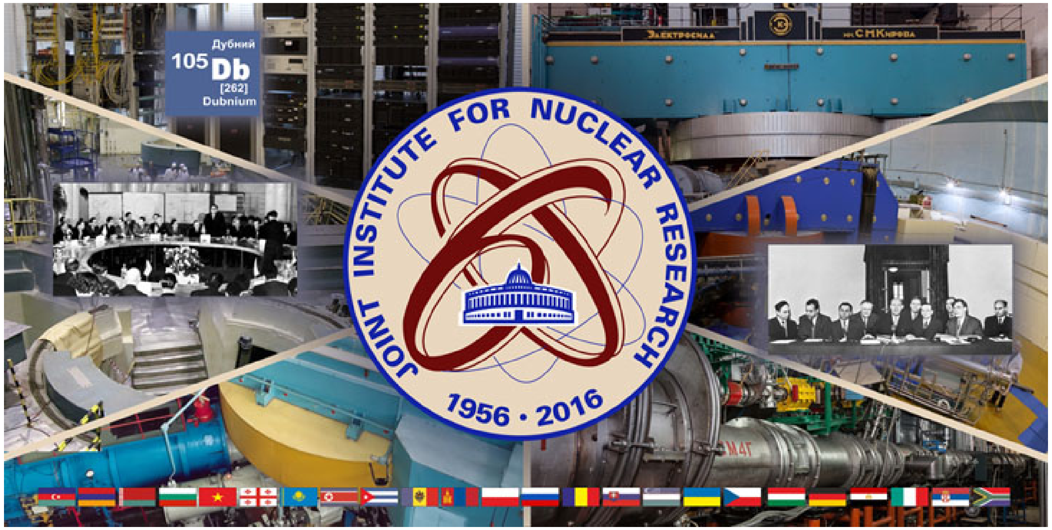

The Top Quark Physics

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Reviews: Willenbrock; Han; Hill and Simmons; Bernreuther; Rainwater; Morrissey, Plehn, and Tait; Incandela, Quadt, Wagner, and Wicke; Boos, Dudko, and Slabospitsky; ...

History (I)

- By the 1960s physicists discover a lot of resonances (hadrons) from accelerator and cosmic ray experiments

$$\begin{pmatrix} & \bar{s}d & & \bar{s}u & \\ \bar{u}d & & \bar{u}u, \bar{d}d, \bar{s}s & & \bar{d}u \\ & \bar{u}s & & \bar{d}s & \end{pmatrix}$$

$$\left\langle \begin{array}{ccccc} & ddu & & duu & \\ dds & & dus & & uus \\ & dss & & uss & \end{array} \right\rangle$$

$$\begin{array}{ccccccc} ddd & & ddu & & duu & & uuu \\ & dds & & dus & & uus & \\ & & dss & & uss & & \\ & & & sss & & & \end{array}$$

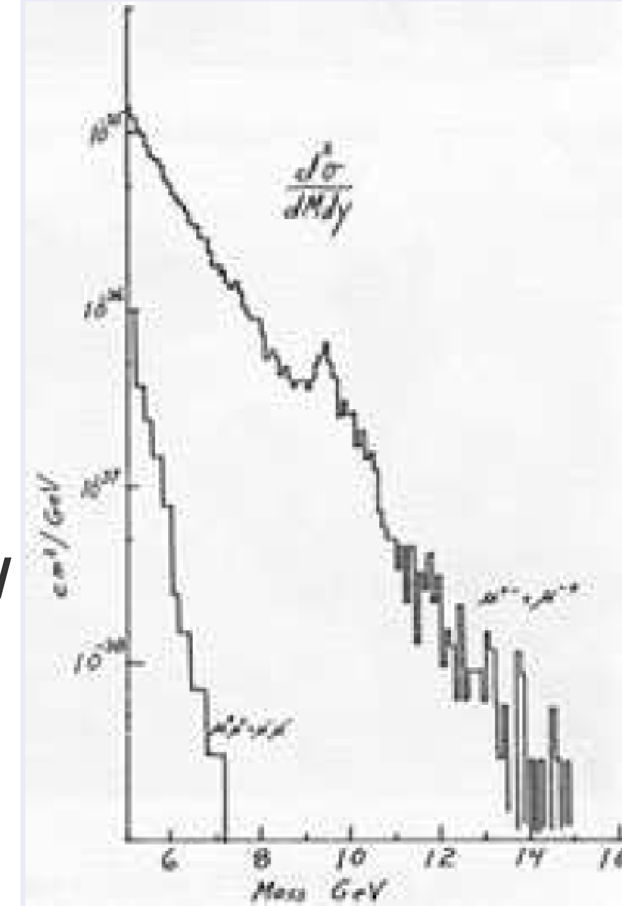
- To describe the zoo of particles, in 1964 Gell-Mann and Zweig proposed idea of 3 quarks (u,d,s) with spin ½ and electric charge 2/3 (u), -1/3 (d,s) and masses of 300 MeV (u,d) and 500 MeV (s)

History (II)

$(u, d)\ (c, s)$
$(\nu_e, e)\ (\nu_\mu, \mu)$

- In 1970, based on the decays of K-mesons **Glashow, Iliopoulos and Maiani predict** the 4^{th} quark c "**charm**" (u, d, s, c)
- In 1973, **Makoto Kobayashi** and **Toshihide Maskawa** predict the third generation of quarks to accommodate the observed violation of CP invariance in K^0 decays
- In 1974, **Sam Ting** et al (BNL) and **Burt Richter** et al (SLAC) **discover J/Ψ** and the fourth **charm** quark;
- In 1975, **τ lepton** was **discovered** by **Martin Perl** et al (SLAC) providing support for a third generation of fermions

History (III)



- In 1977, Leon Lederman et al (Fermilab) **discover** Υ(1s)→μ+,μ− interpreted as bound state of a new quark **b** (beauty or bottom, m_b≈4.5 GeV, spin ½, el.charge -1/3)
- b weak isospin = -½, need +½ partner, **have to add top quark** to cancel chiral anomaly $\sum_f Y_f = \sum_f Q_f = 0$

$$(Q_t + Q_b) \times N_c + Q_{tau} = (2/3 - 1/3) \times 3 - 1 = 0$$

Top Quark in the Standard Model

				$SU(3)$	$SU(2)$	$U(1)_Y$
$Q_L^i =$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	3	2	$\frac{1}{6}$
$u_R^i =$	u_R	c_R	t_R	3	1	$\frac{2}{3}$
$d_R^i =$	d_R	s_R	b_R	3	1	$-\frac{1}{3}$

$$\mathcal{L}_{\mathrm{SM}} = -\frac{1}{\sqrt{2}} \sum_{q=u,c,t} \bar{t}\left(v_{tq}^H + \gamma_5 a_{tq}^H\right) q\, H - g_s \bar{t}\gamma^\mu t^a\, t\, G_\mu^a - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \bar{t}\gamma^\mu \left(v_{tq}^W - a_{tq}^W \gamma_5\right) q\, W_\mu^+$$
$$-Q_t e \bar{t}\gamma^\mu\, t\, A_\mu - \frac{g}{2\cos\vartheta_W} \sum_{q=u,c,t} \bar{t}\gamma^\mu \left(v_{tq}^Z - a_{tq}^Z\gamma_5\right) q\, Z_\mu + \text{h.c.}$$

$$\begin{aligned}
v_{tt}^H &= y_t = \sqrt{2}\frac{m_t}{v_{ew}}, && a_{tt}^H = 0,\ v_{ew} \approx 246 \text{ ГэВ} \\
v_{tq}^H &= a_{tq}^H = 0, && q \neq t \\
v_{tq}^W &= a_{tq}^W = \frac{V_{tq}}{2} && \\
v_{tt}^Z &= \frac{1}{2} - 2Q_t \sin^2\vartheta_W, && a_{tt}^Z = \frac{1}{2} \\
v_{tq}^Z &= a_{tq}^Z = 0, && q \neq t
\end{aligned}$$

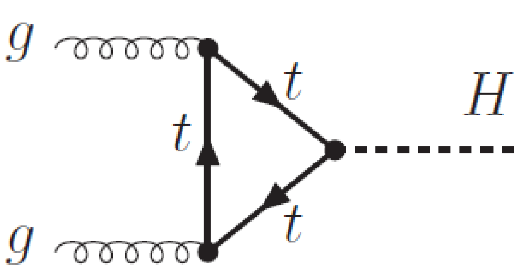
Top Quark Mass (I)

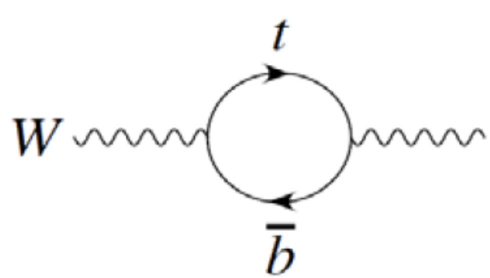
- Top quark mass is not constrained by theory
- Mass is defined by Yukawa interaction with Higgs boson and Yukawa constant:

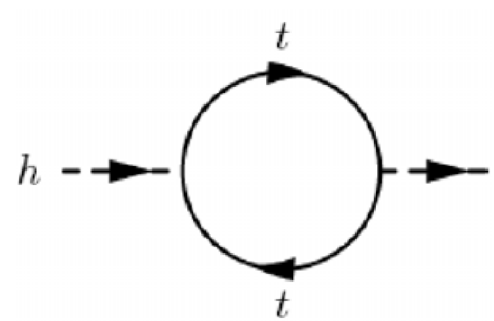
$$\lambda_t = 2^{3/4} G_f^{1/2} m_t = \sqrt{2}\, m_t / v_{ew} \, ; \, v_{ew} \approx 246\, GeV$$

(≈ 1 for m_t = 173 GeV)

- Owing to high value of Yukawa constant top quark gives main contribution in many loop diagrams e.g.

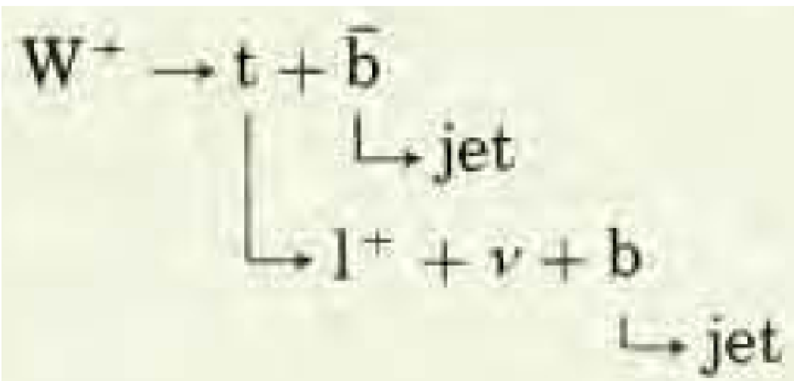






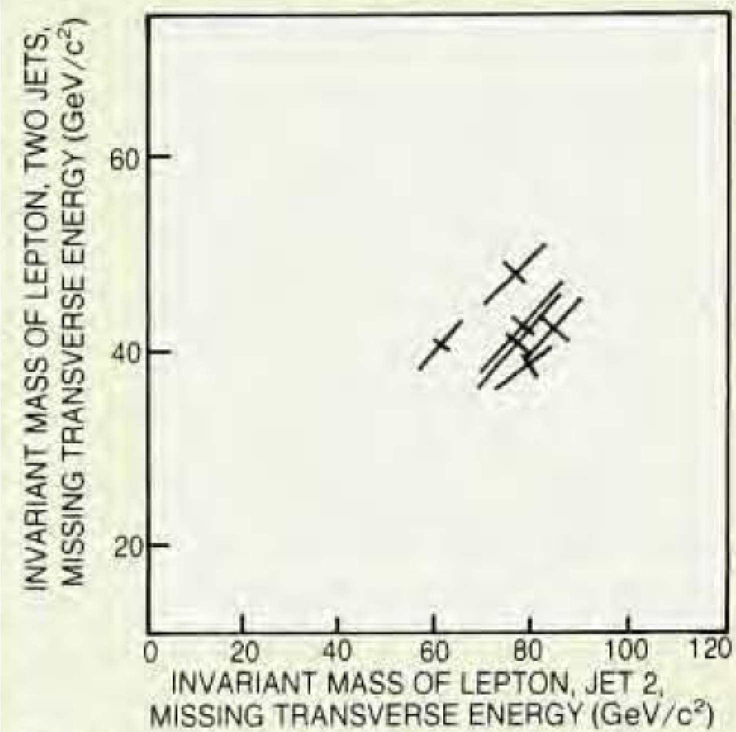
Top Quark first (false) evidence

- In 1984 UA1 group (Carlo Rubbia et al.) claims of a discovery of the top quark with mass 40±10 GeV



Physics Today 37, 8, 17 (1984); https://doi.org/10.1063/1.2916347

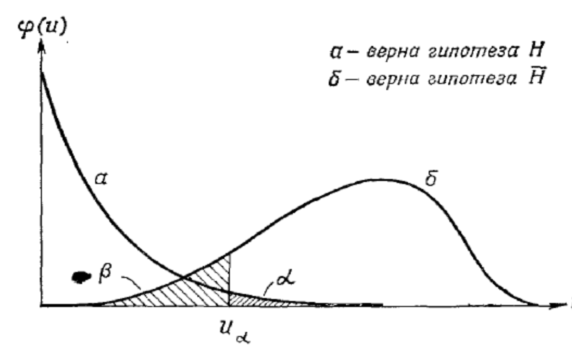
- UA2 never confirmed the evidence
- Poor modeling of W→τ,ν background was the reason of the mistake (T. Wyatt)



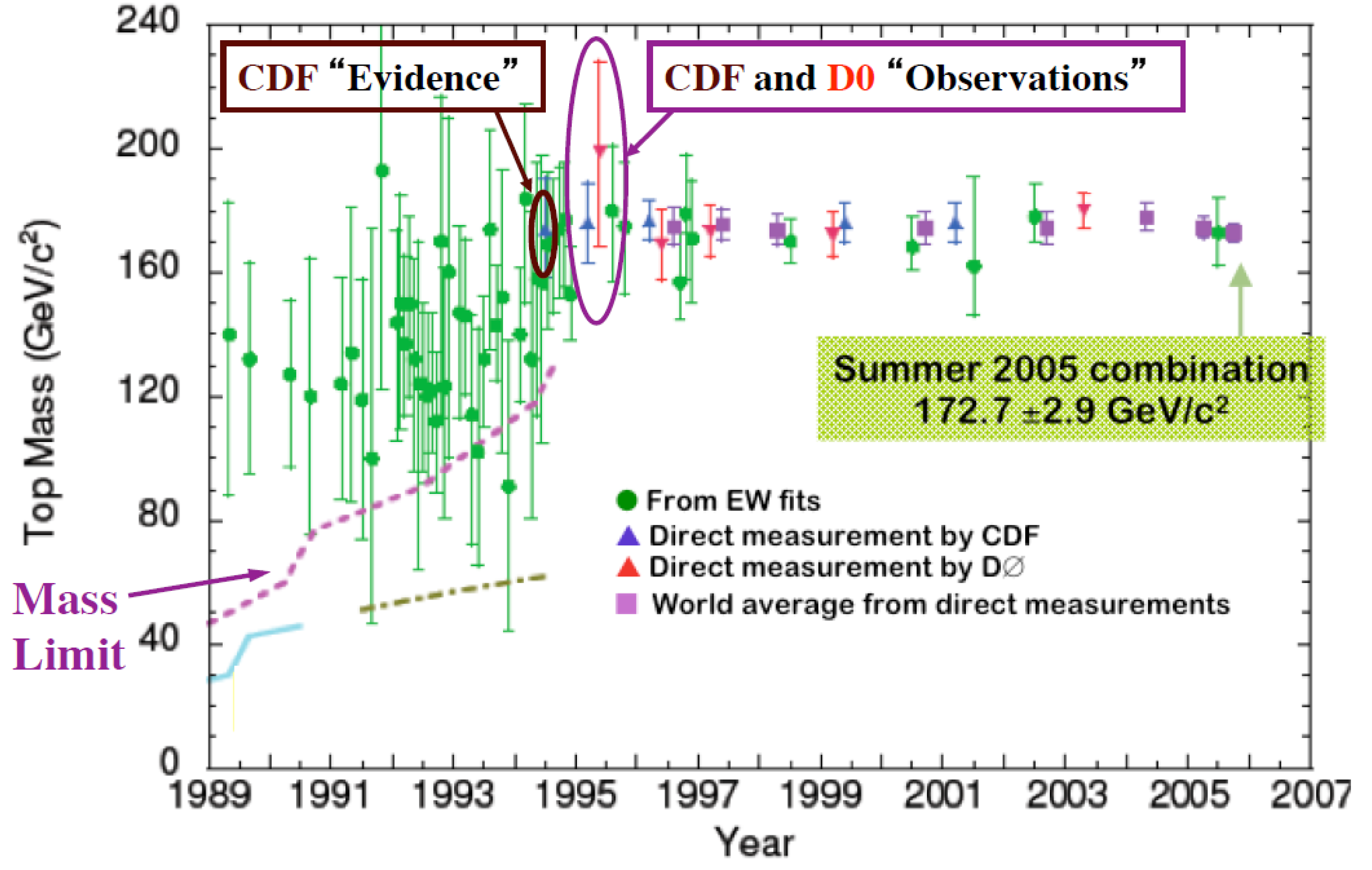
Evidence for top quark from UA1 group assumes the W decays into $t\bar{b}$, that the b produces jet 1, and that t decays into a lepton, a neutrino and a b, which decays into jet 2. The peak at 70–80 GeV suggests W decay and the peak at 40–45 GeV suggests top decay. From the six events shown, UA1 obtains a top mass range 30–50 GeV.

Remark

- Enrico Fermi advised his colleagues never publish any new effect unless it had a significance of more than 3 standard deviations (3σ).
- Trying to maintain his sterling reputation, Fermi multiplied all uncertainties by a √2
- Modern agreement is to call “evidence” with 3σ deviation of the signal from the background and “observation” with 5σ statistical significance.



