QCD, top and LHC
Lecture IV: Top Physics

ICTP Summer School on Particle Physics, June 2013

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QCD and top physics

The basic idea is to apply the methods of the first three lectures to top physics.

- Top decay
- Top mass
- Top production
  - ⋆ Top pair production Leading order
  - ⋆ Higher order corrections
  - ⋆ Single top production
  - ⋆ Associated top production
- Top spin
- Top forward-backward asymmetry

Why top now?

- Top is unstudied.
  - ⋆ Tevatron studies of the top quark have limited statistical precision.
- Top is special
  - ⋆

$1/m_t <$	$1/\Gamma_t <$	$1/\Lambda <$	m_t/Λ^2
Production time<	Lifetime <	Hadronization time <	Spin decorrelation time

- Top is ubiquitous
  - ⋆ Top cross section is large at the LHC because of the large gluon flux
  - ⋆ Top-related processes are significant backgrounds in the search for new physics.

LHC is the new elephant in the room

Process	$\sqrt{s}$ [GeV]	σ [pb]	Integrated luminosity [fb^{-1}]	$\sigma_{Q\bar{Q}}/\sigma_{tot}$
$e^+e^- \to b\bar{b}$	10.48	~ 1000 pb	530, (1998-2002)	25%
$pp \to t\bar{t}$	14000	~ 1000 pb	~ 3000, (2010-2030)	10^{-8}

- LHC accumulated luminosity will in $\sim$ ten years surpass the B-factories
- Cross sections are roughly the same for $b\bar{b}$ at B-factories, $t\bar{t}$ at LHC
- Top is produced in pairs and singly.
- Production dynamics of top will be studied in exquisite detail.

Top quark physics

We need to measure:-

- Top mass and width
- Top spin
- Top charge
- Top couplings, to W, Z, γ, G and H.
- Distributions of produced top quarks, (information about partons, search for resonances).

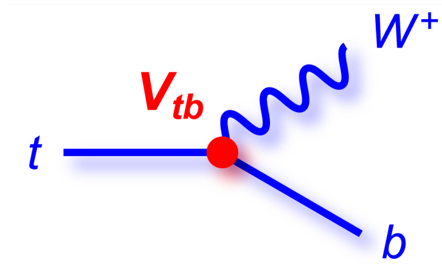
to W boson	$\frac{g_W}{\sqrt{2}} \sim 0.45$	$\frac{g_W}{\sqrt{2}} V_{tq} \bar{t}_L \gamma^\mu q_L \; W^-_\mu$
to Z boson	$g_Z = \frac{g_W}{4\cos\theta_W} \sim 0.14$	$g_Z t_L \left[(1 - \frac{8}{3}\sin^2\theta_W)\gamma^\mu - \gamma^\mu\gamma_5\right] t_L \; Z_\mu$
to photon	$e_t = \frac{2}{3} e \sim 0.21$	$e_t \bar{t} \gamma^\mu t \; A_\mu$
to gluon	$g_s \sim 1.12$	$g_s \bar{t}_j \gamma^\mu \; T^{SU(3)}_{jk} t_k \; G_\mu$
to Higgs	$Y_t = \frac{g_W m_t}{\sqrt{2} M_W} \sim 1$	$\frac{Y_t}{\sqrt{2}} \bar{t} t \; H$

Top quark decays

- Since $m_t > M_W + m_b$ a top quark decays predominantly into a b quark and an on-shell W boson

$$t \rightarrow W^+ + b \quad \hookrightarrow l^+ + \nu$$

$$t \rightarrow W^+ + b \quad \hookrightarrow q + \bar{q}$$

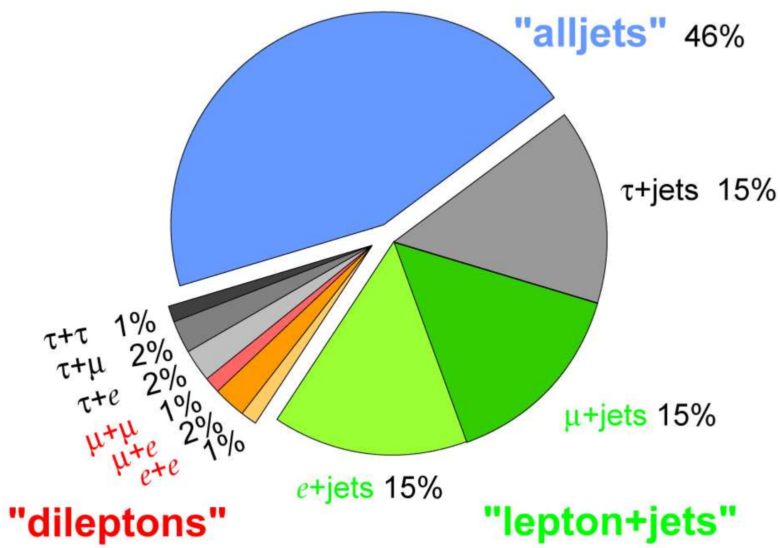


- the branching ratio to leptons is given by counting the decay modes of the W, $e\bar{\nu}_e$, $\mu\bar{\nu}_\mu$, $\tau\bar{\nu}_\tau$ and three colours of $u\bar{d}$ and $c\bar{s}$,

$$\mathrm{BR}(W^+ \rightarrow e^+\bar{\nu}) = \frac{1}{3+3+3} \approx 11\%.$$

- the branching ratio of top pairs to one flavour lepton + jets is $2 \times \frac{1}{9} \times \frac{2}{3} \simeq 0.15$

Top Pair Branching Fractions



W polarization on top decay

- The W boson coming from top decay can be either left-handed ($-$) or longitudinally (0) polarized.

$$\overline{\sum}|\mathcal{M}_-|^2 = \frac{2G_F m_t^4}{\sqrt{2}}|V_{tb}|^2\left[2x^2(1-x^2+y^2)\right]$$

$$\overline{\sum}|\mathcal{M}_0|^2 = \frac{2G_F m_t^4}{\sqrt{2}}|V_{tb}|^2\left[1-x^2-y^2(2+x^2-y^2)\right],$$

where $x = M_W/m_t, y = m_b/m_t$.

