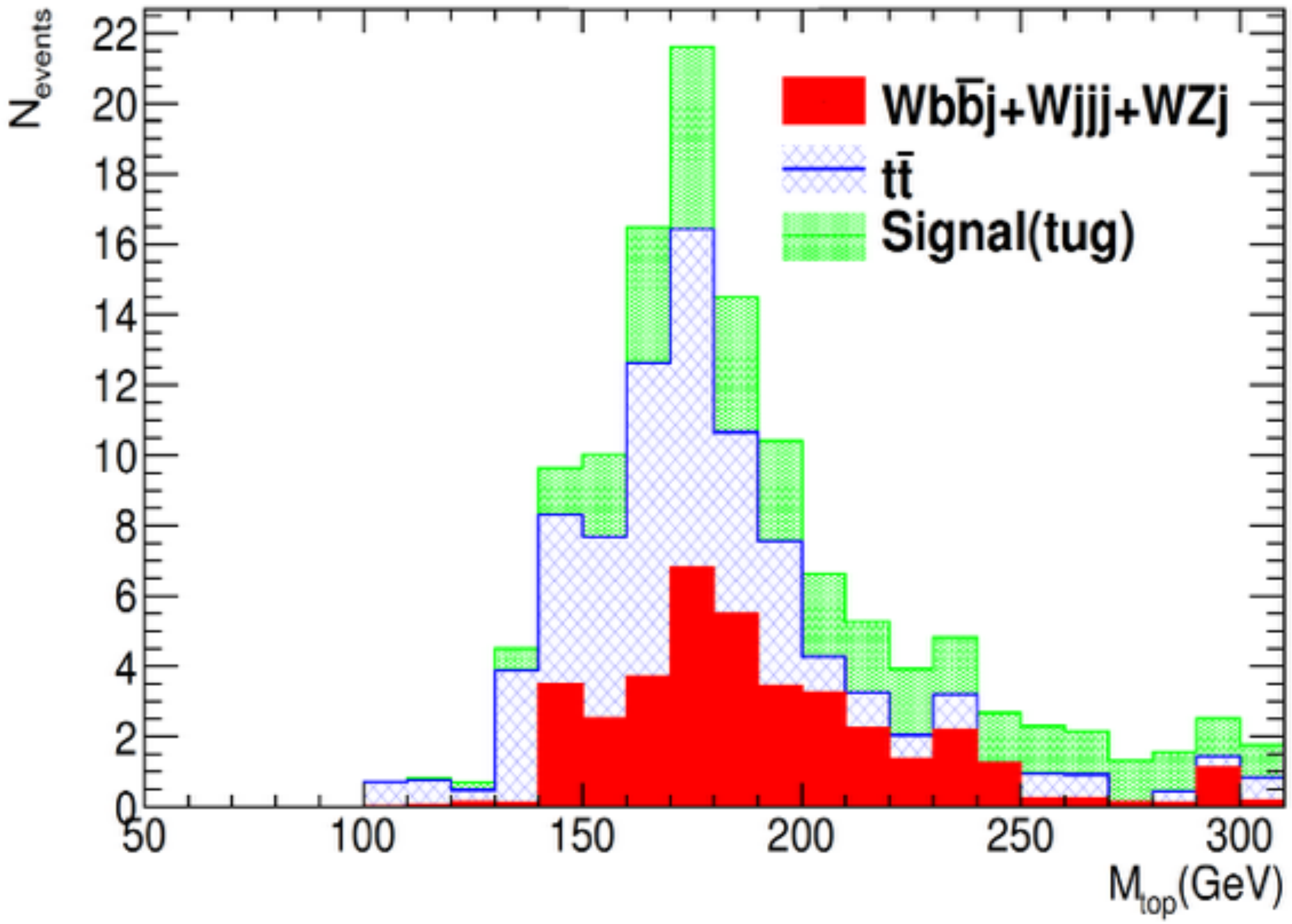
Reconstructed top quark mass after all cuts for signal and backgrounds:



Top quark has been reconstructed well!