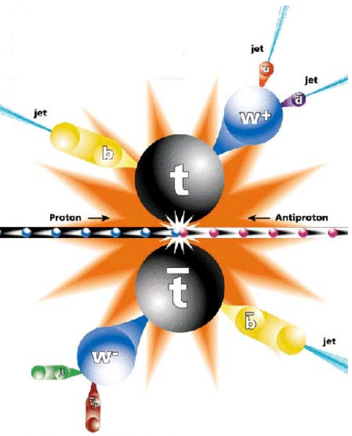
Top Quark Mass (II)

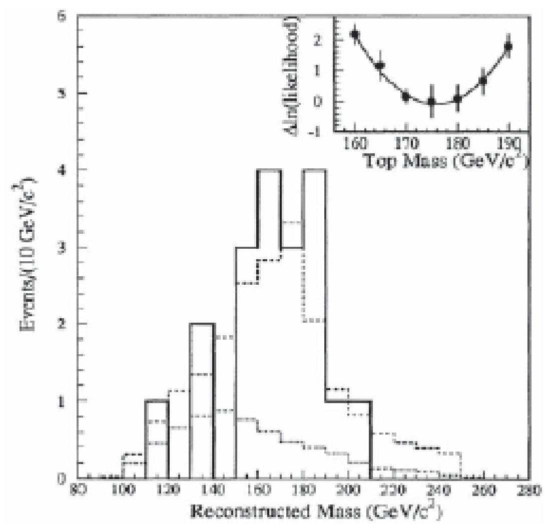


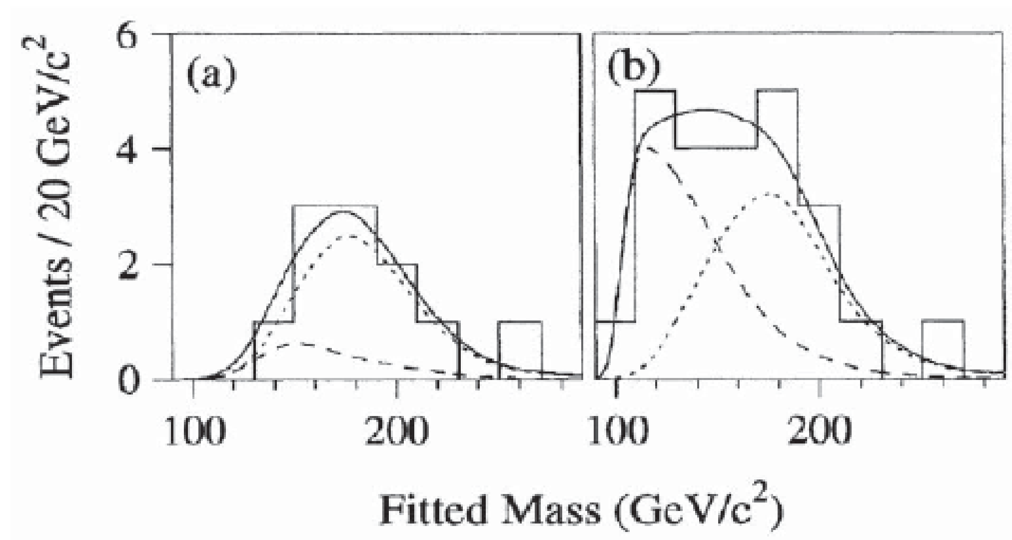
Observation of top quark

F. Abe et al. [CDF Collaboration], Phys. Rev. Lett. 74, 2626 (1995)

S. Abachi et al. [D0 Collaboration], Phys. Rev. Lett. 74, 2632 (1995)







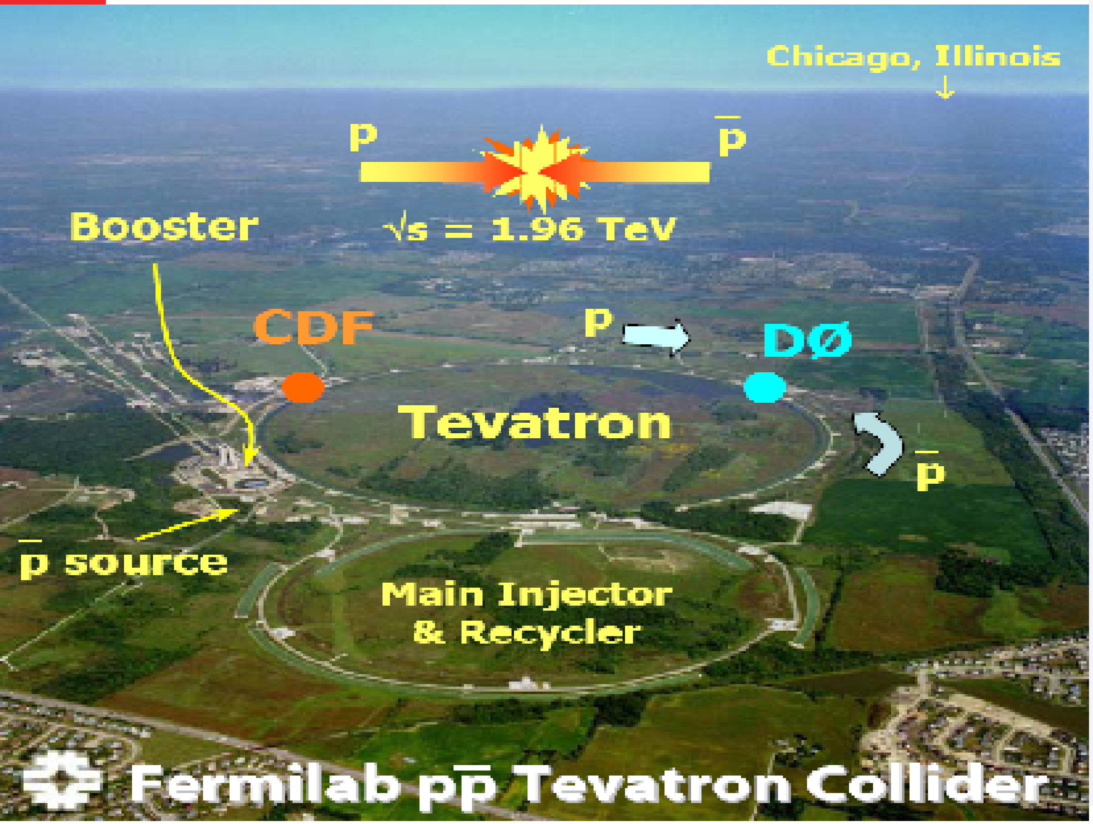
$$m_t = 176 \pm 13\ \mathrm{GeV}$$

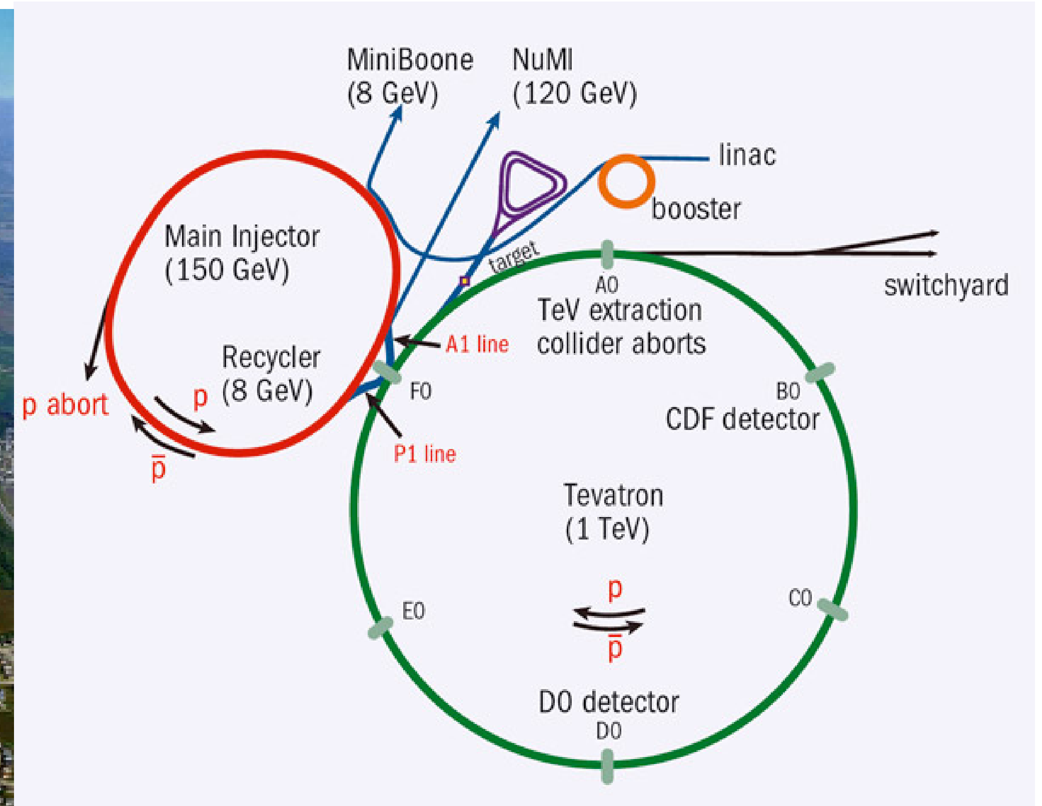
$$\sigma(t\bar{t}) = 6.8^{+3.6}_{-2.4}\ \mathrm{pb}$$