- Setting $y = 0$ we find the longitudinal and left-handed fractions are

$$f_0 = \frac{\overline{\sum}|\mathcal{M}_0|^2}{\overline{\sum}|\mathcal{M}_0|^2+\overline{\sum}|\mathcal{M}_-|^2} = \frac{1}{1+2x^2} = \frac{m_t^2}{m_t^2+2m_W^2} \approx 0.7$$

$$f_- = \frac{\overline{\sum}|\mathcal{M}_-|^2}{\overline{\sum}|\mathcal{M}_0|^2+\overline{\sum}|\mathcal{M}_-|^2} = \frac{2x^2}{1+2x^2} = \frac{2m_W^2}{m_t^2+2m_W^2} \approx 0.3$$

- In the limit $m_t \gg M_W$ the result for the total width is dominated by the width to longitudinally polarized W's. The top quark has a 'semi-weak' decay rate

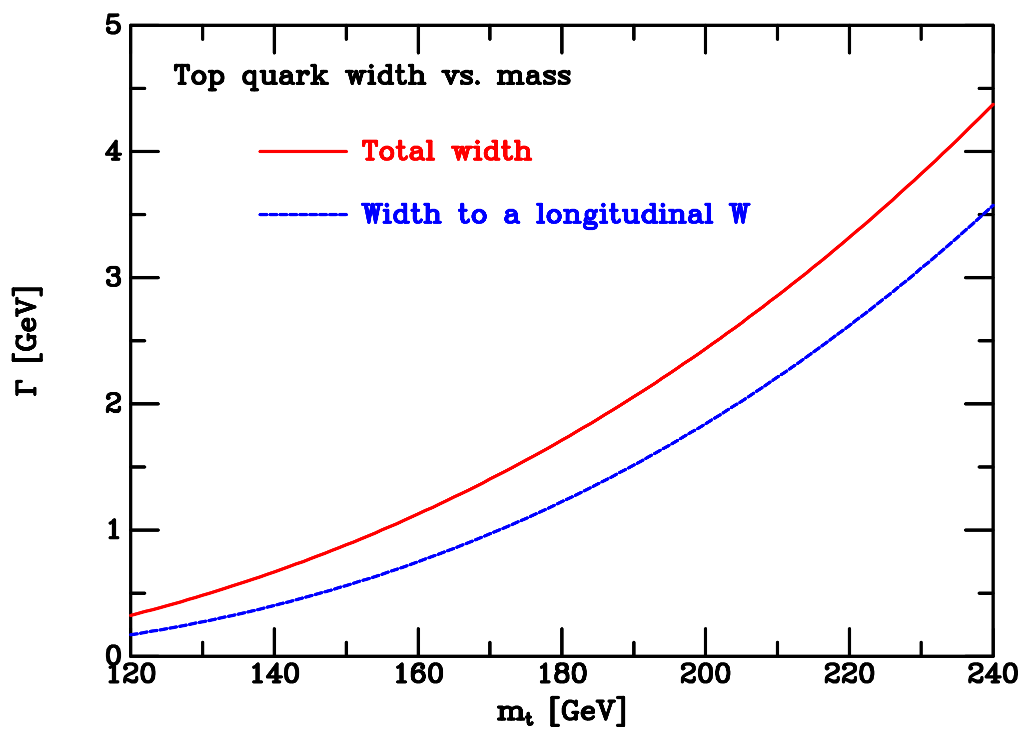
$$\Gamma(t \to bW) = \frac{G_F m_t^3}{8\pi\sqrt{2}}|V_{tb}|^2 \approx 1.76\ \text{GeV}\left(\frac{m_t}{175\ \text{GeV}}\right)^3.$$

Top decay width

- $V_{tb} \approx 1$ as suggested by the unitarity relation

$$|V_{tb}|^2 + |V_{cb}|^2 + |V_{ub}|^2 = 1.$$

- The lifetime of the top quark is only of order 10^{-25} seconds and it therefore decays before it has time to hadronize.



Longitudinal and left-handed W's

- The polarization state of the W controls the angular distribution of the leptons into which it decays. We may define the lepton helicity angle θ_e^*, which is the angle of the charged lepton in the rest frame of the W, with respect to the original direction of travel of the W (*i.e.* anti-parallel to the recoiling b quark). If the b quark jet is identified, this angle can be defined experimentally as

$$\cos\theta_e^* \approx \frac{b\cdot(e^+-\nu)}{b\cdot(e^++\nu)} \approx \frac{2b\cdot e^+}{b\cdot(e^++\nu)} - 1 \approx \frac{4b\cdot e^+}{m_t^2 - M_W^2} - 1,$$

in an obvious notation where t, b, e^+ and ν represent four-momenta.

$$\overline{\sum}|\mathcal{M}^{(t)}|^2 \quad = \quad \left[\overline{\sum}|\mathcal{M}_0|^2 \times |D_0|^2 + \overline{\sum}|\mathcal{M}_-|^2 \times |D_-|^2\right] \frac{\pi}{M_W\Gamma_W}\,\delta(w^2 - M_W^2).$$