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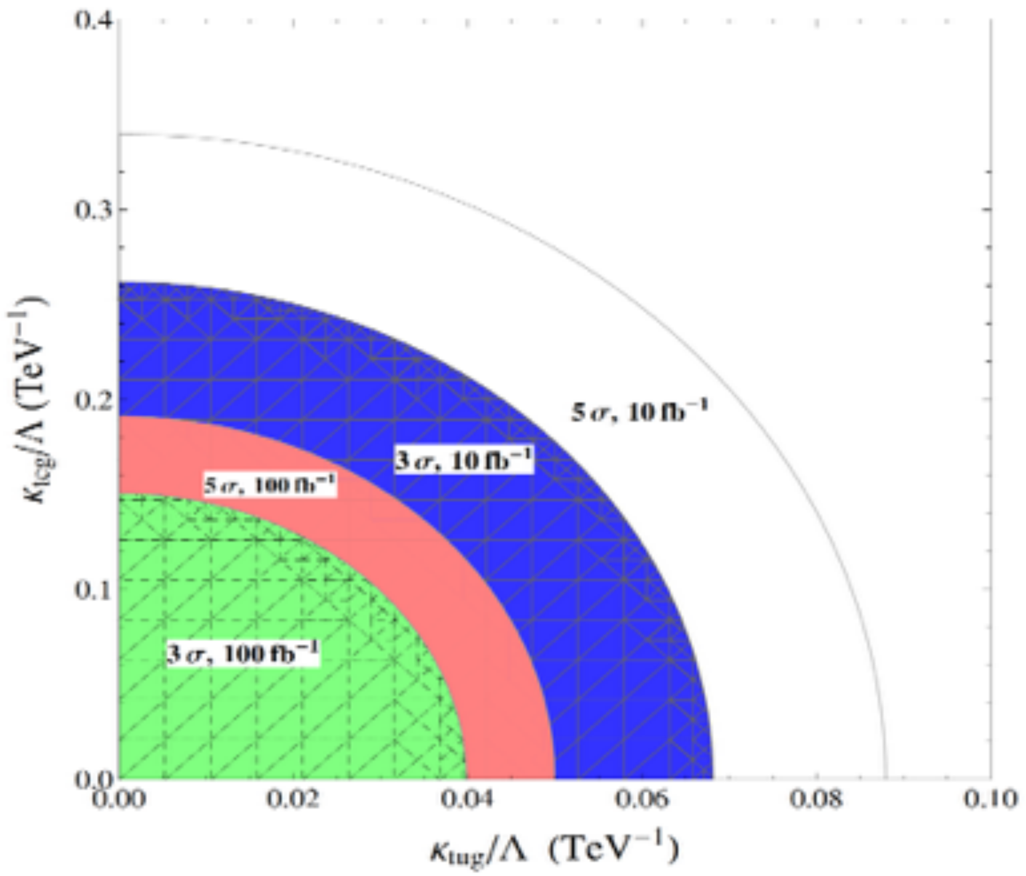
Results for FCNC t-q-gluon Couplings