$$m_t = 199 \pm 30\ \mathrm{GeV}$$

$$\sigma(t\bar{t}) = 6.4 \pm 2.2\ \mathrm{pb}$$

Fermilab Tevatron Collider

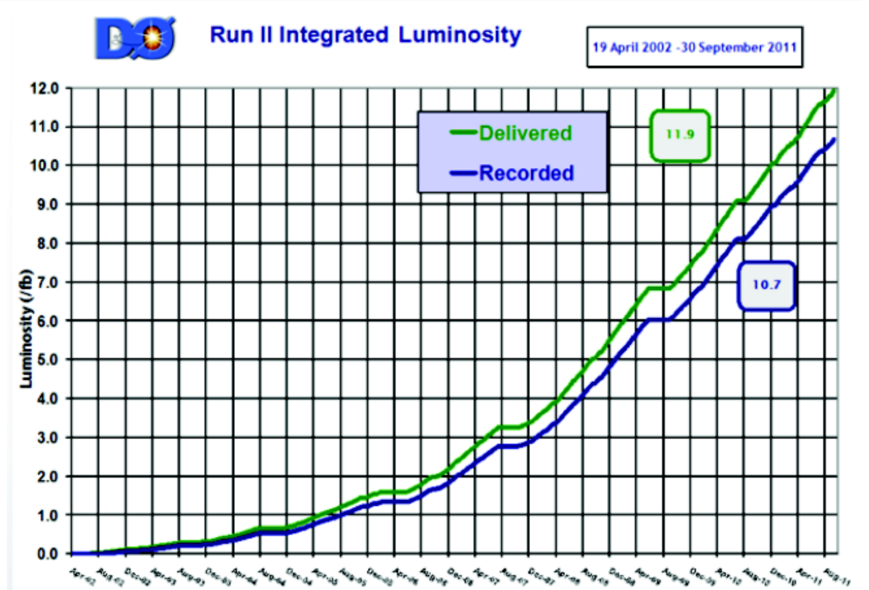




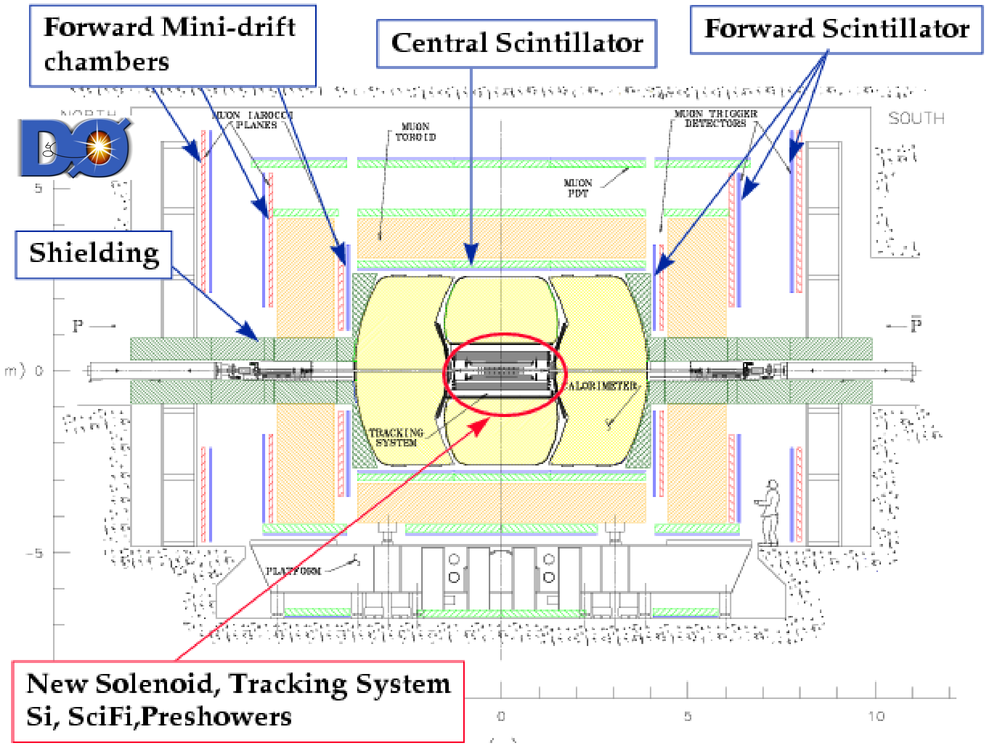
1983 - 2011

Run I: 1.8 TeV 1992-1996, 100 pb^{-1}

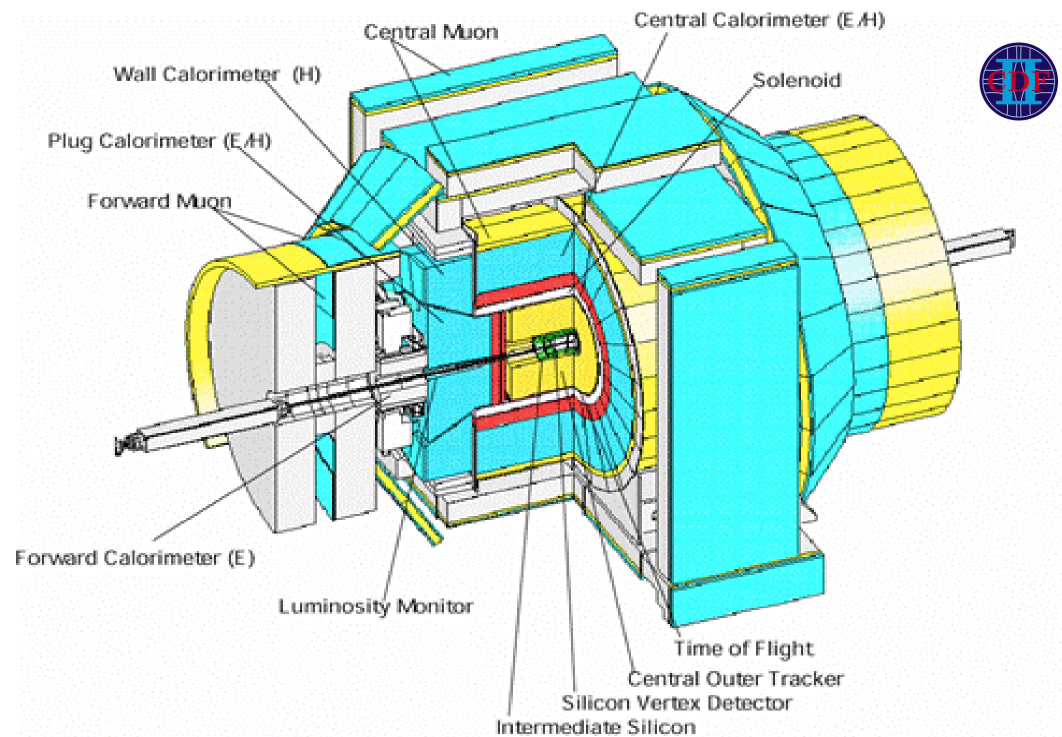
Run II: 1.96 TeV, 2001-2011, 10 fb^{-1}

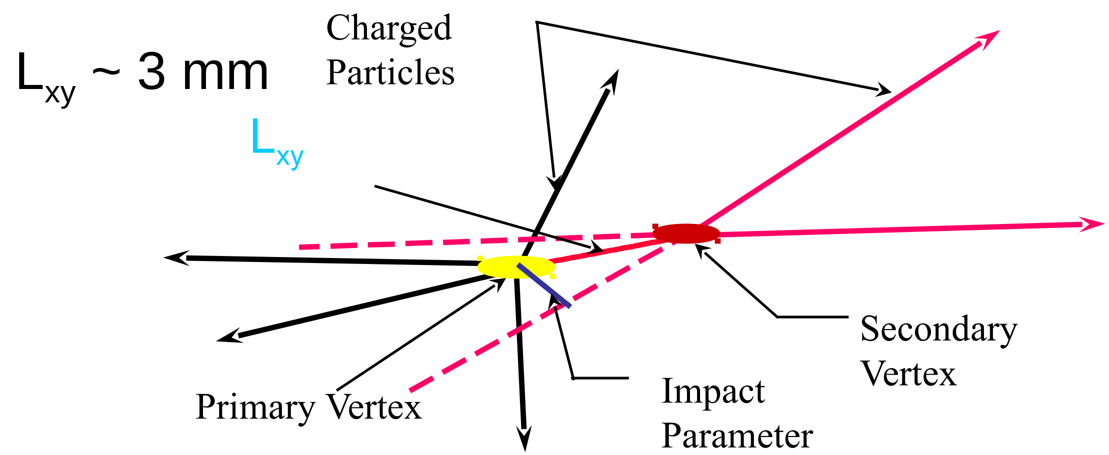


Tevatron collider, D0 and CDF detectors



+ New Electronics, Trig, DAQ

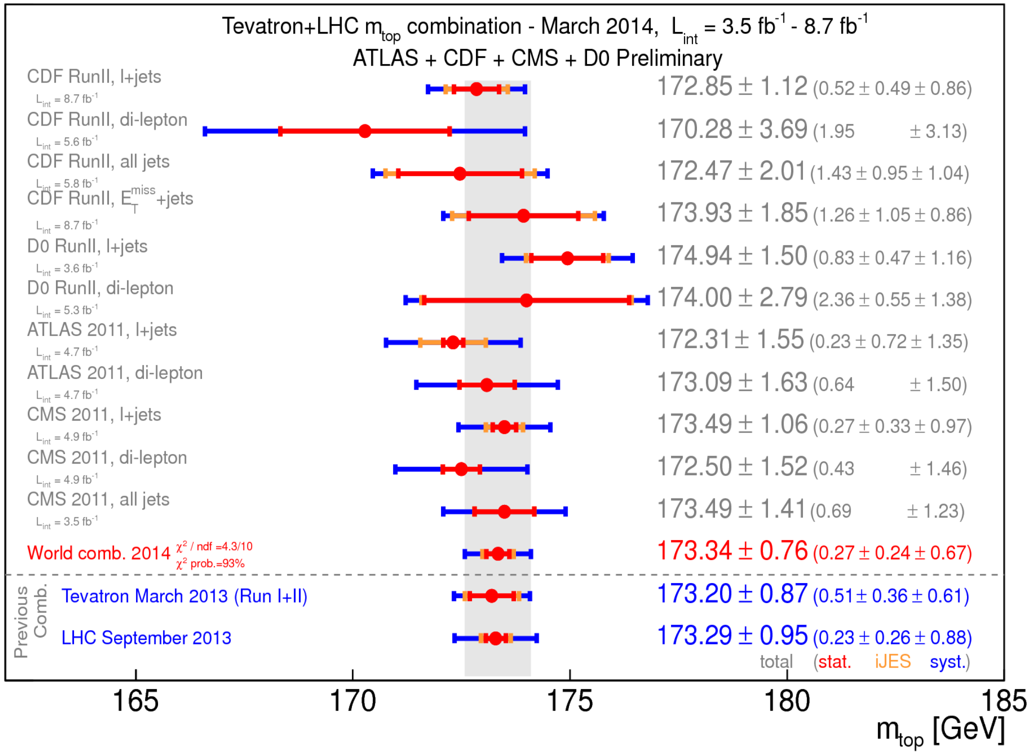


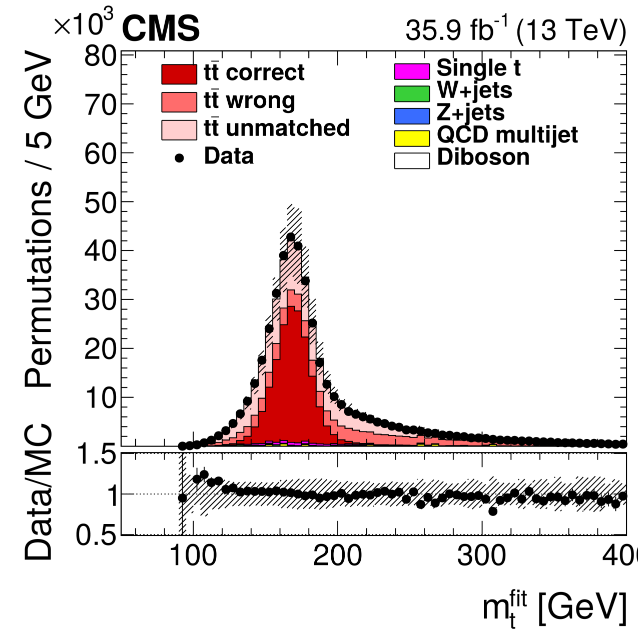


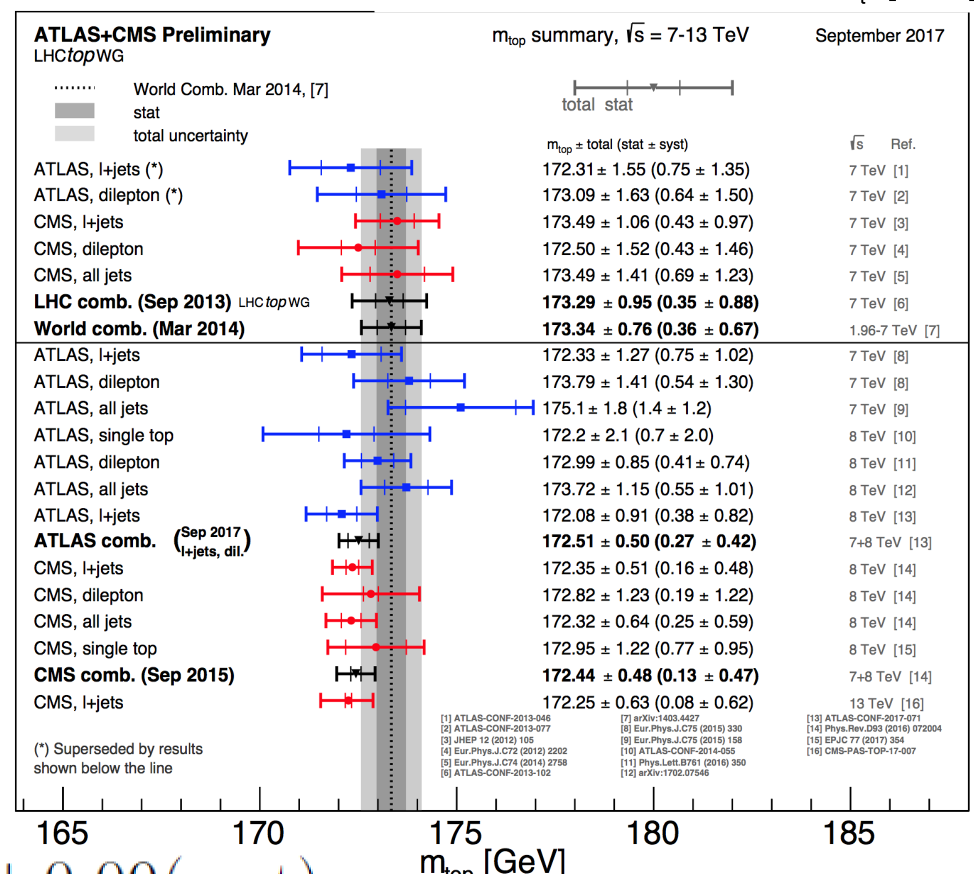
Secondary VerteX Tagging

ε(SVX) ~ 50%

Top Quark Mass (III)







$$\sigma(pp \to t\bar{t}) = f(m_t)$$

$$\overline{MS},\ m_t = 160.0 \pm 4.8\ \textit{ГэВ}$$

$$\Delta m_t = m_t - m_{\bar{t}} = -0.15 \pm 0.19(\text{stat}) \pm 0.09(\text{syst})$$

Mixing with other quarks, Cabibbo–Kobayashi–Maskawa matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$V_{CKM} = (U_L^u)^\dagger U_L^d$$

$$VV^+ = 1$$

$$\lambda = 0.2257^{+0.0009}_{-0.0010}, \quad A = 0.814^{+0.021}_{-0.022}$$

$$\bar\rho = 0.135^{+0.031}_{-0.016}, \quad \bar\eta = 0.349^{+0.015}_{-0.017}$$

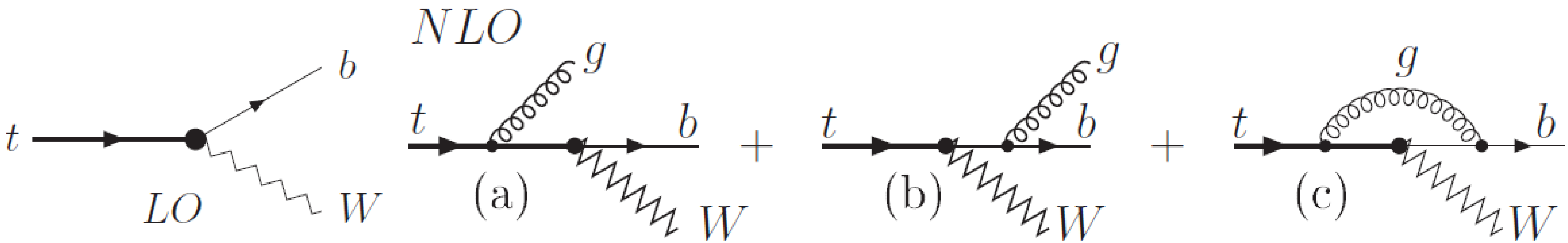
$$V_{tb} \approx 0.9989 \div 0.9993,\ V_{ts} \approx 0.034 \div 0.046,\ V_{td} \approx 0.004 \div 0.014.$$

$$tW^\pm q \;=\; \frac{e}{2\sqrt{2}\sin\vartheta_W} V_{tq}\gamma^\alpha(1-\gamma^5)$$

$$\sin^2\vartheta_W \;\approx\; 0.23$$

4th generation is restricted by LEP precision measurements of Z decays, mass of 4th neutrino should be greater than Z boson mass

Top Quark Decay Width



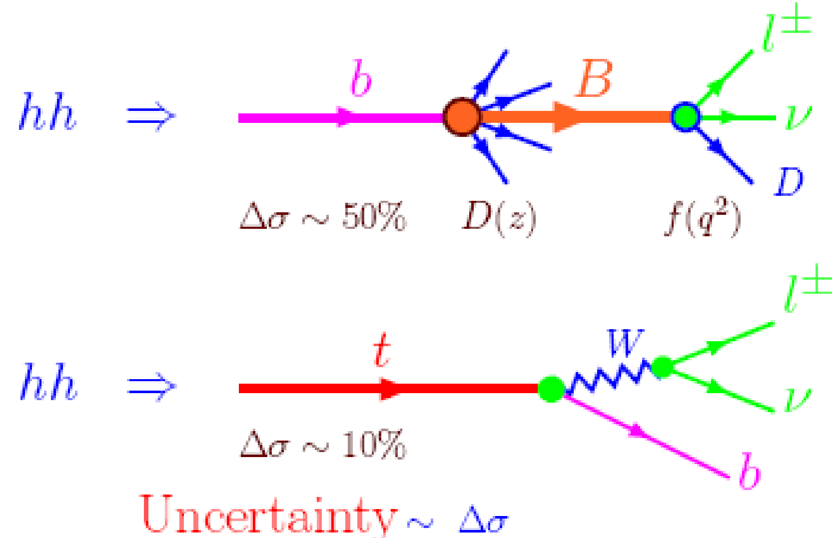
$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right]$$

$$\Gamma_t^{tot} \approx 1.6\,(LO),\, 1.42\,(NLO)\,GeV$$

$$\tau_t = 1/\Gamma_t^{tot} \approx 4\times10^{-25}\,sec\,,$$

$$\tau_{hadron} = 1/\Lambda_{QCD} \approx 3\times10^{-24}\,sec\,,$$

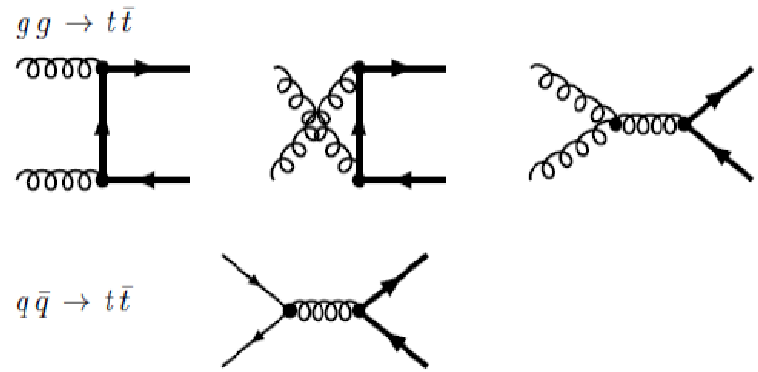
$$(\Lambda_{QCD} \approx 200\,MeV)$$



Top Quark production processes

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

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

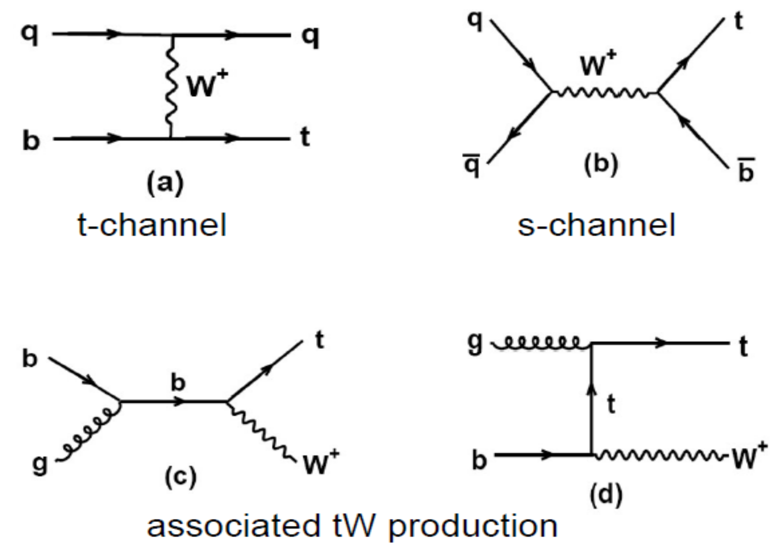


90%

10%

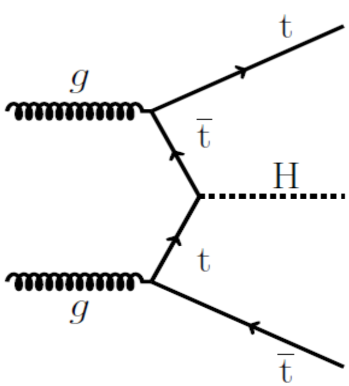
$t(\bar{t})$ single production (electroweak)

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



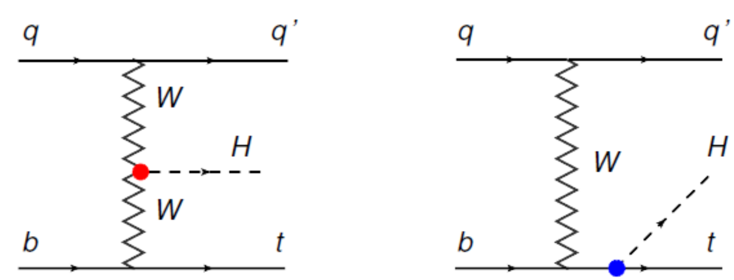
$t\bar{t}$H(W,Z,A) production

~ 0.1 - 1 pb
>5σ

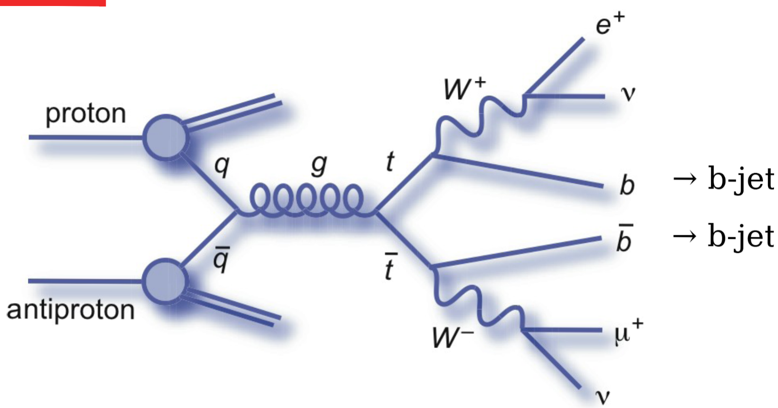


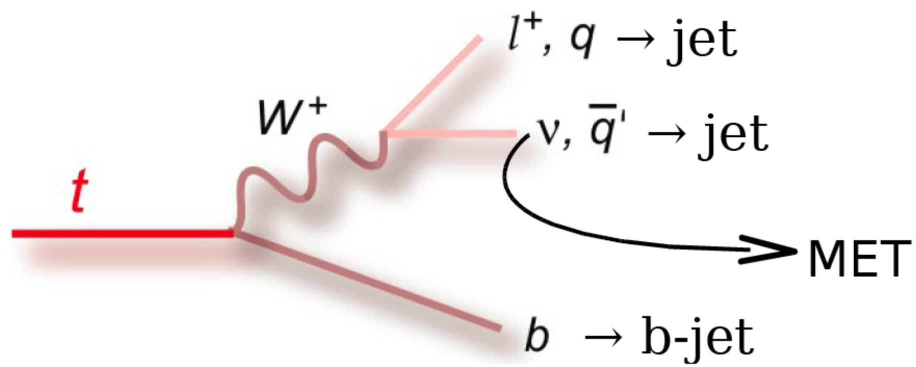
tHq (tZq,tAq) production

~ 0.01 pb
$\mu < 3$ @95CL

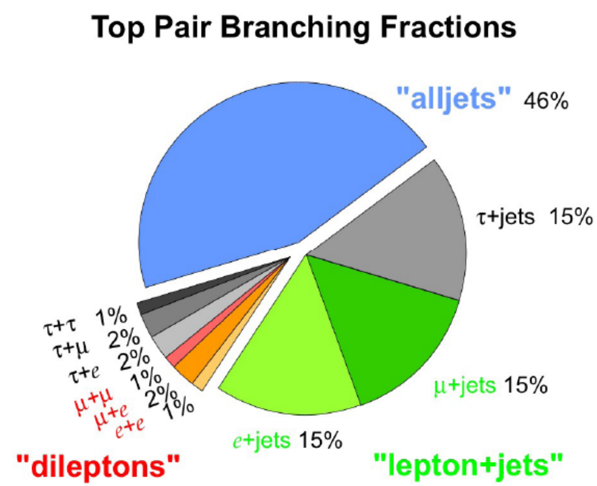


Final signatures of the processes

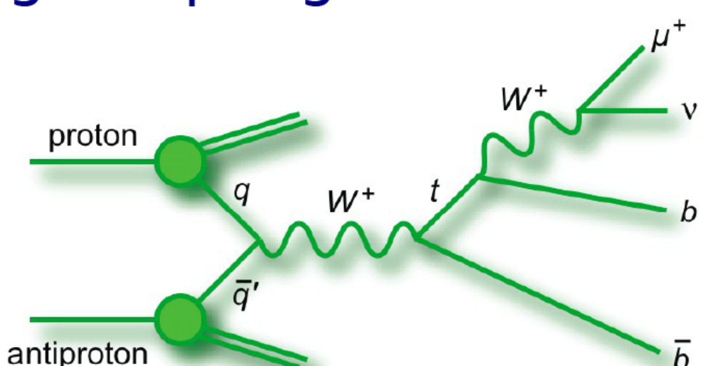


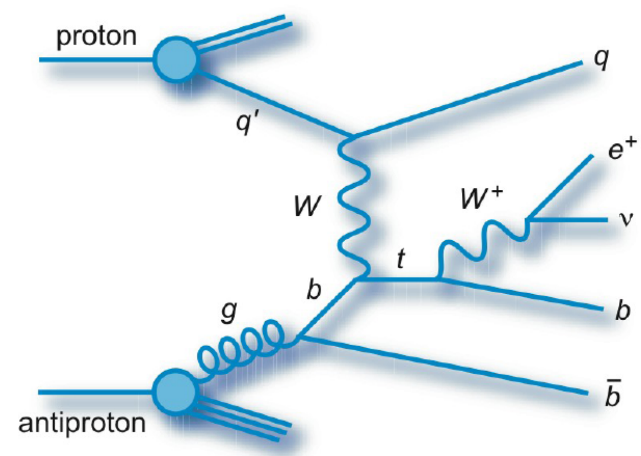


- Top pair signatures:
  - lepton + jets
  - dilepton
  - all jets



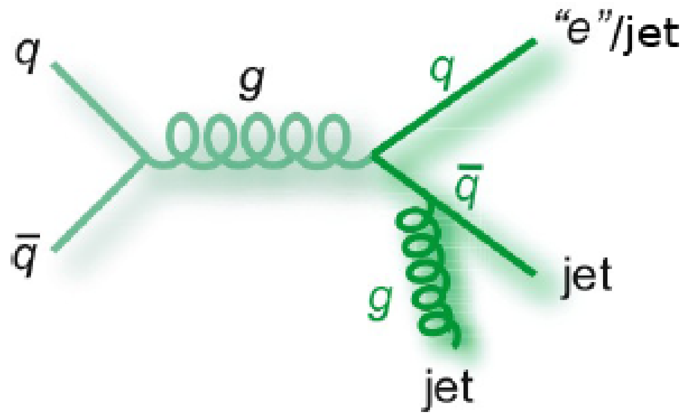
- Single Top Signatures:





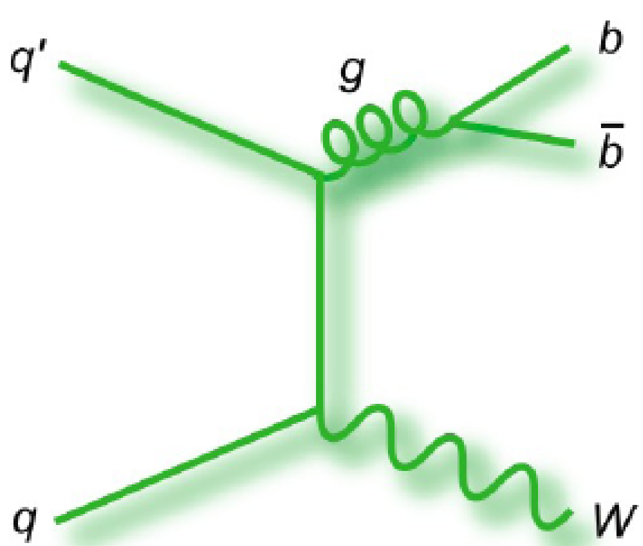
Main Background Processes

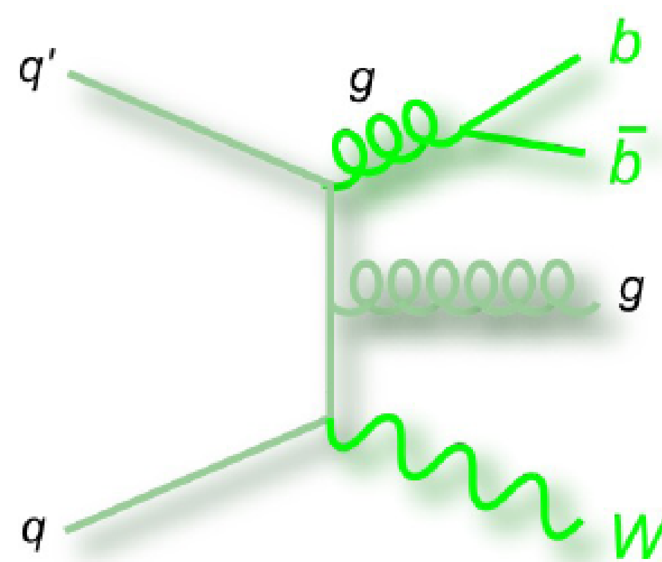
- Multi-jet



From data:
- Orthogonal sample with looser lepton ID
- B-tag jets randomly

- W+jets





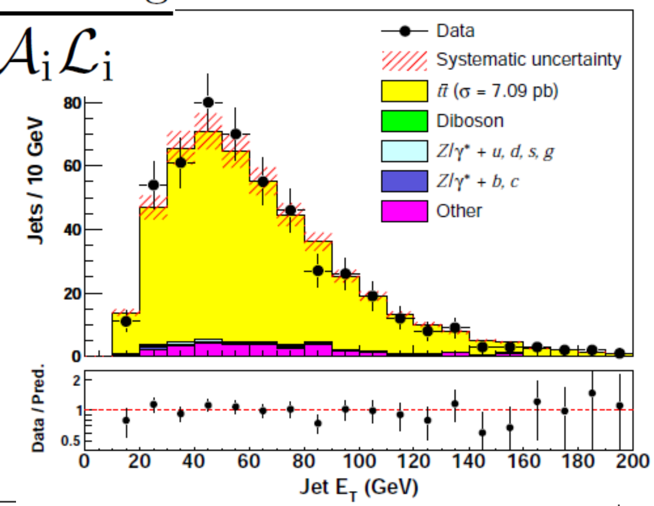
MC

- Z+jets, diboson (WW,ZZ,WZ)
- Top pair is a background to single top!