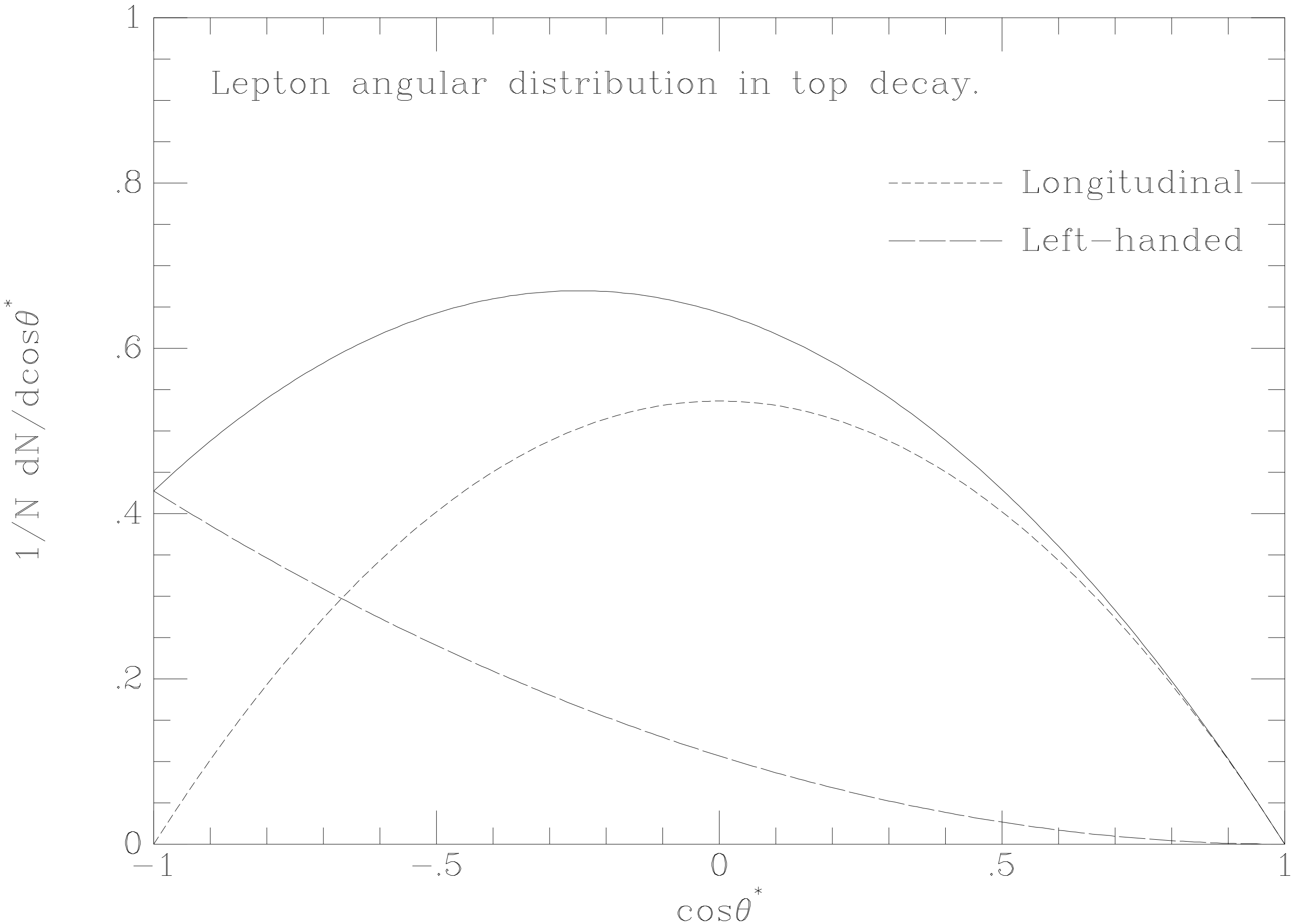
Here M_0, M_- are as given above with $y = 0$ and D_0, D_- are the helicity amplitudes for the decay of a longitudinal and left-handed W boson respectively:

$$|D_0|^2 = \frac{G_F M_W^4}{\sqrt{2}}\frac{1}{2}\sin^2\theta_e^* \qquad |D_-|^2 = \frac{G_F M_W^4}{\sqrt{2}}\frac{1}{4}(1-\cos\theta_e^*)^2.$$