- *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:*

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

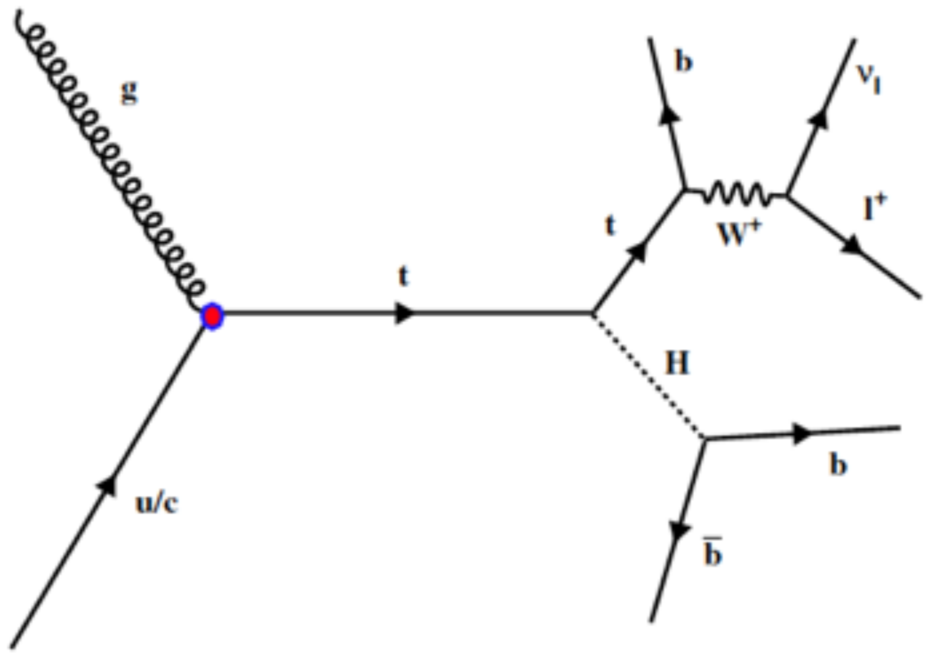
Requiring significance > 3(5) leads to :

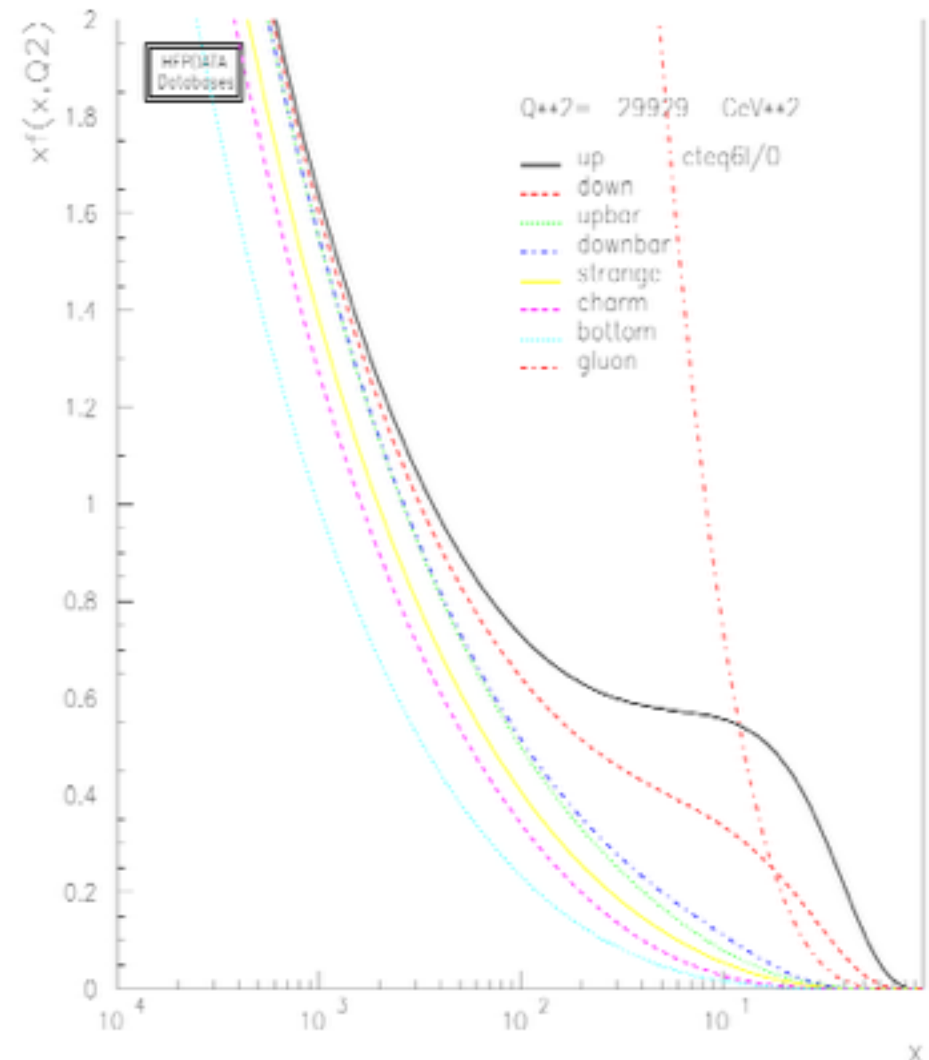
$$\frac{\kappa_{tug}}{\Lambda} \geq 0.069\ (0.088)\ TeV^{-1},$$
$$\frac{\kappa_{tcg}}{\Lambda} \geq 0.26\ (0.34)\ TeV^{-1}.$$