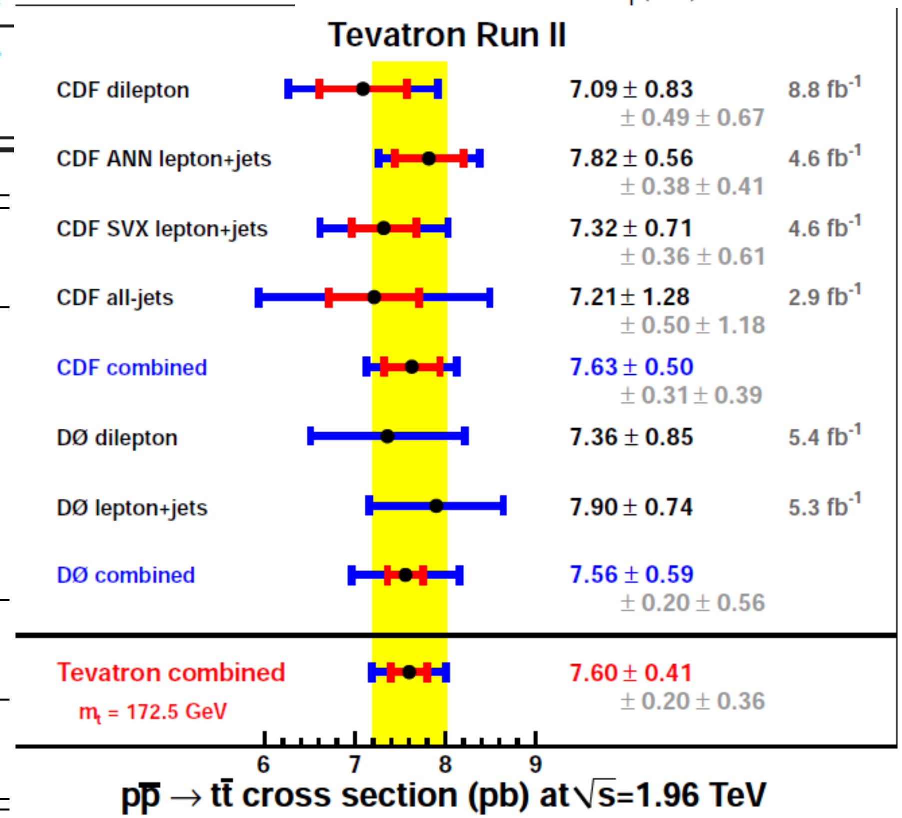
Pair Top Quark production Cross Section, Tevatron

$$\sigma_{t\bar{t}} = \frac{N_{\rm obs} - N_{\rm bkg}}{\sum_i \mathcal{A}_i \mathcal{L}_i}$$

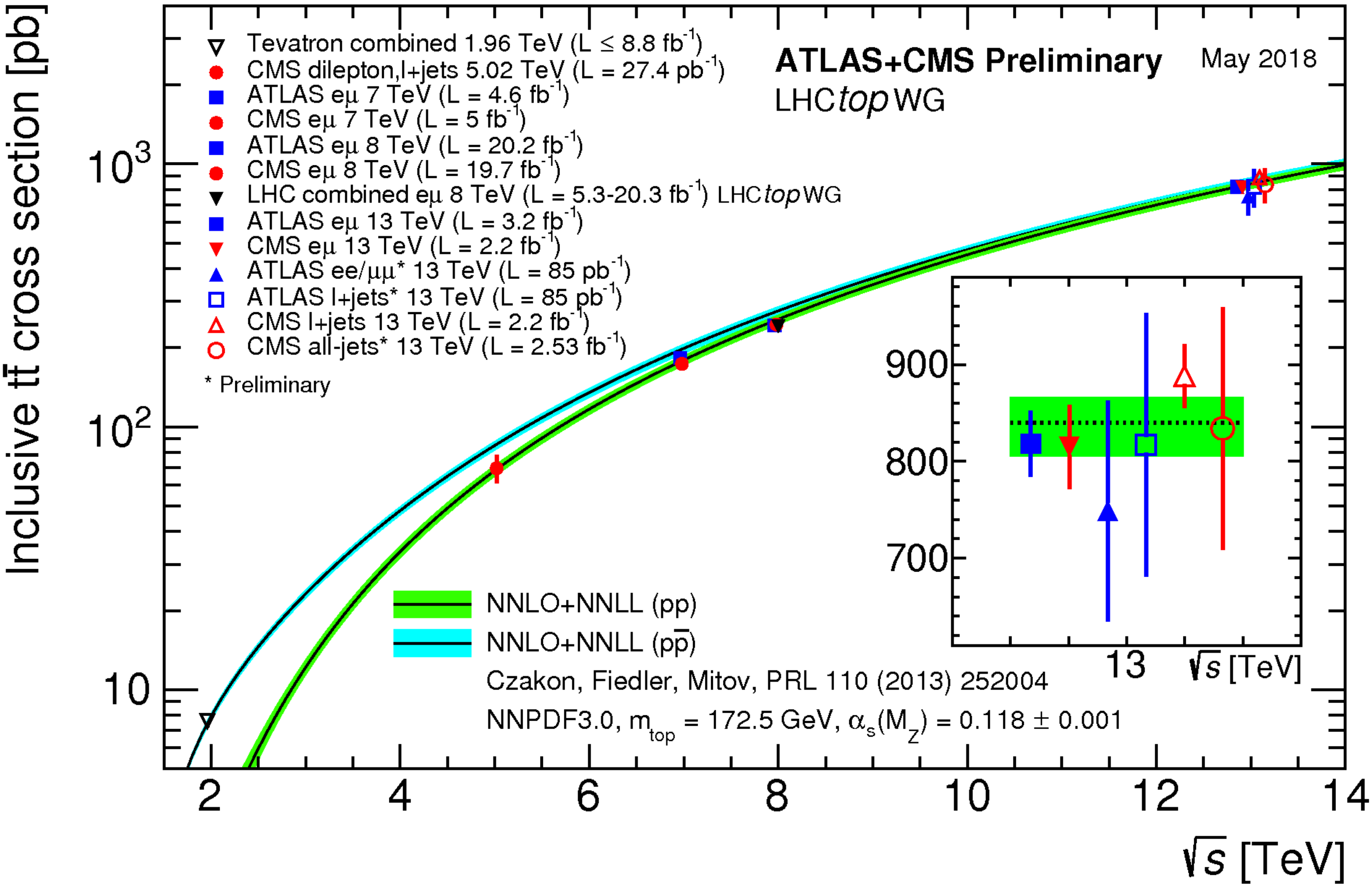
Process	μ+jets	e+jets
Multijet	31.1 ± 10.0	75.1 ± 56.3
W+jets	164.9 ± 15.9	148.8 ± 14.3
Diboson	9.1 ± 0.8	10.5 ± 0.9
Z/γ^*+jets	11.9 ± 1.2	12.4 ± 1.5
Single top	16.1 ± 2.2	21.8 ± 3.0
$t\bar{t}$, $\ell\ell$	22.6 ± 2.0	33.5 ± 2.9
$\sum$ bgs	254.4 ± 19.1	302.1 ± 58.3
$t\bar{t}$, ℓ+jets	838.7 ± 72.5	1088.7 ± 94.2
$\sum$ (sig + bgs)	1093.1 ± 75.0	1390.8 ± 110.8
Data	1137	1403



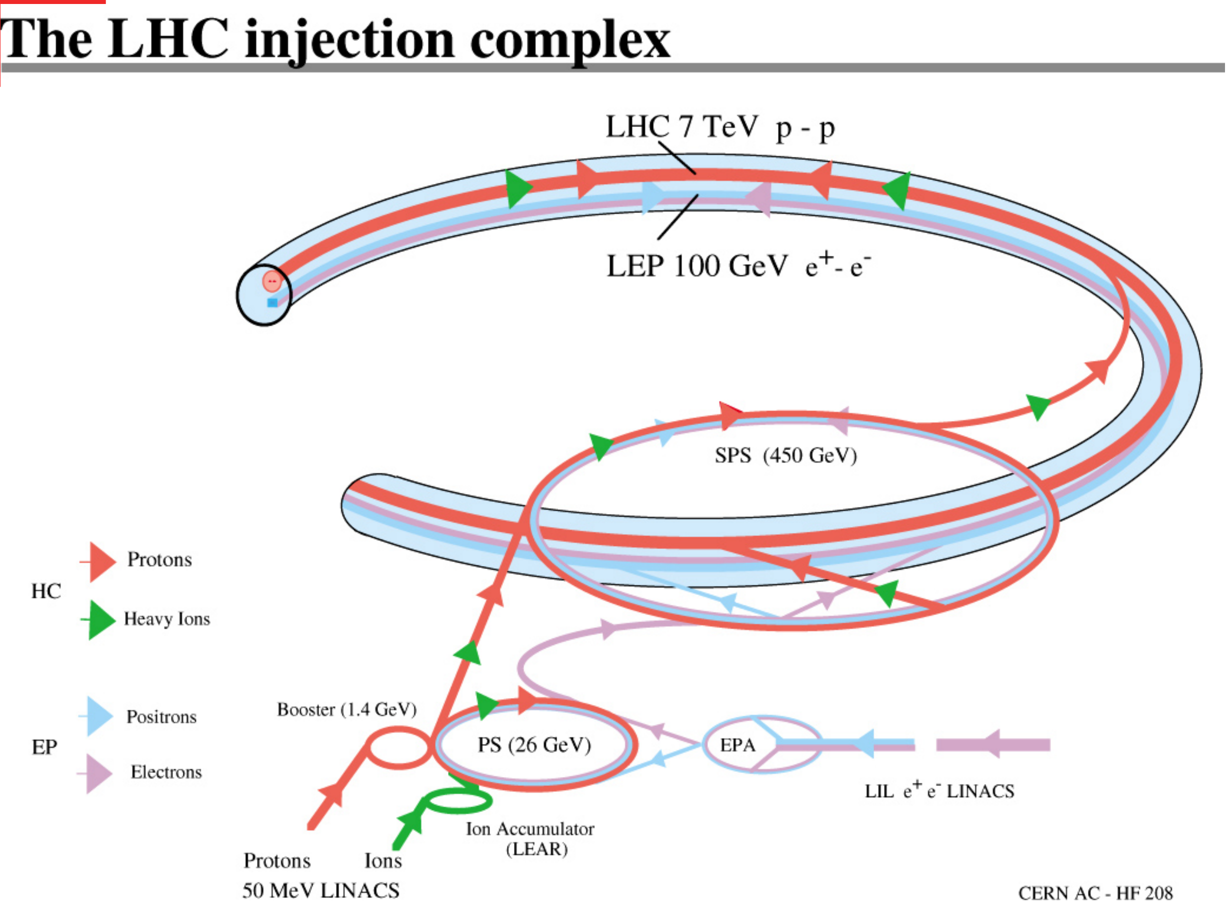
Source	1 jet (Validation region)	≥ 2 jets (H_T+OS) (Signal region)
WW	0.8 ± 0.2	0.6 ± 0.2
WZ	0.2 ± 0.0	0.1 ± 0.0
ZZ	0.1 ± 0.0	0.3 ± 0.1
$Z/\gamma^* + u, d, s, g$	2.1 ± 0.2	2.8 ± 0.3
$Z/\gamma^* + b, c$	1.8 ± 0.2	2.5 ± 0.2
Other	1.9 ± 0.7	16 ± 5
Total background	6.9 ± 0.9	22 ± 5
$t\bar{t}$ ($\sigma = 7.09$ pb)	20.2 ± 1.4	224 ± 15
Total SM expectation	27.1 ± 2.2	246 ± 20
Observed	29	246

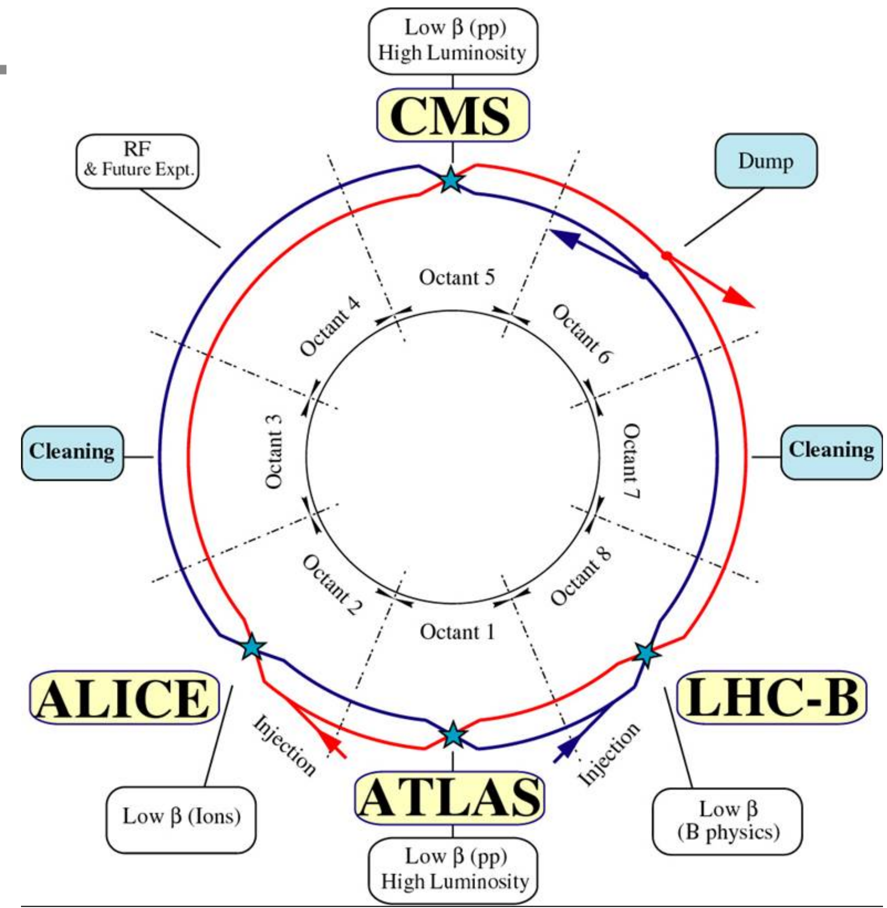


Pair Top Quark production Cross Section, LHC

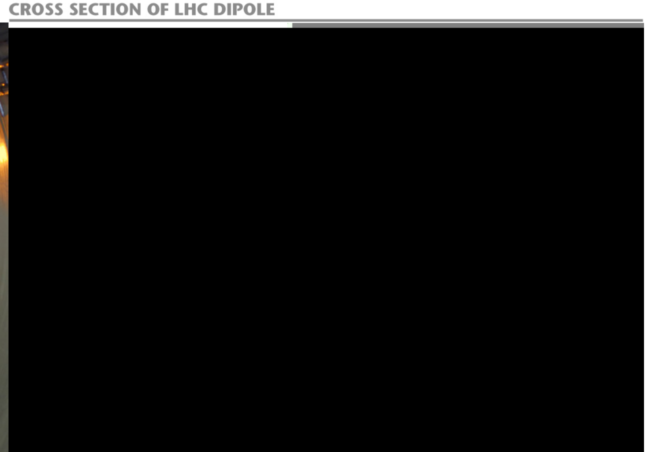


Large Hadron Collider (LHC)





CROSS SECTION OF LHC DIPOLE

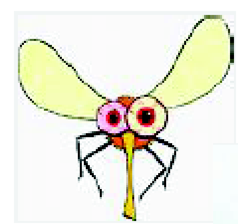


1232 sections of dipoles
T= 1.9 K
B= 8.4 T
I= 11700 A

LHC (II)

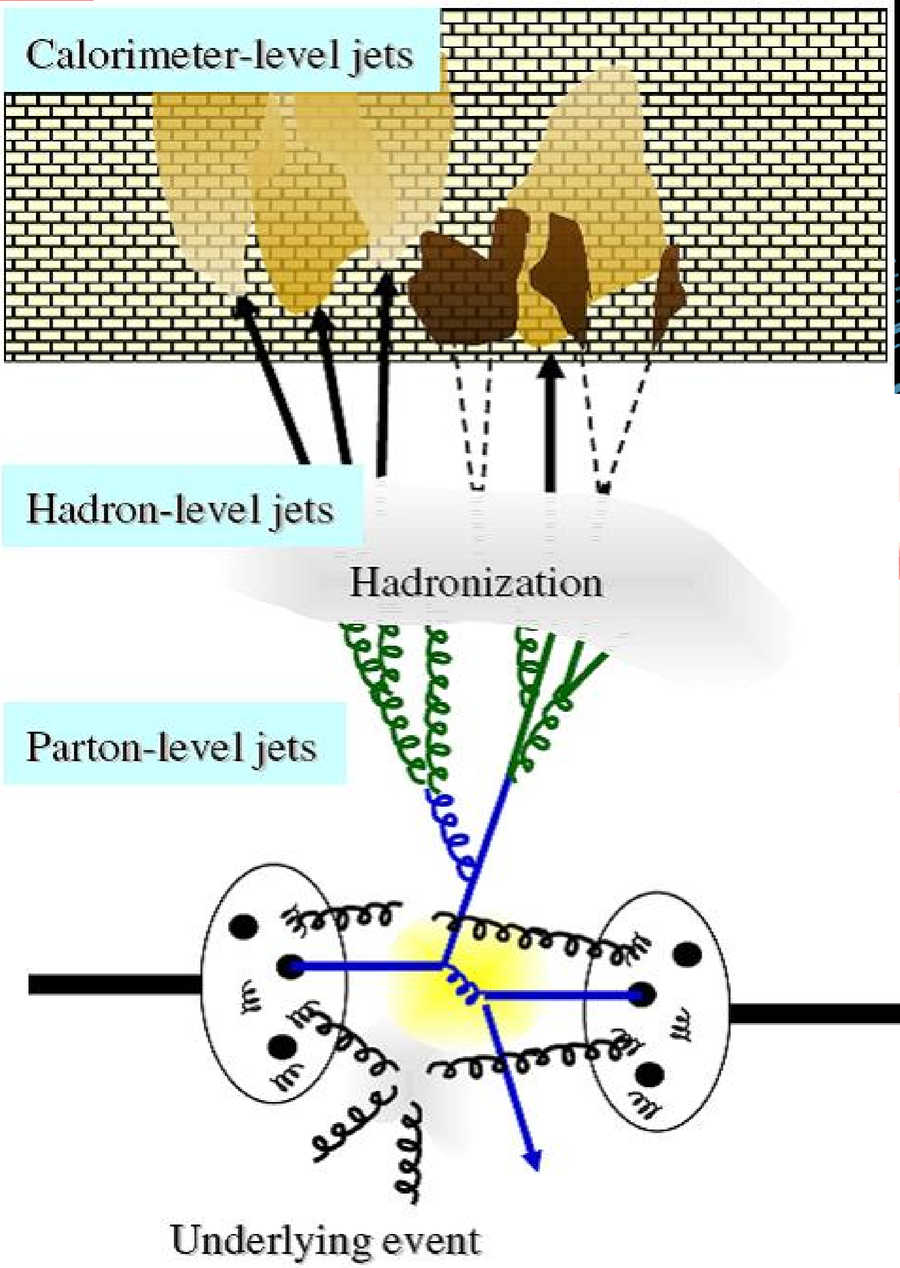
- Start 10.09.2008, 18.09.2008 at 10 TeV Quench incident
- 2009-2011, 7 TeV, 5 fb^{-1}
- 2012, 8 TeV, 20 fb^{-1} (Higgs discovering)
- 2015–2018, 13 TeV, ≈100 fb^{-1}