Longitudinal W's

- Longitudinal fractions are predicted

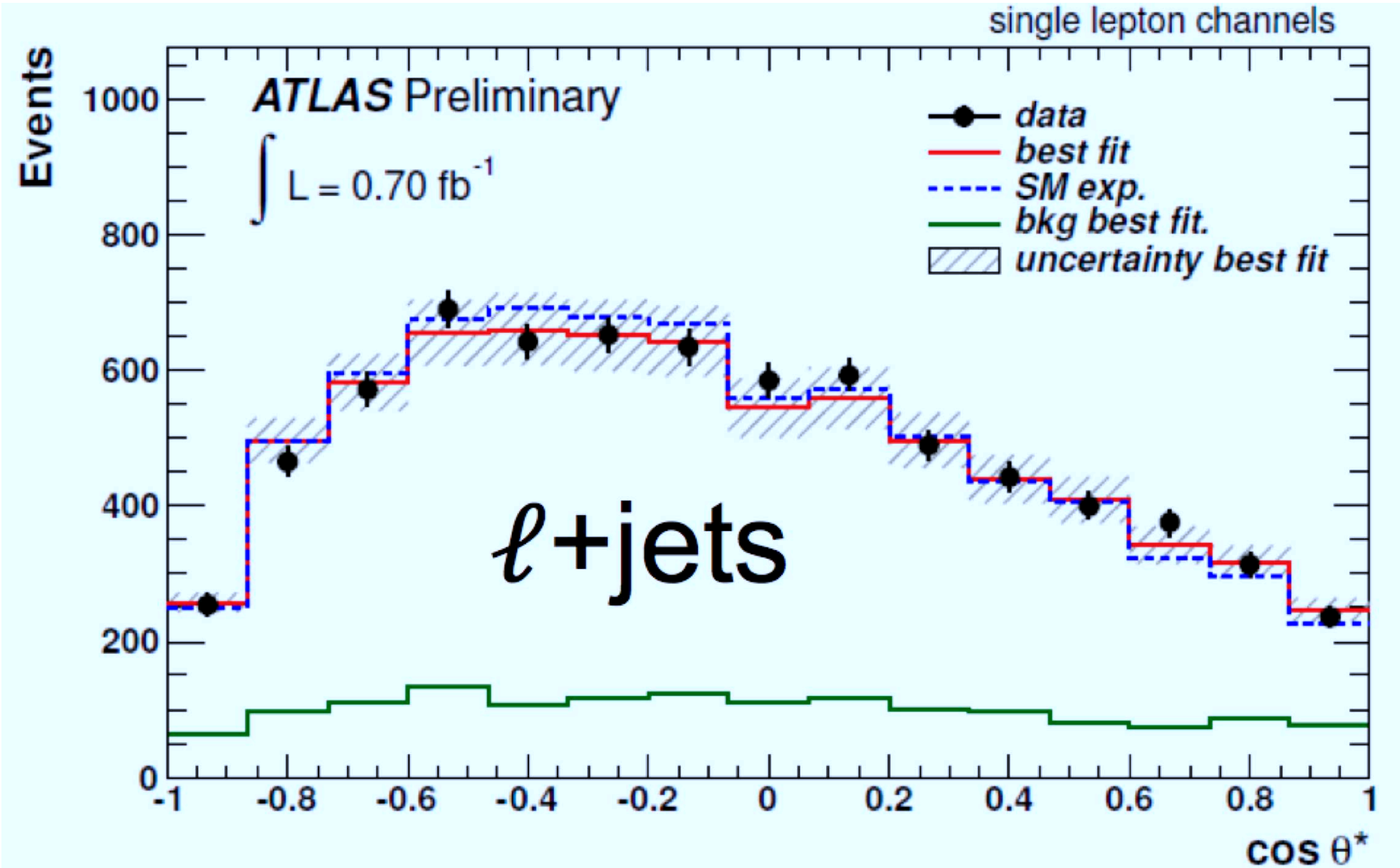
$$f_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} \approx 0.7, \qquad f_- = \frac{2m_W^2}{m_t^2 + 2m_W^2} \approx 0.3, \qquad f_+ = 0$$



Longitudinal W's

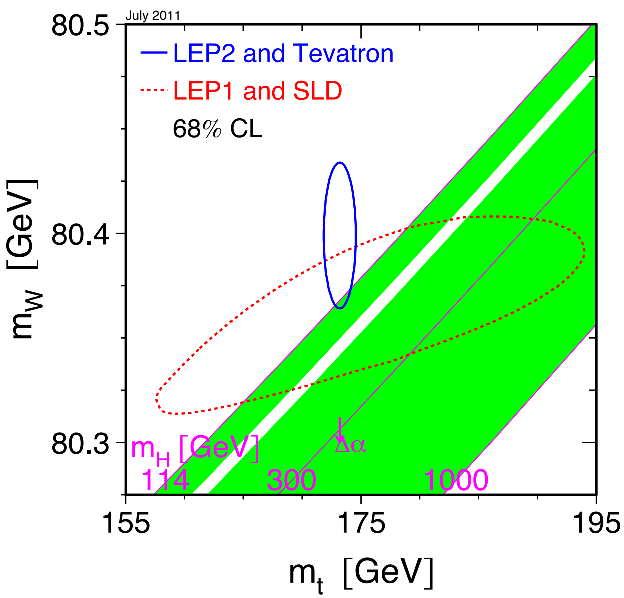
- Atlas measurement (2011)

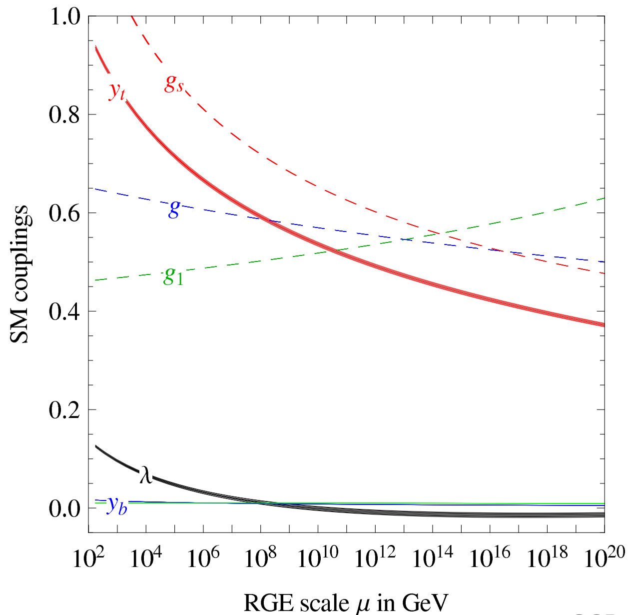
$$f_0 = 0.7 \pm 0.1, \qquad f_+ = 0.01 \pm 0.04$$