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 :

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

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

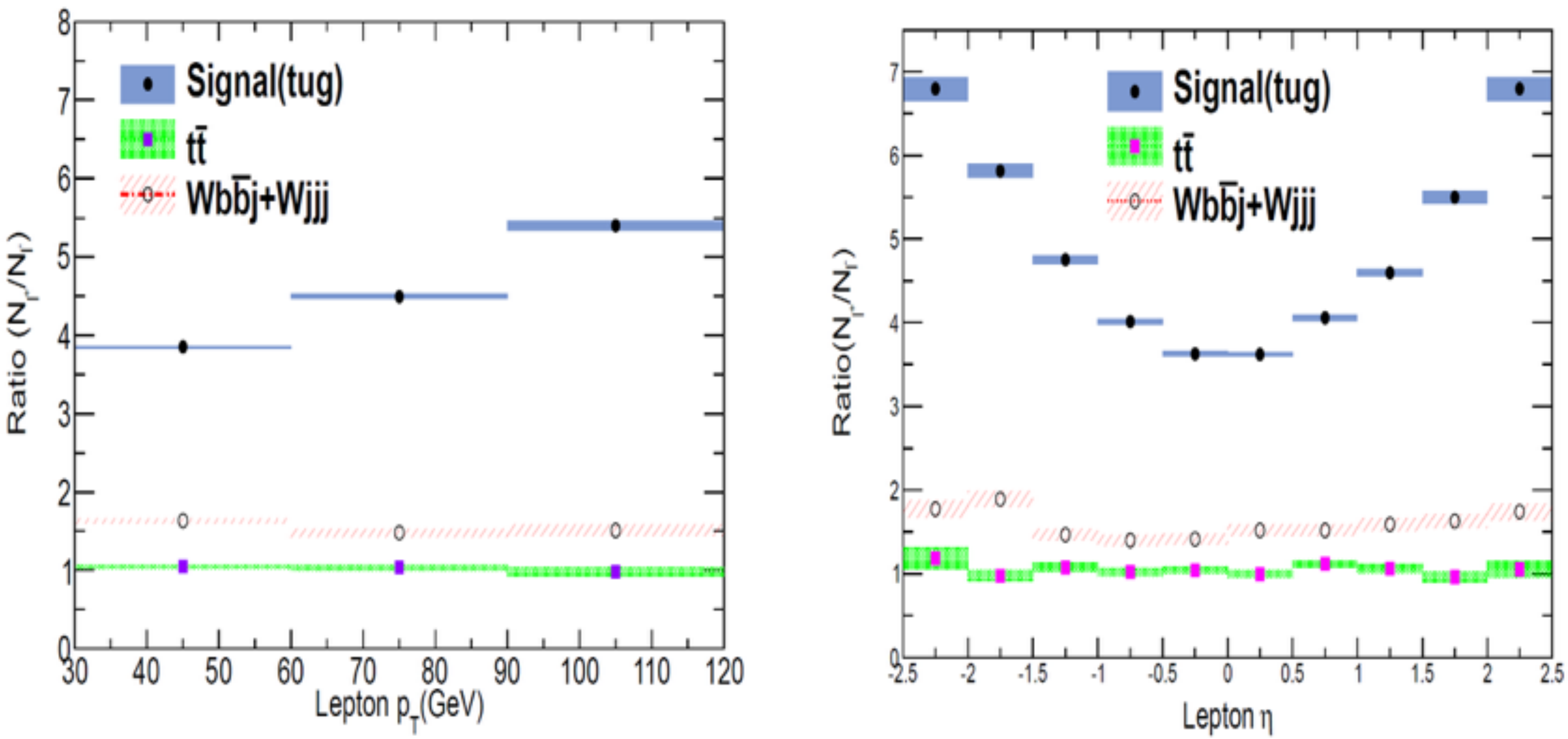
$$R_{t\bar{t}} = 1.04 \pm 0.03,$$

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

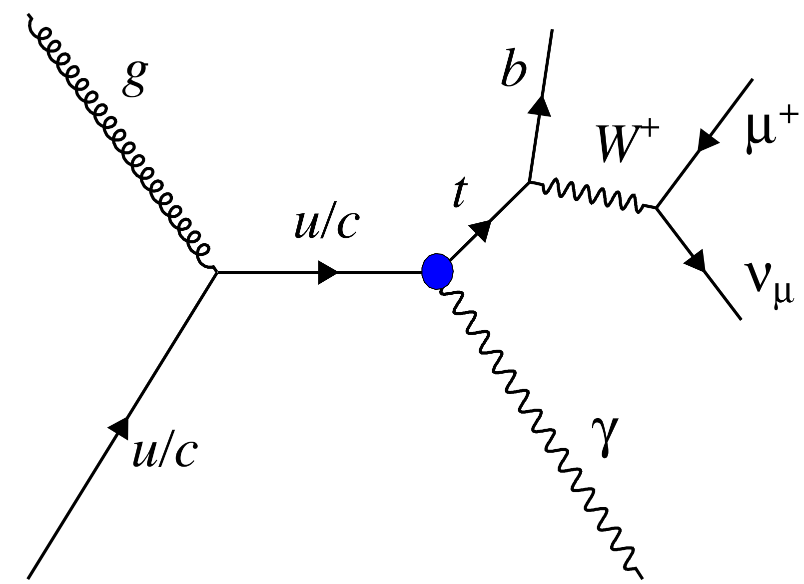
Dependence of the charge ratio on the transverse momentum and pseudorapidity of the charged lepton.