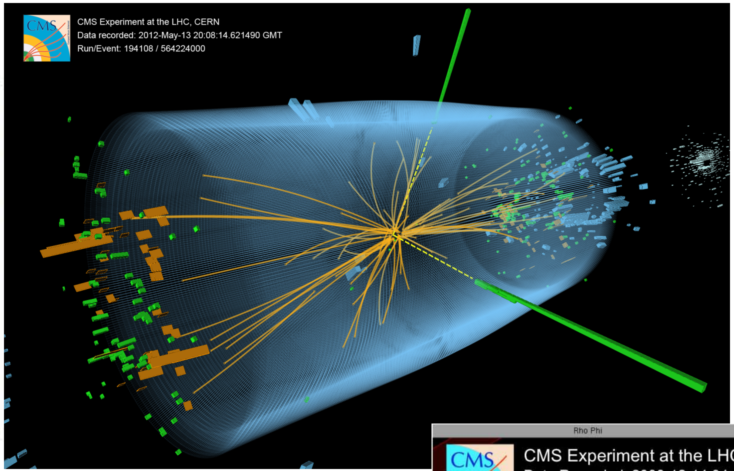
- 1 proton at 7 ТэВ $\approx 10^{-6}$ Joule $\approx$

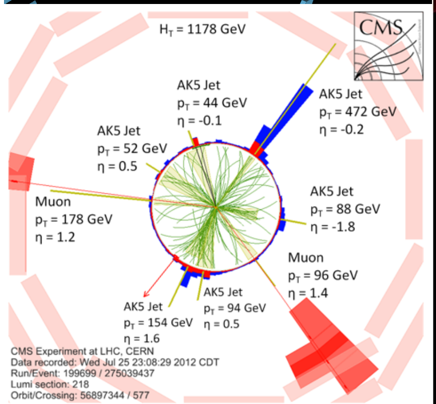


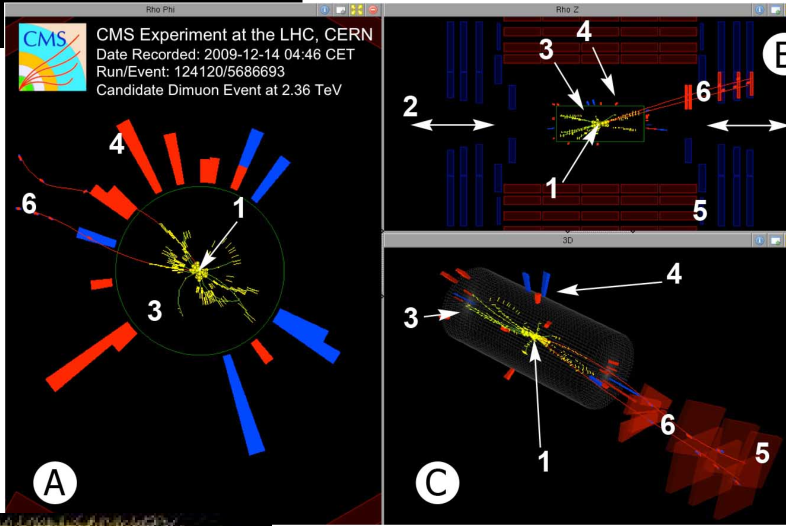
- 2808 bunchs $\times\ 10^{11}$ protons/bunch $\times$ 7 TeV/proton = 360 MJoule $\approx$

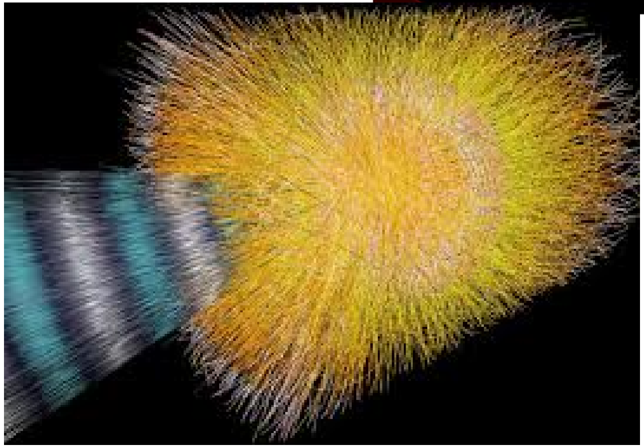
Typical LHC event



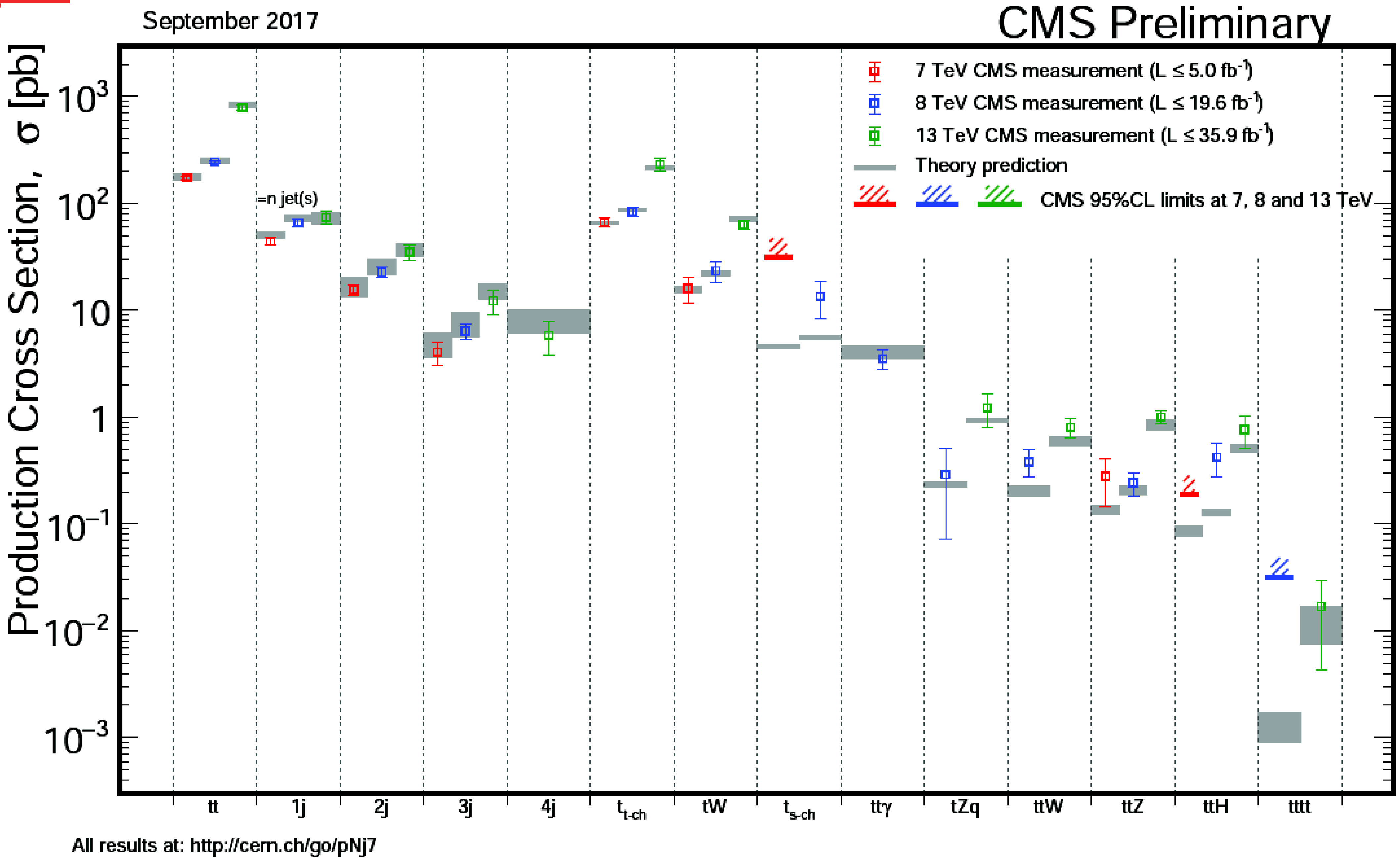








Top Quark Production Cross section Measurments



Top Quark Properties

- Spin ½. Spin 0 or 1 is excluded since t decays to W and b. For spin 3/2 the cross sections are completely different.
- Electric charge +2/3. ATLAS has measured $Q_{top} = 0.64 \pm 0.02(stat.) \pm 0.08(syst.)$ also, deviation from 2/3 violate cancelation of chiral anomalies and interactions with other particles
- Color triplet. Inherits color states from b-quark, since top decays to W (colorless) and b (triplet)
- Weak Isospin ½. Requires precise measurements of electroweak top quark interactions and rare top decay channels.

Possible Beyond of Standard Model (BSM) Contributions

- Collision energy E is above production thresholds
  - New resonances decaying to top quark
  - New states produced in association with top

- Collision energy E is less than production thresholds
  - New effective anomalous interactions of the top quark with other SM particles
    (modification of top decay and production properties)
    Effective Field Theory approach
    [W.Buchmuller, D.Wyler 1985]

Possible Beyond of Standard Model interactions of top quark (I)

$$\mathcal{L}_{SM}(t\,g\,t) = \quad \bar{\psi}_t \hat{O}_g^{\mu,\,a} \psi_t\, G_{a,\mu}; \quad \hat{O}_g = g_s\, t^a \gamma^\mu$$

$$\mathcal{L}_{SM}(t\,W\,q) = \quad \bar{\psi}_q \hat{O}_W \psi_t; \quad \hat{O}_W = \frac{e}{2\sqrt{2}\sin\theta_W}\, V_{tq}\gamma^\mu(1-\gamma^5)\, W_\mu$$

$$\begin{aligned}\mathcal{L}_{\rm SM} \;=\; & -\frac{1}{\sqrt{2}} \sum_{q=u,c,t} \bar{t}\left(v_{tq}^H + \gamma_5 a_{tq}^H\right) q\, H - g_s \bar{t}\gamma^\mu t^a\, t\, G_\mu^a - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \bar{t}\gamma^\mu \left(v_{tq}^W - a_{tq}^W \gamma_5\right) q\, W_\mu^+ \\ & - Q_t e \bar{t}\gamma^\mu\, t\, A_\mu - \frac{g}{2\cos\vartheta_W} \sum_{q=u,c,t} \bar{t}\gamma^\mu \left(v_{tq}^Z - a_{tq}^Z \gamma_5\right) q\, Z_\mu + \text{h.c.}\end{aligned}$$

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \kappa_4 \bar{\psi}_q \hat{O}^{(4)} \psi_t + \frac{\kappa_5}{\Lambda} \bar{\psi}_q \hat{O}^{(5)} \psi_t + \frac{\kappa_6}{\Lambda^2} \bar{\psi}_q \hat{O}^{(6)} \psi_t + \cdots$$

Λ is a scale of “New Physics”, e.g. Λ=1 TeV
k are couplings constants to parameterize strength of anomalous interactions

Possible Beyond of Standard Model interactions of top quark (II)

$$\mathcal{L}_{EFT} = \left.\begin{array}{l} -g_s \sum_{q=u,c,t} \frac{\kappa^g_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} t^a \left(f^g_{tq} + i h^g_{tq}\gamma_5\right) q\, G^a_{\mu\nu} \\ -\frac{g}{\sqrt{2}} \sum_{q=d,s,b} \frac{\kappa^W_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} \left(f^W_{tq} + i h^W_{tq}\gamma_5\right) q\, W^+_{\mu\nu} \\ -e \sum_{q=u,c,t} \frac{\kappa^\gamma_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} \left(f^\gamma_{tq} + i h^\gamma_{tq}\gamma_5\right) q\, A_{\mu\nu} \\ -\frac{g}{2\cos\vartheta_W} \sum_{q=u,c,t} \frac{\kappa^Z_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} \left(f^Z_{tq} + i h^Z_{tq}\gamma_5\right) q\, Z_{\mu\nu} \end{array}\right\} + \text{h.c.}$$

$$G^q_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu, \ \ldots \qquad |f|^2 + |h|^2 = 1$$

$$\mathcal{L}_{\mathrm{tWb}} = -\frac{g}{\sqrt{2}} \bar{b}\gamma^\mu \left(f^{\mathrm{L}}_{\mathrm{V}} P_{\mathrm{L}} + f^{\mathrm{R}}_{\mathrm{V}} P_{\mathrm{R}}\right) t\, W^-_\mu - \frac{g}{\sqrt{2}} \bar{b} \frac{\sigma^{\mu\nu}\partial_\nu W^-_\mu}{M_{\mathrm{W}}} \left(f^{\mathrm{L}}_{\mathrm{T}} P_{\mathrm{L}} + f^{\mathrm{R}}_{\mathrm{T}} P_{\mathrm{R}}\right) t + \text{h.c.}$$

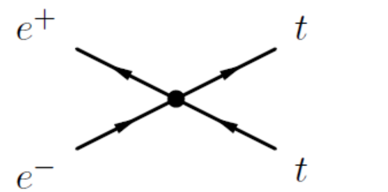
$$P_{\mathrm{L,R}} = (1 \mp \gamma_5)/2, \ \sigma_{\mu\nu} = (\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)/2$$

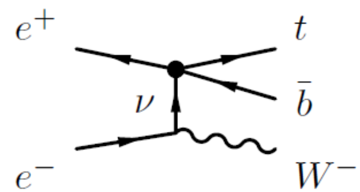
SM: $f^{\mathrm{L}}_{\mathrm{V}} = V_{\mathrm{tb}}, f^{\mathrm{R}}_{\mathrm{V}} = f^{\mathrm{L}}_{\mathrm{T}} = f^{\mathrm{R}}_{\mathrm{T}} = 0$

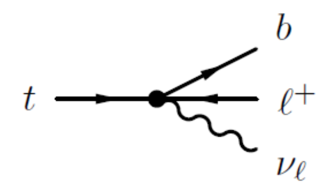
Effective Field Theory interpretation of BSM top quark interactions

arXiv:1802.07237
arXiv:1807.02121
Warsaw basis

Include all possible gauge invariant operators of dimension 6, e.g.







$$O_{\varphi q}^{1} \equiv \frac{y_t^2}{2} \quad \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, \qquad O_{uG} \equiv y_t g_s \quad \bar{q}T^A\sigma^{\mu\nu}u \quad \epsilon\varphi^* G_{\mu\nu}^A,$$

$$O_{\varphi q}^{3} \equiv \frac{y_t^2}{2} \quad \bar{q}\tau^I\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi, \qquad O_{uW} \equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}u \quad \epsilon\varphi^* W_{\mu\nu}^I,$$

$$O_{\varphi u} \equiv \frac{y_t^2}{2} \quad \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, \qquad O_{dW} \equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}d \quad \epsilon\varphi^* W_{\mu\nu}^I,$$

$$O_{\varphi ud} \equiv \frac{y_t^2}{2} \quad \bar{u}\gamma^\mu d \quad \varphi^T\epsilon\, iD_\mu\varphi, \qquad O_{uB} \equiv y_t g_Y \quad \bar{q}\sigma^{\mu\nu}u \quad \epsilon\varphi^* B_{\mu\nu},$$

$$O_{u\varphi} \equiv y_t^3 \; \bar{q}u \; \epsilon\varphi^* \; \varphi^\dagger\varphi,$$

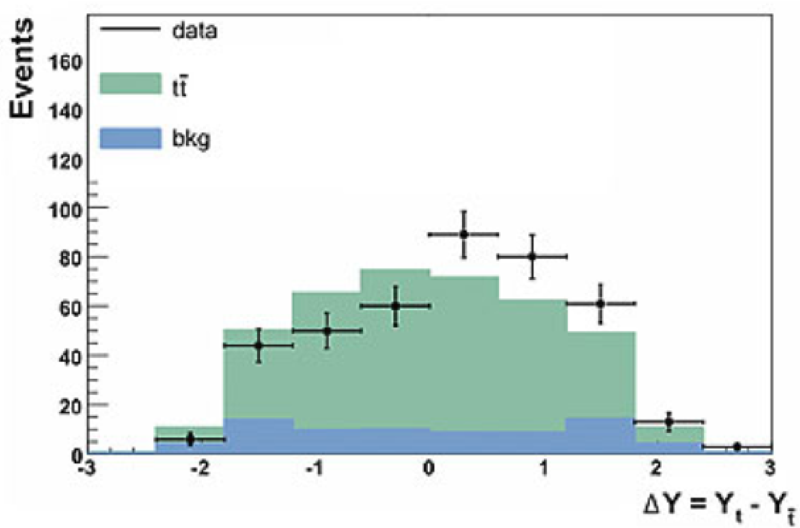
For some of the anomalous vertices there is a direct correspondence to EFT operators, e.g. Wtb:

$$\frac{ig}{\sqrt{2}}\left[\gamma^\mu(F_{1L}^W P_L + F_{1R}^W P_R) + \frac{i\sigma^{\mu\nu}q_\nu}{2m_t}(F_{2L}^W P_L + F_{2R}^W P_R)\right]$$

$$F_{1R}^W = \frac{m_t^2}{\Lambda^2}C_{\varphi ud}^{(33)*}, \qquad F_{2L}^W = 8\frac{m_t^2}{\Lambda^2}C_{dW}^{(33)*},$$

$$F_{1L}^W = 1 + \frac{m_t^2}{\Lambda^2}2\left[C_{\varphi q}^{3(33)} = \frac{1}{2}(C_{\varphi q}^{+} - \frac{1}{2}[C_{\varphi q}^{V} - C_{\varphi q}^{A}])\right], \qquad F_{2R}^W = 8\frac{m_t^2}{\Lambda^2}\left[C_{uW}^{(33)} = s_W^2 C_{uA} + s_W c_W C_{uZ}\right]$$

Do we see an experimental evidence for a deviation in top quark interactions?