Top quark mass

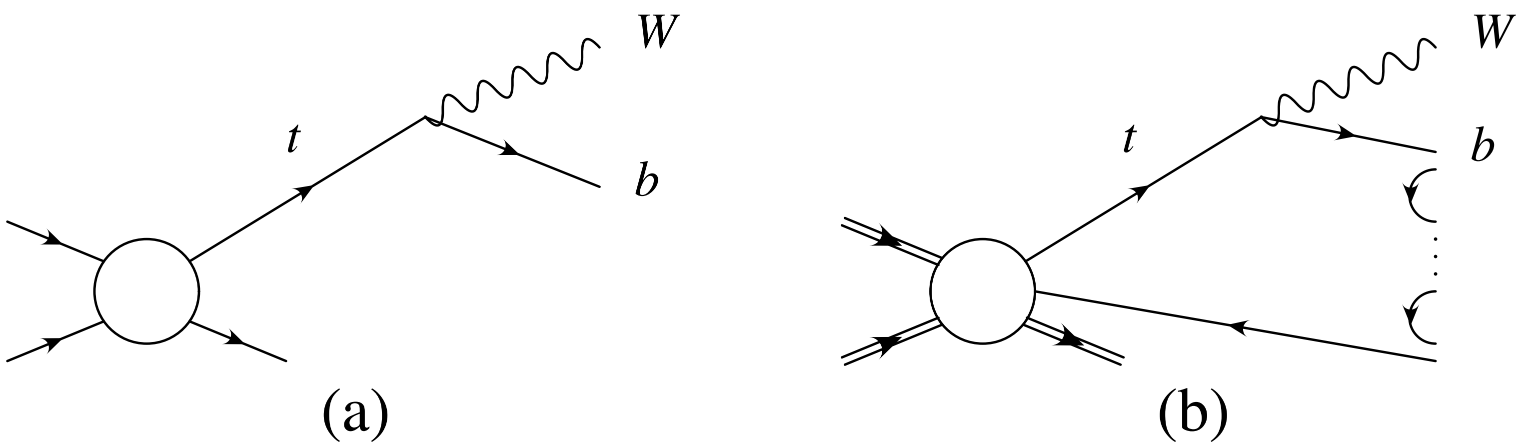
- Why would one want to measure the top quark mass?
  - ⋆ As a fundamental parameter of the standard model??
  - ⋆ As an input to precision electroweak calculations?
  - ⋆ As an input parameter in a Monte Carlo program?
  - ⋆ As an input parameter for extrapolation of couplings to high scale?
- It is important to remember that the top quark mass is a scheme and scale dependent quantity.
- With the metric provided by the standard model Higgs bounds, the top quark is well known compared to the W-mass.
- In normal units, Tevatron combination $m_t = 173.2 \pm 0.9$ GeV, $m_W = 80.420 \pm 0.031$ GeV, W-mass is much better known.





Top quark mass

- The physical amplitude cannot have a pole at the top quark mass; colour conservation forbids it.
- Therefore any measurement that relies on the fact that perturbative amplitude has such a pole is not fully controlled by short distance physics.
- Measurement of the mass of a coloured object (the top quark) by examination of the colour neutral decay products is inherently ambiguous by Λ_{QCD} and this remains true even if the top quark decays before hadronization.
- It is important to measure the top quark in as many ways as possible to constrain the hadronization model dependence.

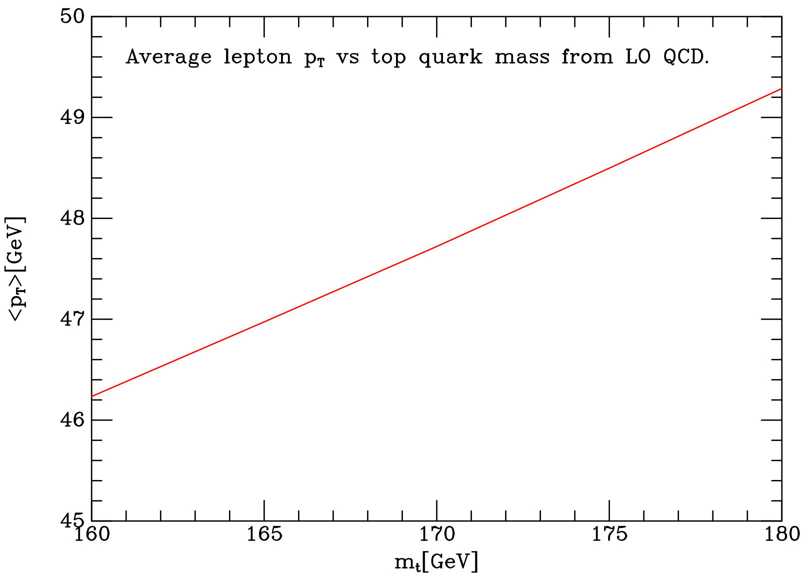


Top quark mass

- The two common masses for the top quark (pole mass and MSbar mass) differ by of order 8 GeV!