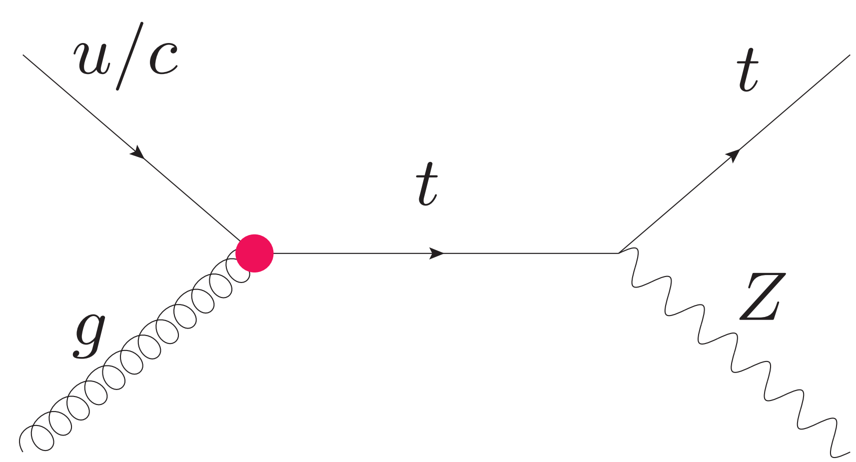
Charge Ratio

- 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.

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



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



Summary

- Top FCNC interactions can be important to search for New Physics.
- Top FCNC still has much room for New Physics.
- It must be explored indirectly by flavor physics and directly by collider physics in as many as possible channels.