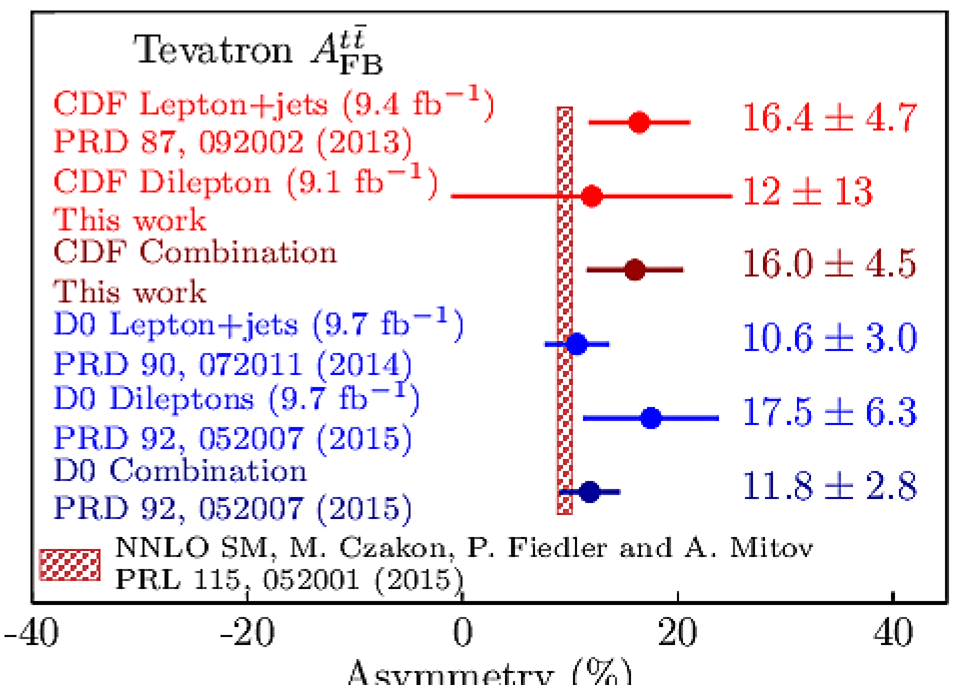


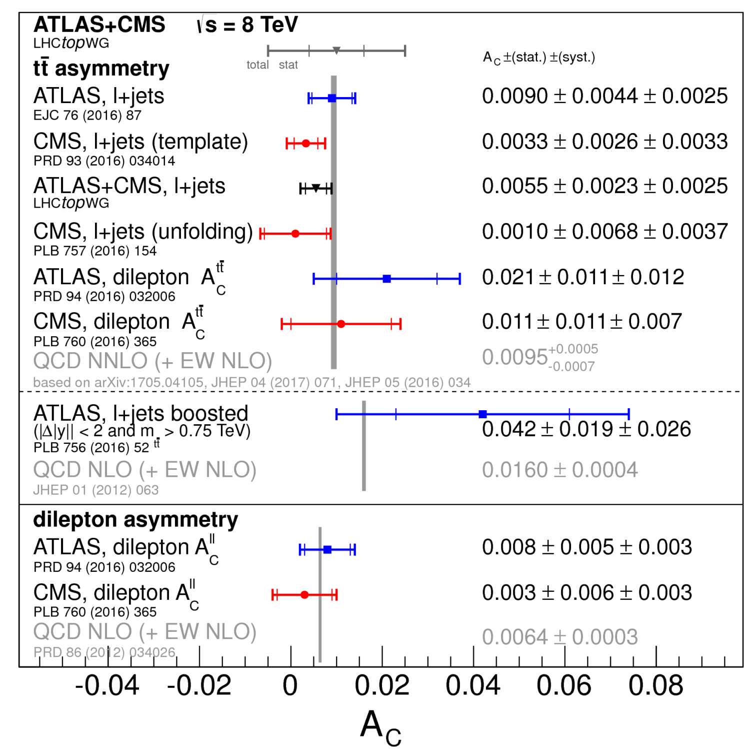
$$A_{\mathrm{FB}}^{t\bar{t}} = \frac{N(\Delta Y > 0) - N(\Delta Y < 0)}{N(\Delta Y > 0) + N(\Delta Y < 0)}$$

$$Y_t - Y_{\bar{t}} = Q_\ell \cdot (Y_{t_\ell} - Y_{t_h})$$

Phys. Rev. Lett. 101, 202001

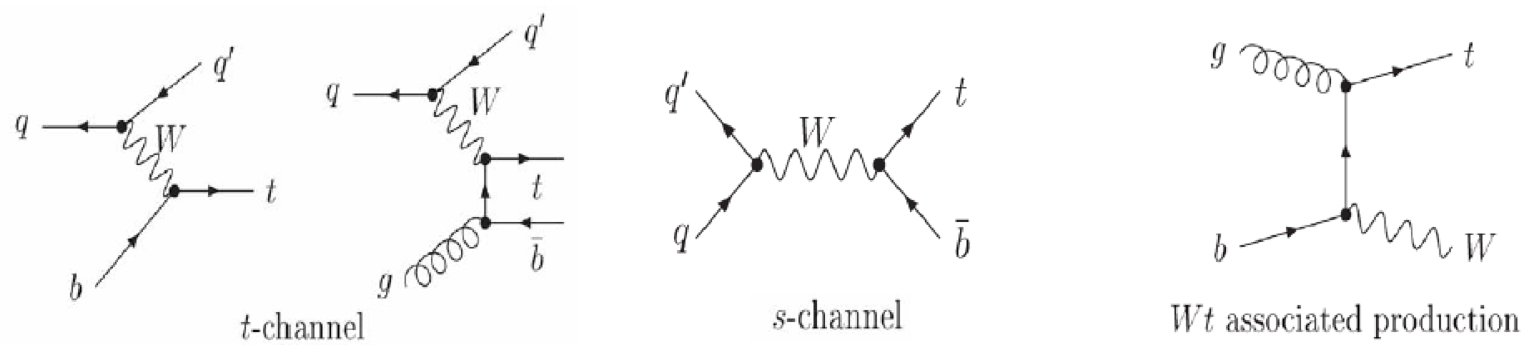
Tevatron, CDF 2006





Electroweak top quark production

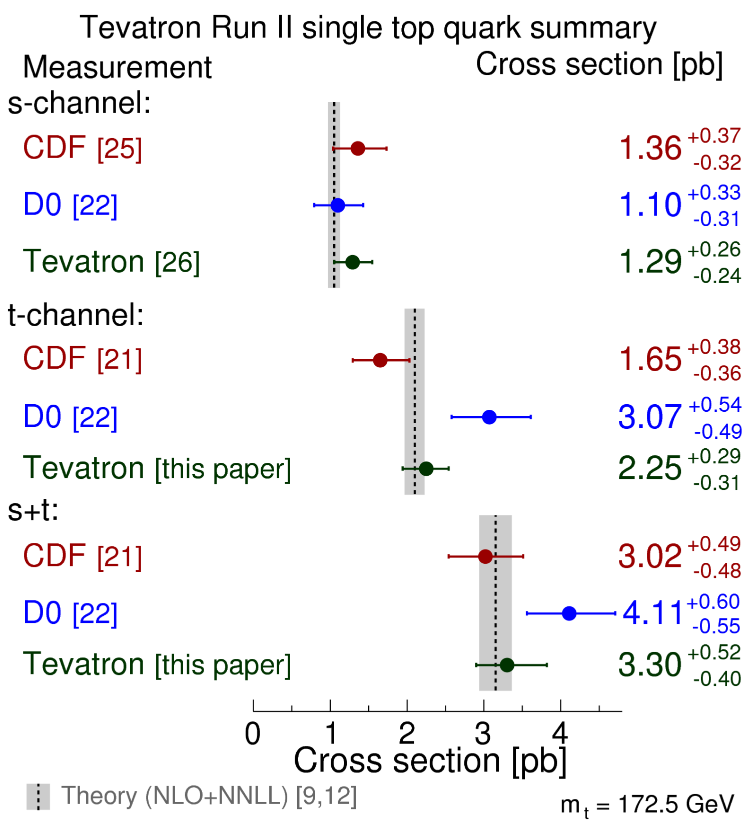
Three mechanisms of single top production:

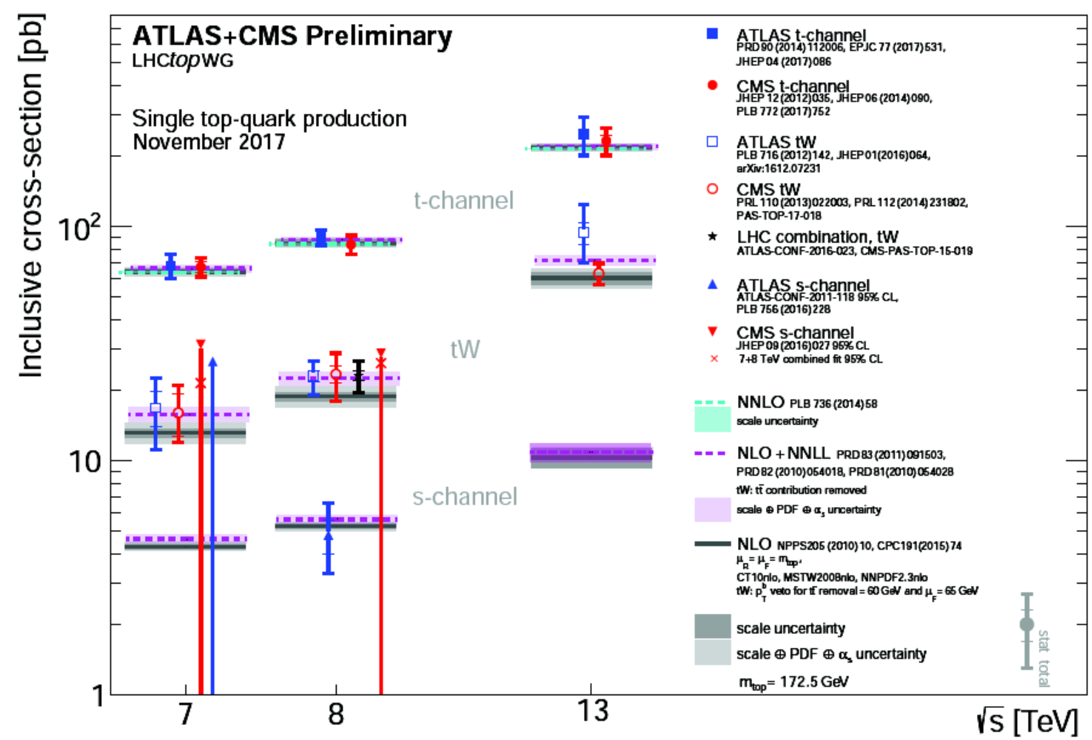


"Observation of Single Top-Quark Production"
Phys. Rev. Lett. 103, 092001 (2009)
(Tevatron)

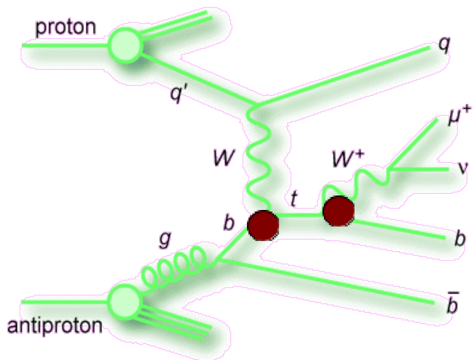
t-channel $(Q_W^2 < 0)$ s-channel $(Q_W^2 > 0)$ associated tW $(Q_W^2 = M_W^2)$

Q_W^2 - W-boson virtuality





Measurment of Vtb parameter of CKM



$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{t\text{-ch.},t+\bar{t}}}{\sigma^{th}_{t\text{-ch.},t+\bar{t}}}},$$

$$|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$$

CMS, 13 TeV, arXiv:1610.00678 :

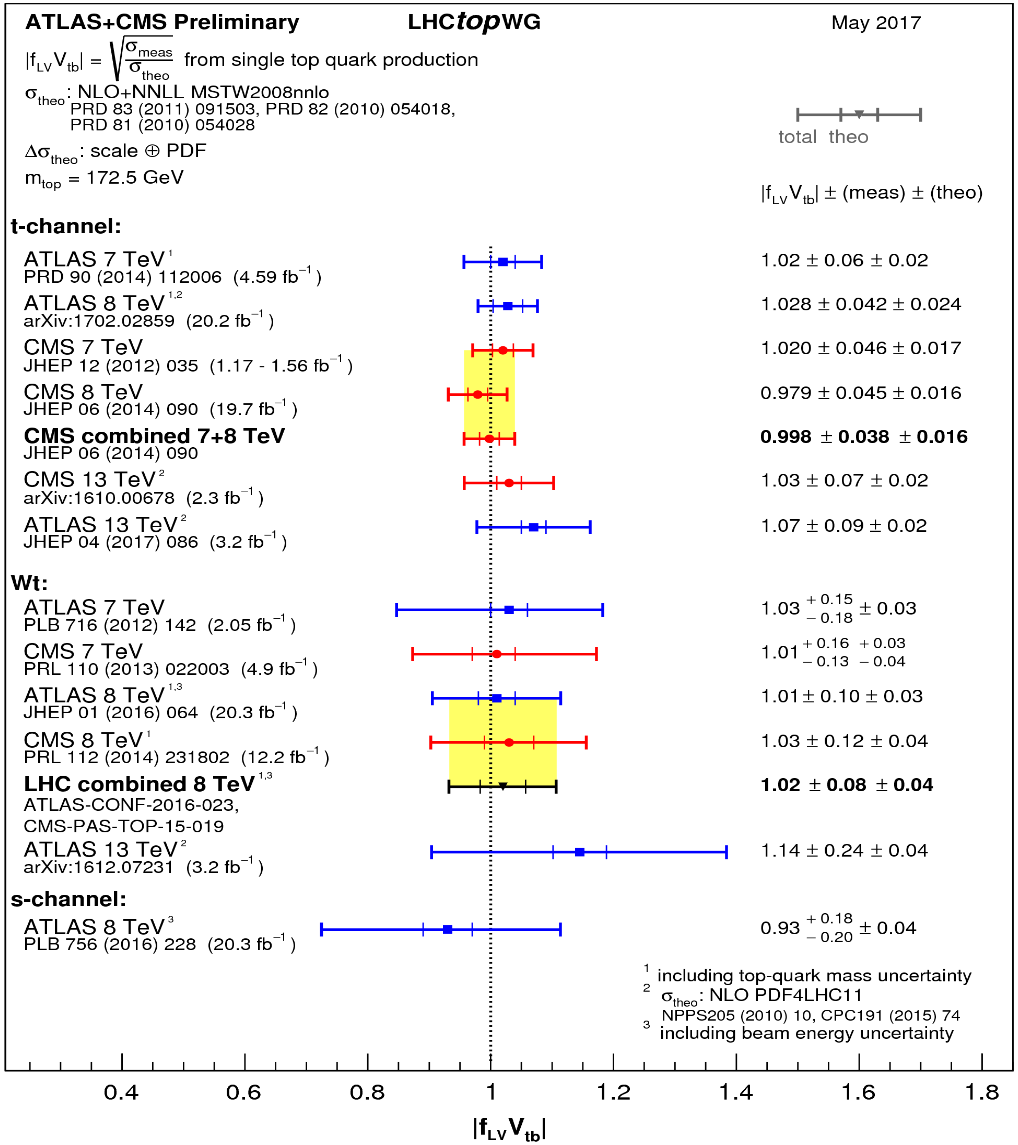
$$|f_{LV}V_{tb}| = 1.03 \pm 0.07\,(\text{exp}) \pm 0.02\,(\text{theo})$$

ATLAS, 8 TeV, arXiv:1702.02859

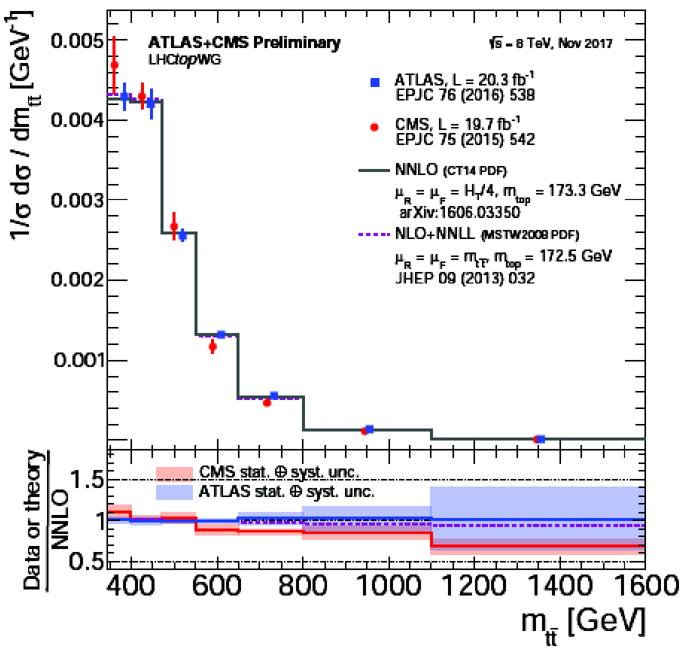
$$f_{LV} \cdot |V_{tb}| = 1.029 \pm 0.048$$

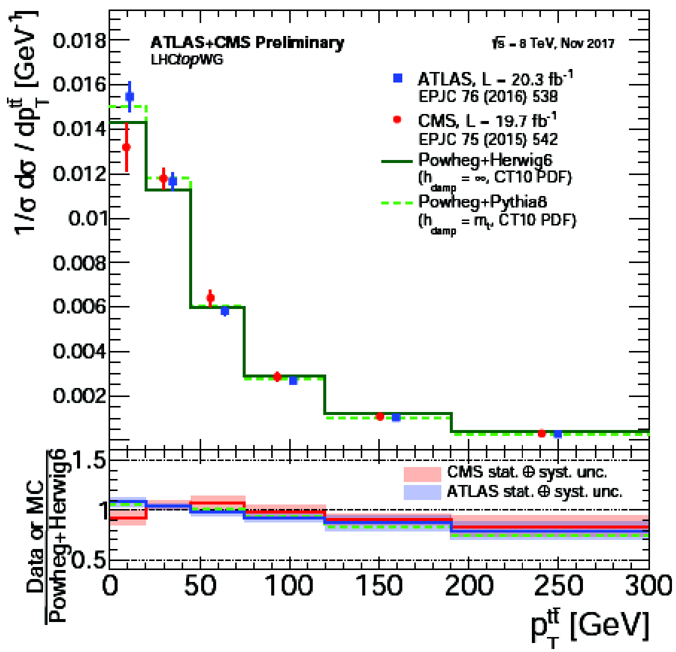
ATLAS, 13 TeV, JHEP04(2017)086

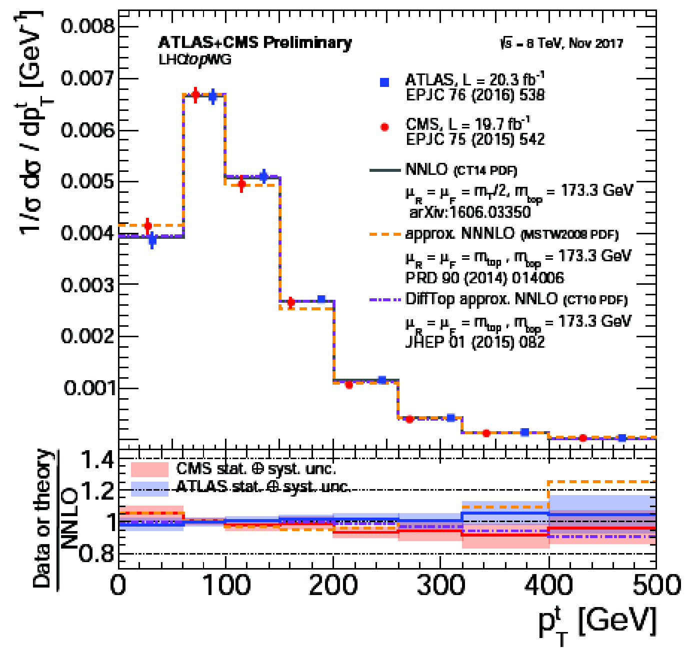
$$f_{LV} \cdot |V_{tb}| = 1.07 \pm 0.09$$