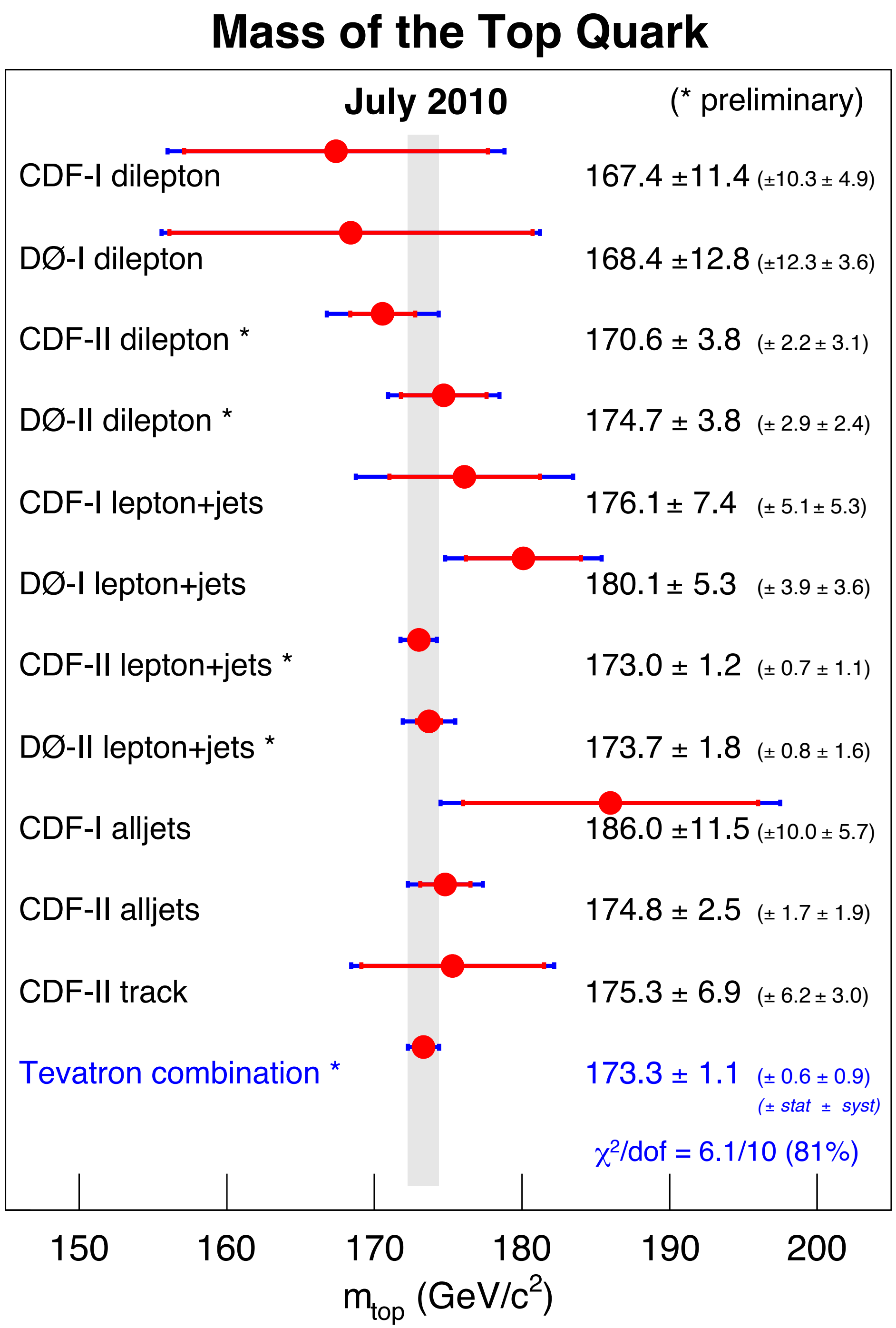
$$m_{\text{pole}} = \bar{m}(\bar{m})\left(1 + \frac{4}{3}\frac{\bar{\alpha}_s(\bar{m})}{\pi} + 8.28\left(\frac{\bar{\alpha}_s(\bar{m})}{\pi}\right)^2 + \ldots\right) + O(\Lambda_{QCD})$$

- It is important to have measurements that are based on short distance physics,that are interpretable in different renormalization schemes. Most current measurements do not belong to that class.
- By the end of the year both major LHC experiments will have 10^6 produced top quark pairs. It is appropriate to consider new methods.
- For example, the spectrum of charged leptons from top decay is sensitive to the mass of the top. At a hadron collider we can look at the charged lepton p_T distribution.



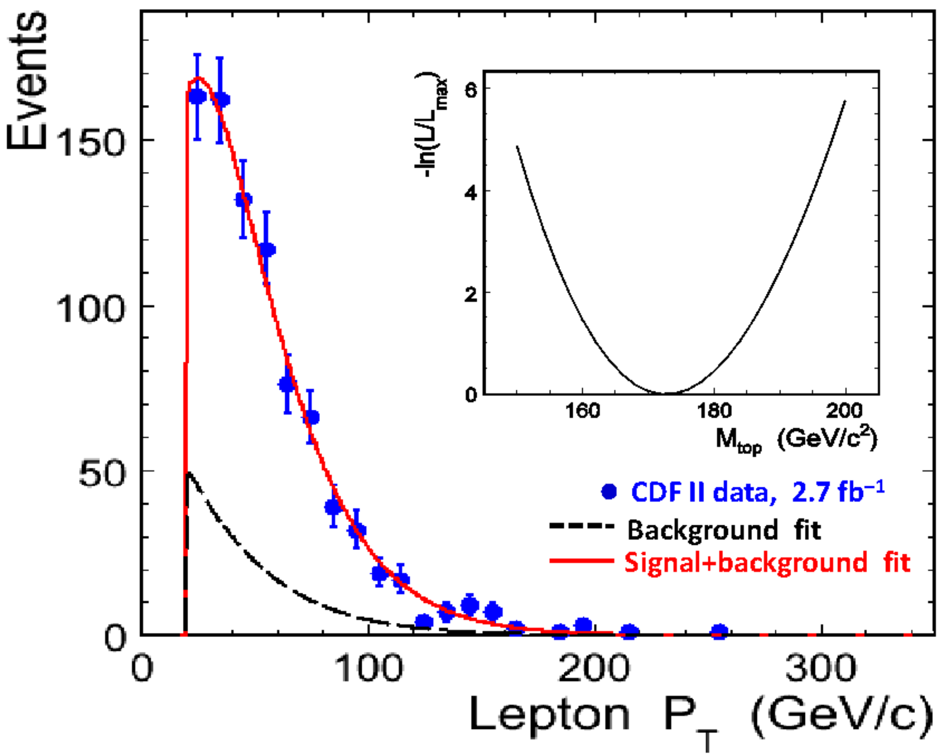
Top quark mass

- Compendium of top quark masses, precision of order 1 GeV.



Lepton p_T measurement

- CDF arXiv:1101.4926
- Treatment based on Pythia, partially upgraded to 'NLO' by including initial state radiation.
- Hence theoretical treatment is not as good as it could be, and since it does not yet include higher orders, not sensitive to the top mass renormalization scheme.
- $m_t = 176.9 \pm 8.0(stat) \pm 2.7(syst)$
- Offers the potential of a theoretically clean measurement of the mass.

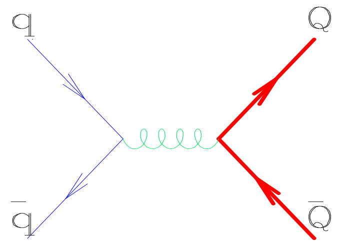


Leading order matrix elements

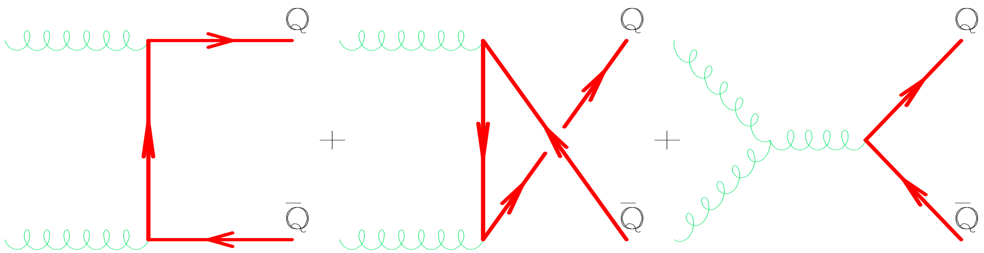
- The leading-order processes for the production of a heavy quark Q of mass m in hadron-hadron collisions

$$
\begin{array}{ll}
(a) & q(p_1) + \overline{q}(p_2) \rightarrow Q(p_3) + \overline{Q}(p_4) \\
(b) & g(p_1) + g(p_2) \rightarrow Q(p_3) + \overline{Q}(p_4)
\end{array}
$$

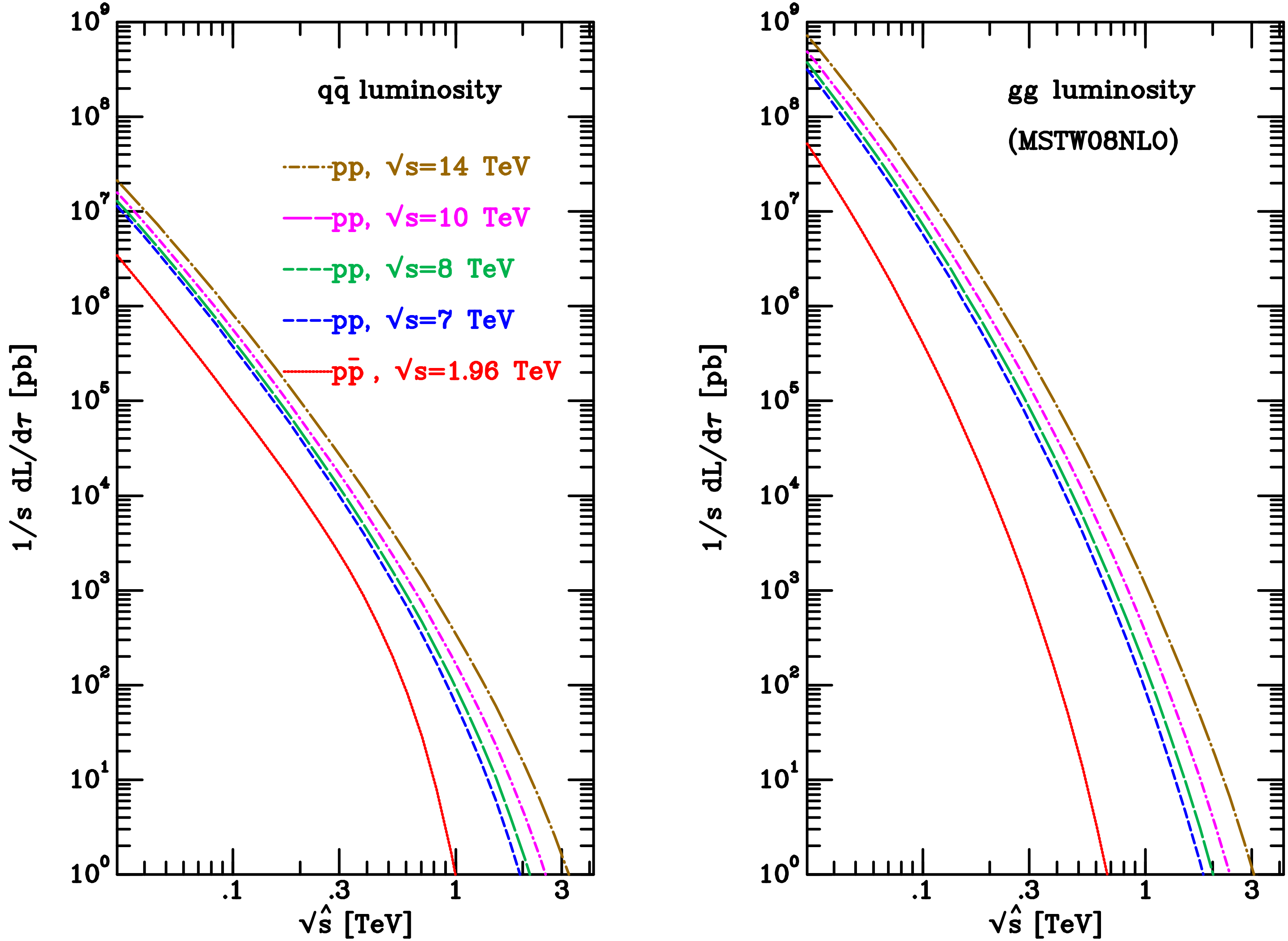
- Tevatron $90\%\ q\bar{q}, 10\%\ gg$, LHC $10\%\ q\bar{q}, 90\%\ gg$.