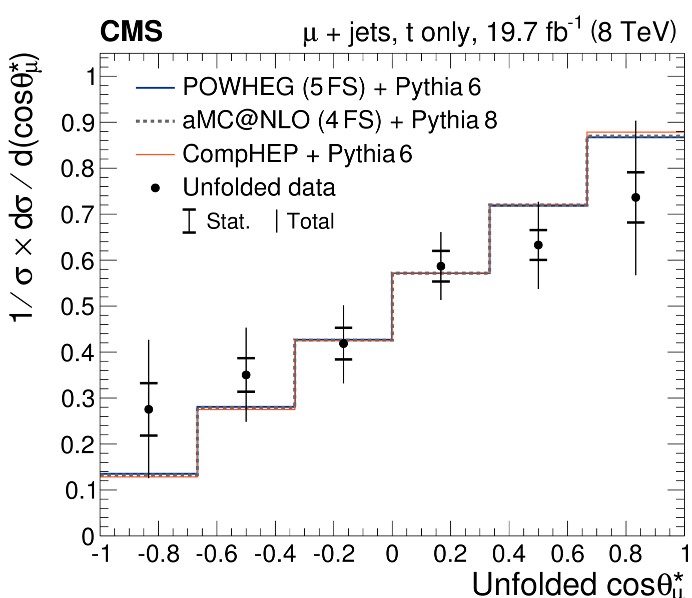


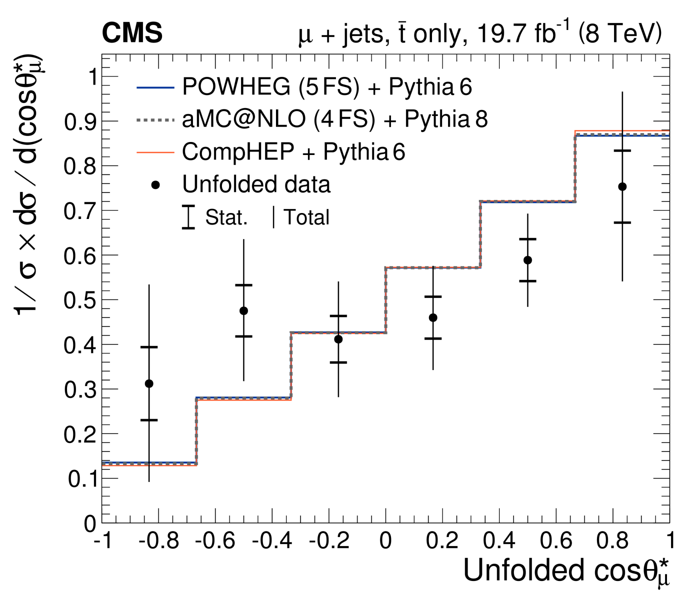
Differential Cross Section Meauserments

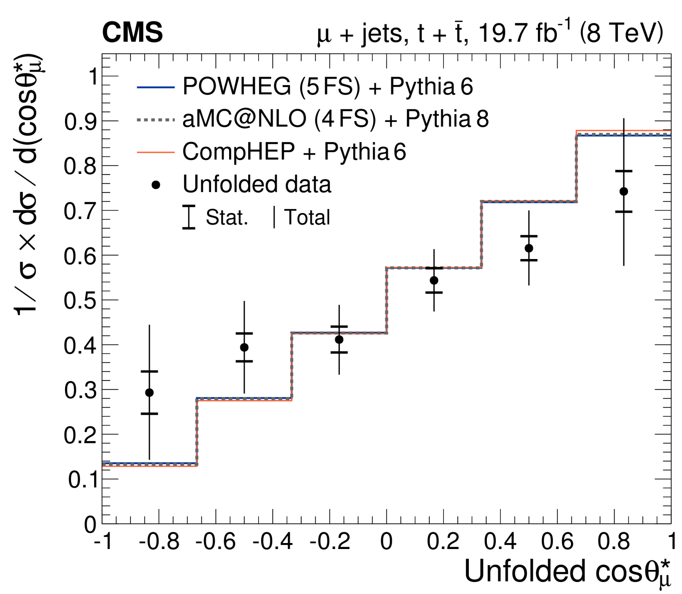








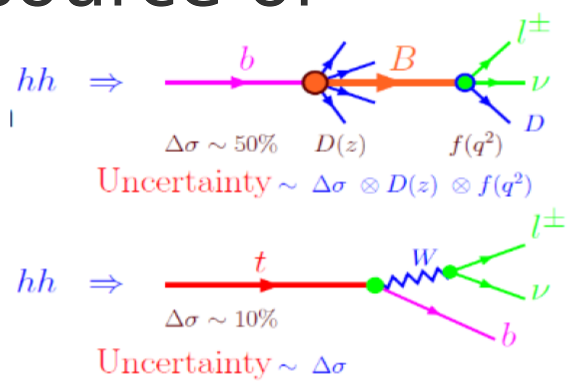




Intermediate Summary (I)

- Top quark is the heaviest in SM and point like object with the mass close to EW scale and comparable with mass of gold nuclear
- There are no top hadrons => clean source of fundamental information

$$\tau_t = \frac{1}{\Gamma_{tot}} \approx 10^{-25} < \tau_{had} \approx 10^{-24}$$



- Mostly one decay channel => simplify analysis

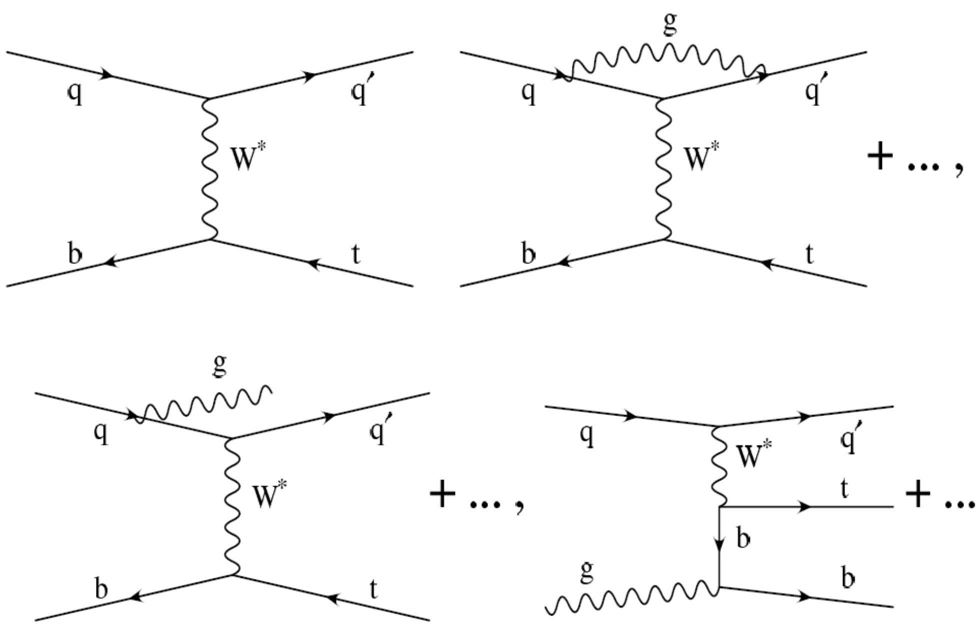
$$t \rightarrow Wb; \qquad Br(t \rightarrow other) < 10^{-3}$$

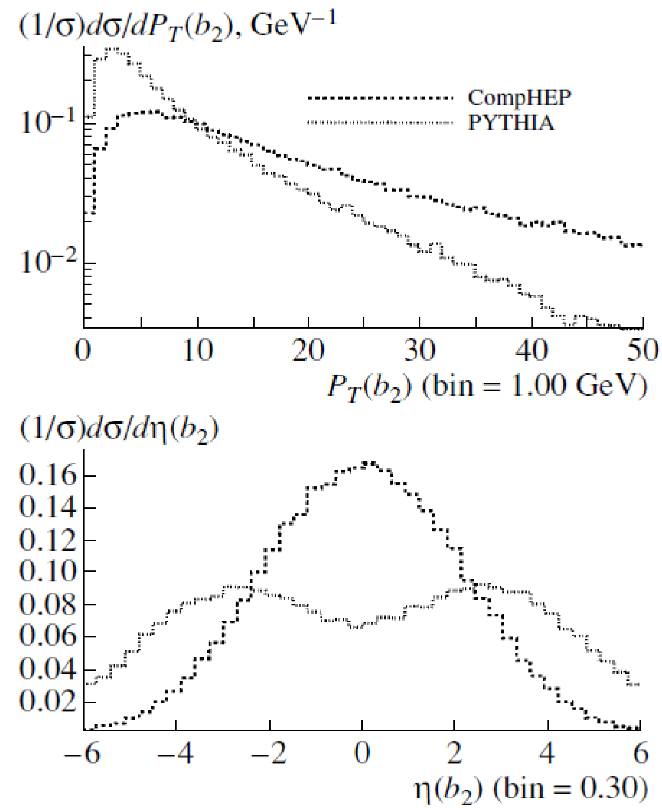
- Wide range of New Physics to search with top quark

Intermediate Summary (II) possible measurements

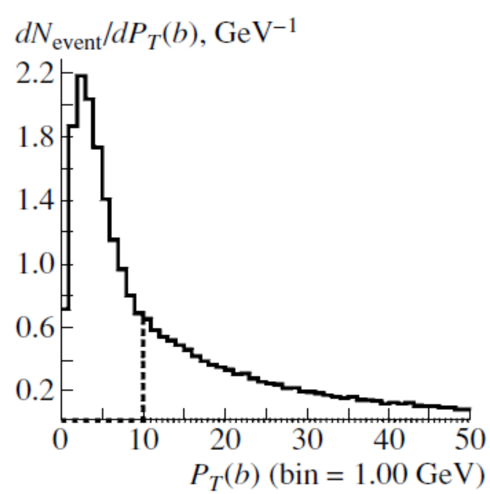
- Top quark mass ($\Delta m \sim 0.3\%$) and other parameters
- Total and fiducial cross sections
- Differential cross sections
- Parameters of interactions with other particles, coupling constants, structure of interactions (gtt, Wtb, FCNC, …)
- Search for new states (resonances) decaying to top quarks ($M>m_t$), in the decays of top ($M<m_t$) or produced in association with top (W’, H^+, T, ...)

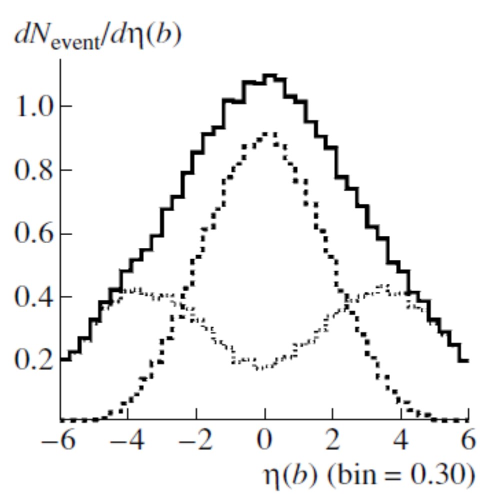
Simulation issues, t-channel single top





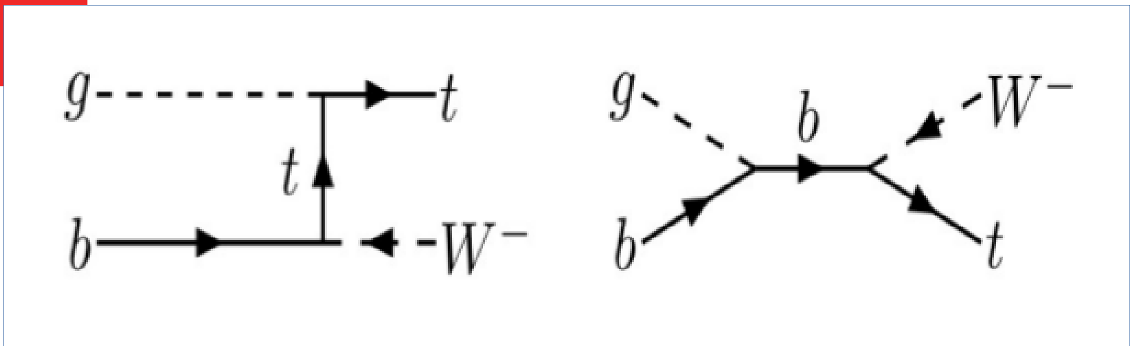
Phys.Atom.Nucl.69(2006)1317





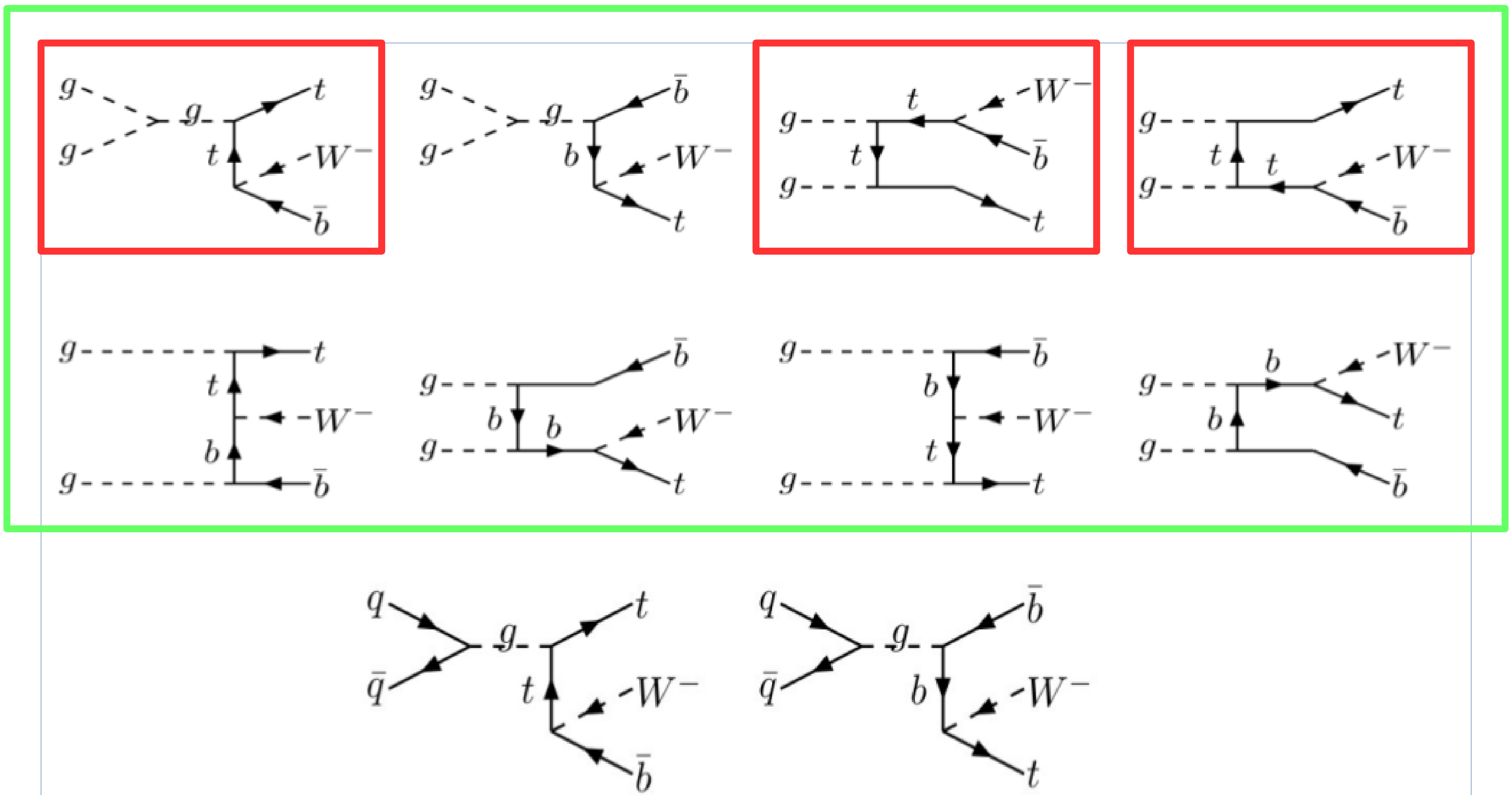
- b-quark in the initial state comes from gluon splitting and direct sum of the above diagrams comes to double counting.
- Consider 5FS (left top diag.) or 4FS (right bottom diag.), or match different orders (5FS LO+NLO) to avoid double counting

Simulation Issues, tW and t$\bar{\text{t}}$ production



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

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

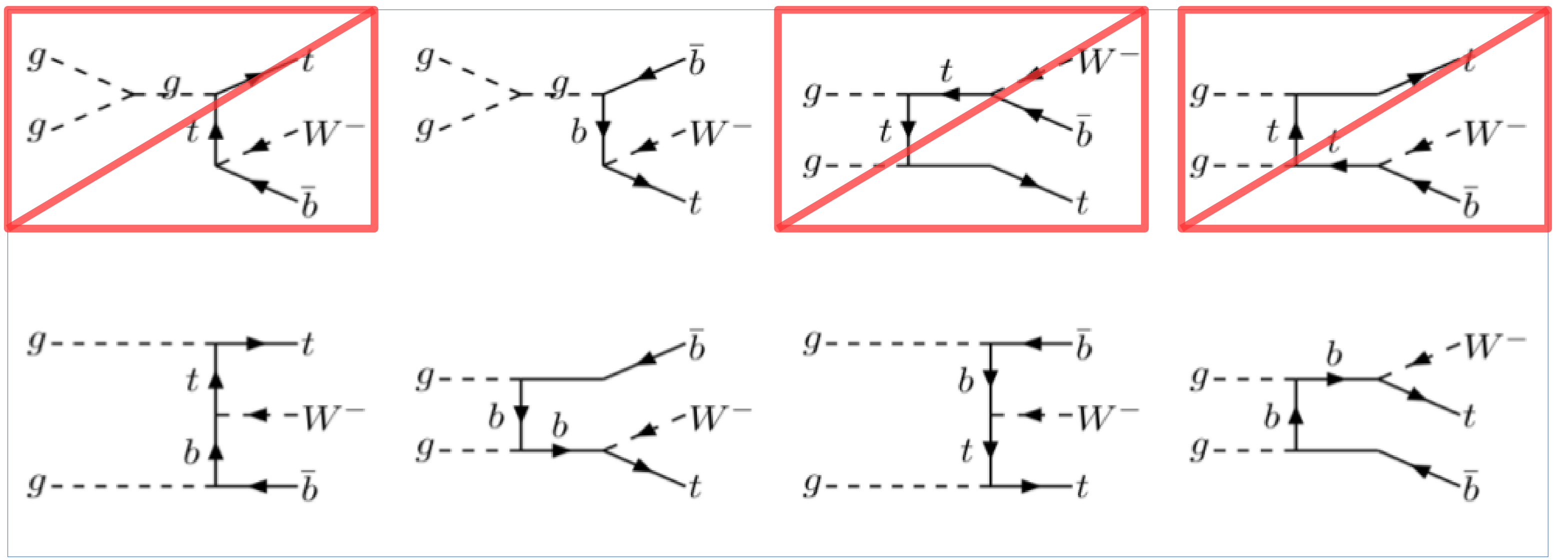


t tbar production

gluon gluon processes

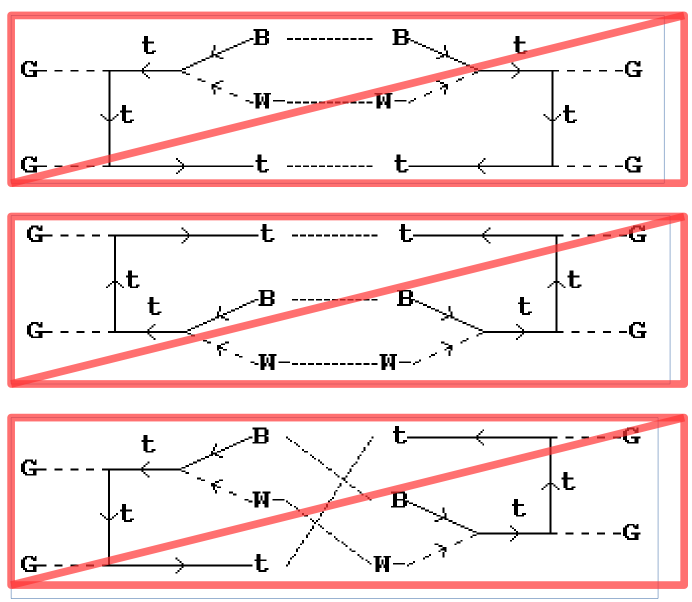
Simulation Issues, tW and $t\bar{t}$ production (II)

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



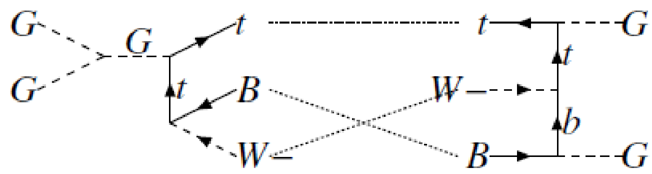
~~t t-bar production~~

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

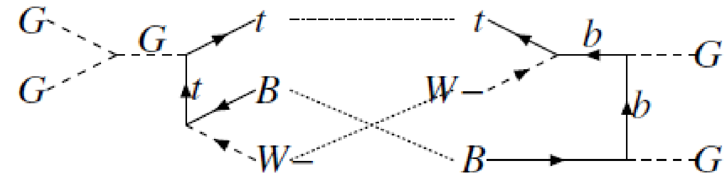


Kinematic separation
A.Belyaev, E. Boos, arXiv:hep-ph/0003260

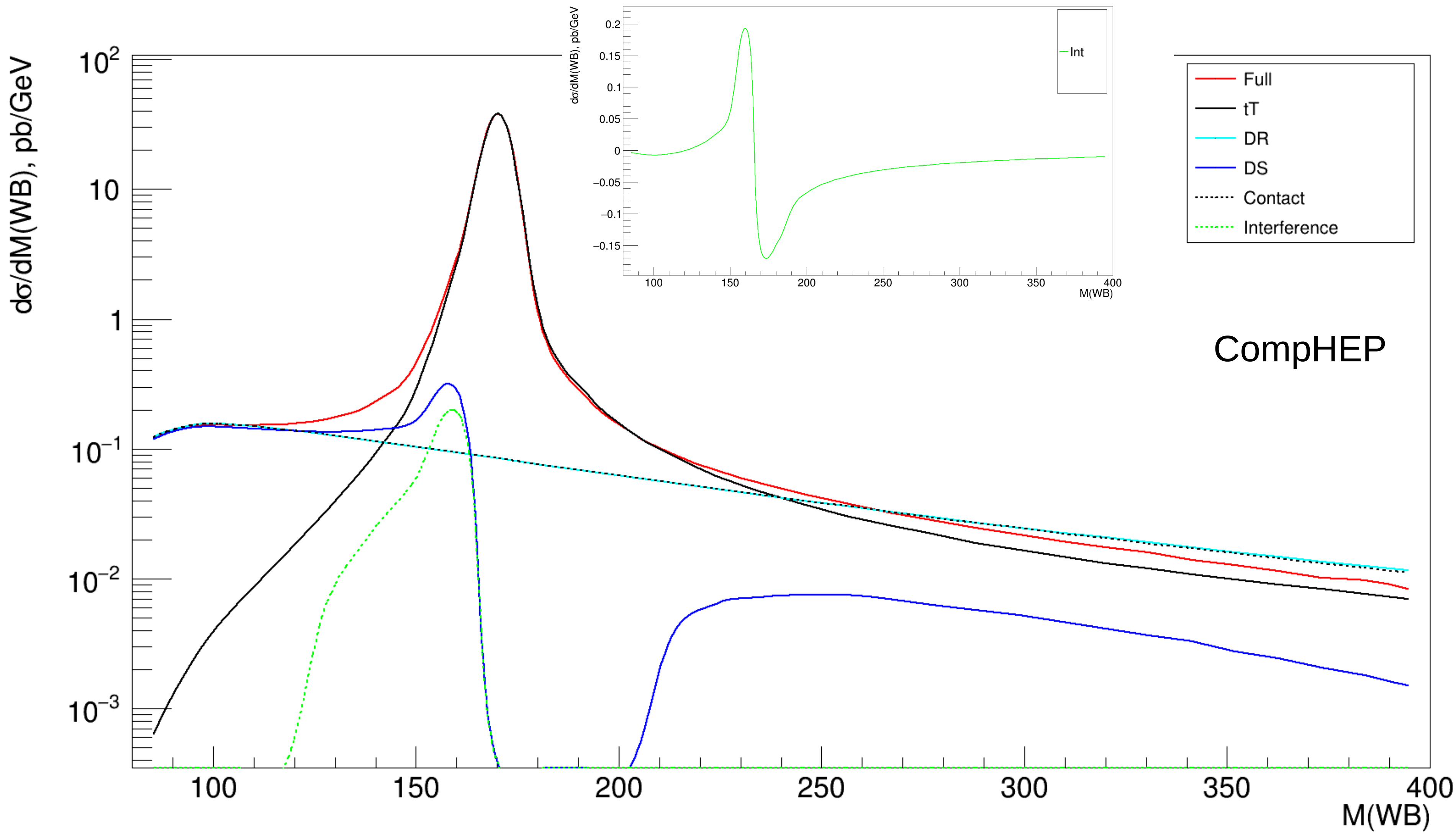
How to simulate associative tWb production correctly?

ttbar^2 + 

...



+ tWb^2



Simulation of tWb, additional plots

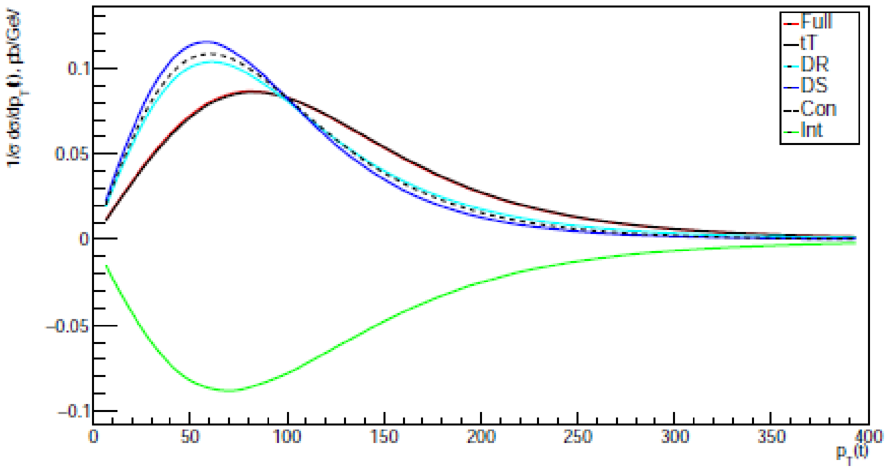


Figure 5: Transverse momentum of top

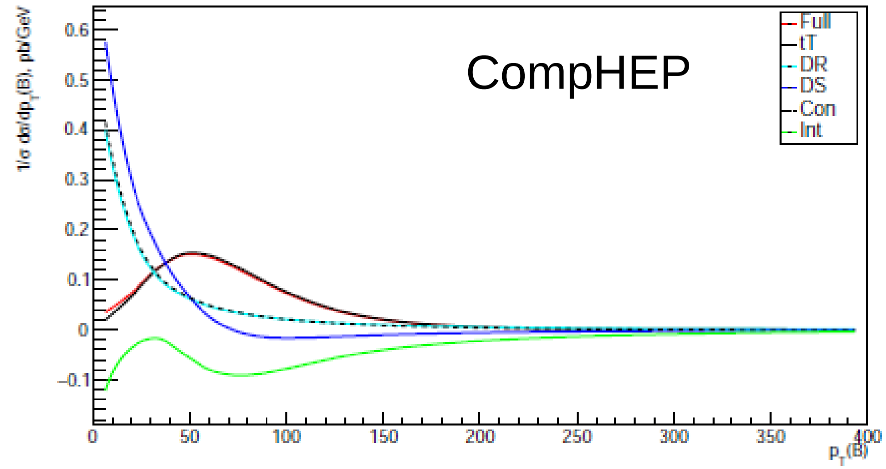


Figure 6: Transverse momentum of b

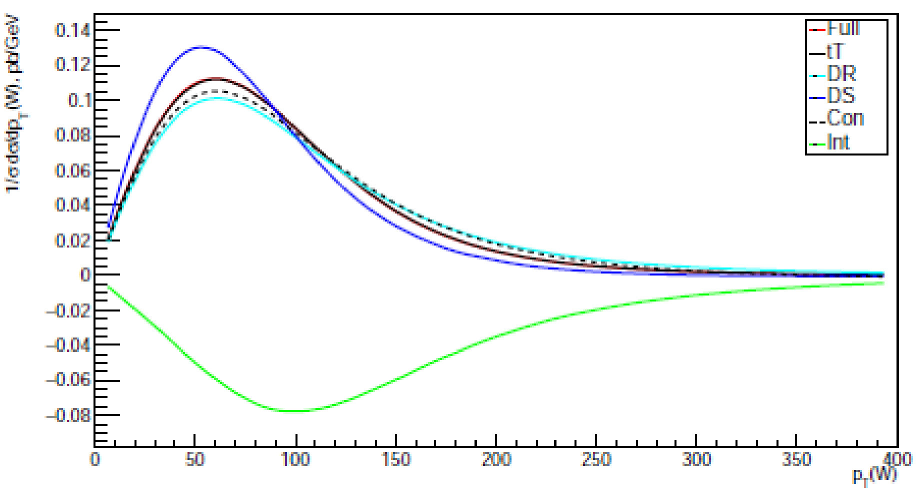


Figure 7: Transverse momentum of W boson

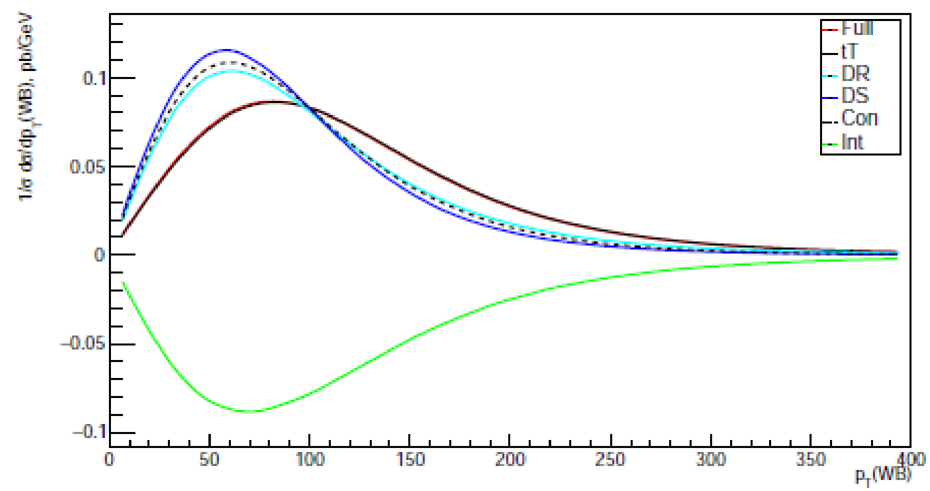


Figure 8: Transverse momentum of system of W boson and b quark.

Simulation of tWb, angular variables

CompHEP

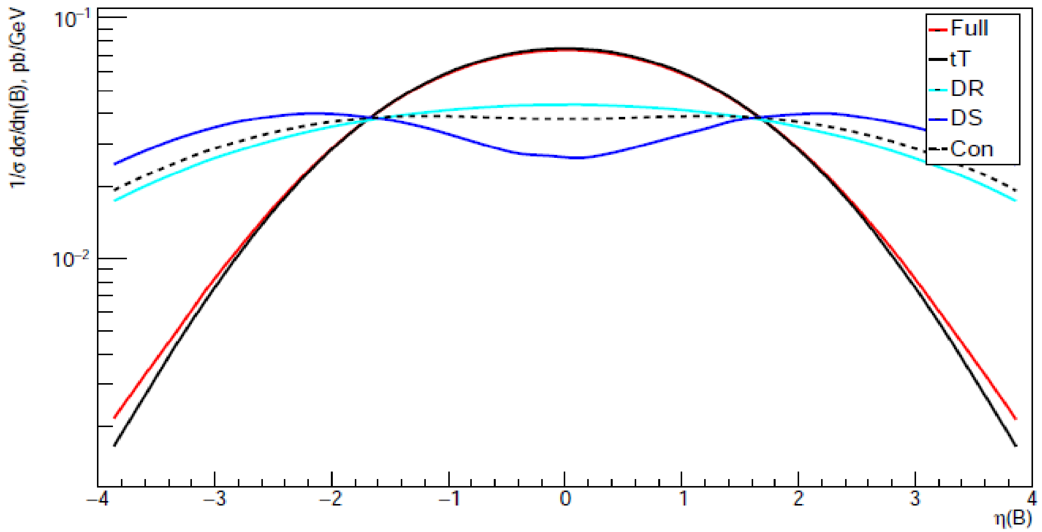


Figure 10: Pseudorapidity of b quark.

EPJ Web Conf. 158 (2017) 04003

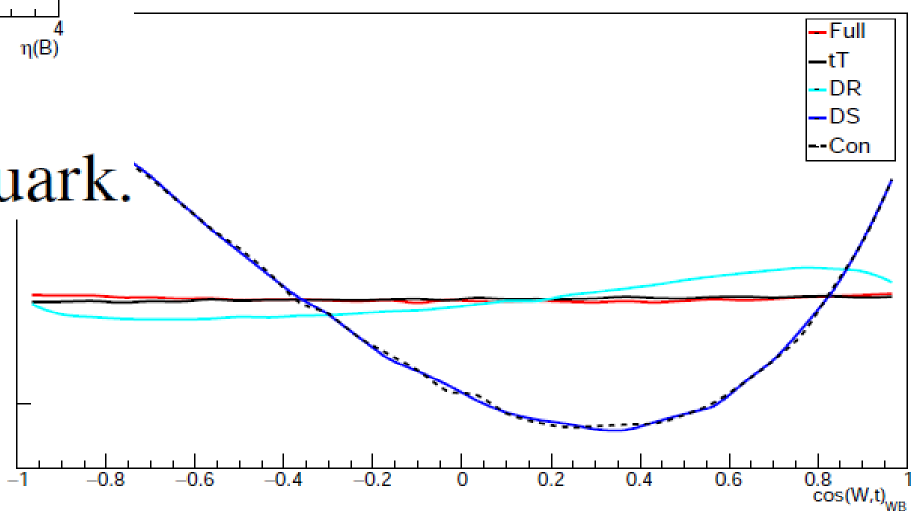


Figure 14: Cosine between W boson and top quark in rest frame of W and b

Practical details and examples from real CMS analysis to search For deviations from SM in Wtb interactions

JHEP 02 (2017) 028

Computations and simulations for LHC

A. SM processes (Backgrounds) as accurate as possible

B. Computation and simulation of large variety of BSM processes

In many cases LO is not enough

NLO, NNLO computations of rates and distributions are needed but also not enough

One needs to have effective LO/NLO (in some cases NNLO) event generators which include (depending on physics case) spin correlations, finite particle masses, finite resonance widths, interferences, proper matching between parton production and hadronization

Two main approaches

1. Programs with implemented list or library of processes

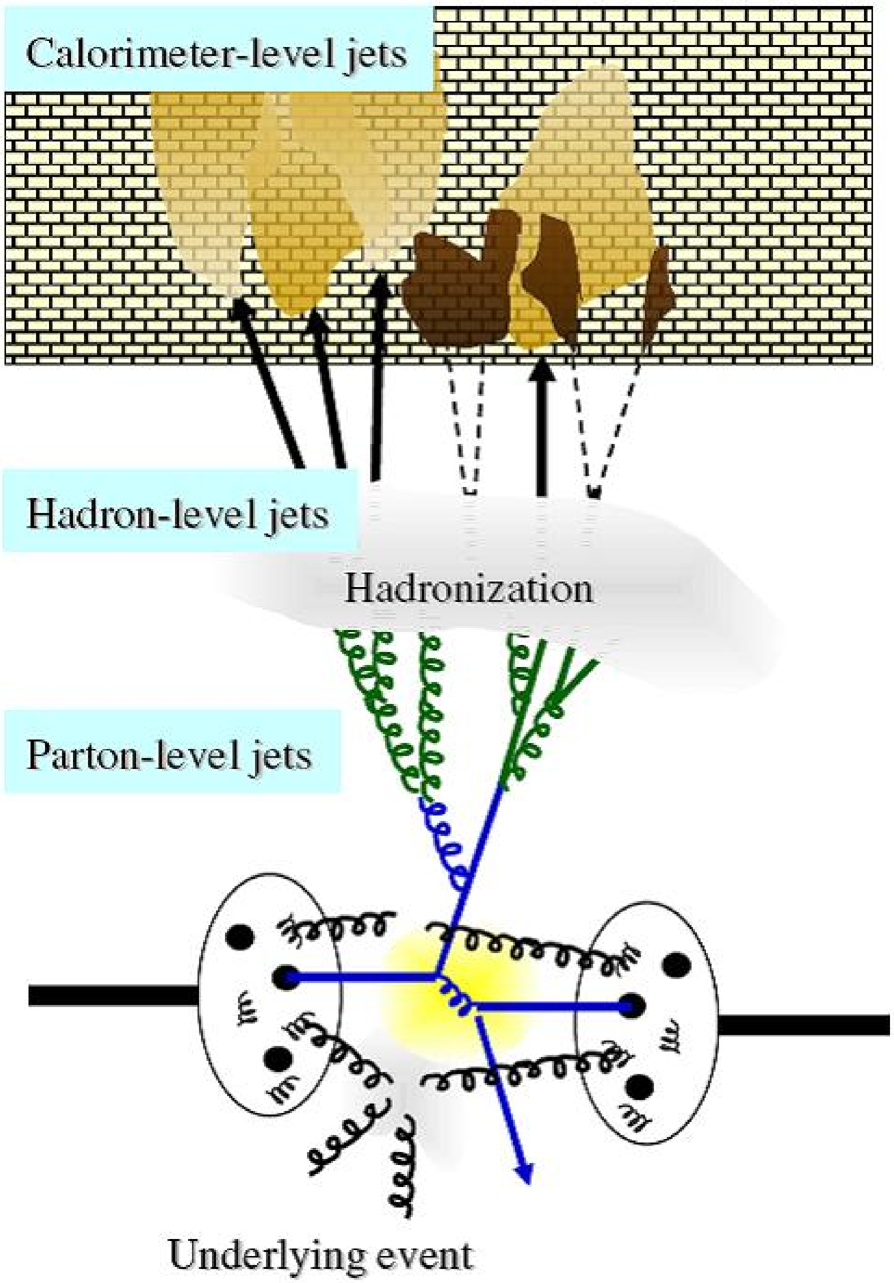
PYTHIA, HERWIG, ALPGEN, ARIADNE, WPHACT and PHASE, TAUOLA, TopREX, MC@NLO, MCFM, SANC …..

2. Automatic programs with implemented Lagrangians (Feynman rules)

CompHEP, Calchep, GRACE, MadGRAPH/MadEvent, WHIZARD/O'MEGA, SHERPA, HELAC …..

Various interfaces, standards (LHE, SLHA…..), data bases (MCDB….)

Simulation steps



- Hard process - Matrix Element 2->2÷7 (ME generator, parton levels events, LHEF)
- Showering, ISR, FSR, fragmentation, Hadronisation (SH generators, particle level events 100s, HepMC)
- Detector response (GEANT, digital signals)
- Reconstruction programs (physics objects: e,mu, jets, b-jets, photon, MET)
- Analysis software (corrections, selection, high level analysis

BSM in CompHEP

Why useful?

Simple structure of Feynman rules, easy to extend, LanHEP helps a lot

Symbolic and numerical computations and event simulation including BSM 2->2,3,…6 (1->2,3,…7) and even more using batch modes, new options for cascades, FORM based version

Symbolic ansewrs for ME squared

specially useful to get formulas for simple 2->2 and 1->2,1->3 processes including BSM contributions and parameters

Needed Interfaces, all LHA, LHEF, link to MCDB

To be continued