(a)



(b)


q$\bar{q}$ luminosity
pp, √s=14 TeV
pp, √s=10 TeV
pp, √s=8 TeV
pp, √s=7 TeV
p$\bar{p}$, √s=1.96 TeV
gg luminosity
(MSTW08NLO)
1/s dL/dτ [pb]
√ŝ [TeV]
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
.1
.3
1
3

Matrix elements to cross sections

Process	$\overline{\sum}\vert\mathcal{M}\vert^2/g^4$
$q\,\overline{q} \to Q\,\overline{Q}$	$\frac{4}{9}\left(\tau_1^2+\tau_2^2+\frac{\rho}{2}\right)$
$g\,g \to Q\,\overline{Q}$	$\left(\frac{1}{6\tau_1\tau_2}-\frac{3}{8}\right)\left(\tau_1^2+\tau_2^2+\rho-\frac{\rho^2}{4\tau_1\tau_2}\right)$

The matrix elements squared have been averaged (summed) over initial (final) colours and spins, as indicated by $\overline{\sum}$.

- We have introduced the following notation for the ratios of scalar products:

$$\tau_1 = \frac{2p_1.p_3}{\hat{s}}, \quad \tau_2 = \frac{2p_2.p_3}{\hat{s}}, \quad \rho = \frac{4m^2}{\hat{s}}, \quad \hat{s} = (p_1+p_2)^2.$$

- The short-distance cross section is obtained from the invariant matrix element in the usual way:

$$d\hat{\sigma}_{ij} = \frac{1}{2\hat{s}}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)\overline{\sum}|\mathcal{M}_{ij}|^2.$$

The first factor is the flux factor for massless incoming particles. The other terms come from the phase space for $2 \to 2$ scattering.

Rapidity distributions

- In terms of the rapidity $y = \frac{1}{2}\ln((E+p_z)/(E-p_z))$ and transverse momentum, p_T, the relativistically invariant phase space volume element of the final-state heavy quarks is

$$\frac{d^3p}{E} = dy\ d^2p_T\ .$$

The result for the invariant cross section may be written as

$$\frac{d\sigma}{dy_3 dy_4 d^2p_T} = \frac{1}{16\pi^2\hat{s}^2}\sum_{ij} x_1 f_i(x_1,\mu^2)\ x_2 f_j(x_2,\mu^2)\overline{\sum}|\mathcal{M}_{ij}|^2.$$

x_1 and x_2 are fixed if we know the transverse momenta and rapidity of the outgoing heavy quarks. In the centre-of-mass system of the incoming hadrons we may write

$$\begin{aligned} p_1 &= \frac{1}{2}\sqrt{s}(x_1,0,0,x_1), \qquad p_2 = \frac{1}{2}\sqrt{s}(x_2,0,0,-x_2) \\ p_3 &= (m_T\cosh y_3, p_T, 0, m_T\sinh y_3) \\ p_4 &= (m_T\cosh y_4, -p_T, 0, m_T\sinh y_4). \end{aligned}$$

Rapidity distributions (continued)

- Applying energy and momentum conservation, we obtain

$$\begin{aligned} x_1 &= \frac{m_T}{\sqrt{s}}\left(e^{y_3}+e^{y_4}\right) \\ x_2 &= \frac{m_T}{\sqrt{s}}\left(e^{-y_3}+e^{-y_4}\right) \\ \hat{s} &= 2m_T^2(1+\cosh\Delta y). \end{aligned}$$

  The quantity $m_T = \sqrt{(m^2+p_T^2)}$ is the transverse mass of the heavy quarks and $\Delta y = y_3 - y_4$ is the rapidity difference between them.

- In these variables the leading order cross section is

$$\begin{aligned} \frac{d\sigma}{dy_3 dy_4 d^2 p_T} &= \frac{1}{64\pi^2 m_T^4 (1+\cosh(\Delta y))^2} \\ &\times \sum_{ij} x_1 f_i(x_1,\mu^2)\, x_2 f_j(x_2,\mu^2)\, \overline{\sum}|\mathcal{M}_{ij}|^2. \end{aligned}$$

Applicability of perturbation theory?

- Consider the propagators in the diagrams.

$$
\begin{aligned}
(p_1 + p_2)^2 = & \quad 2p_1.p_2 & = 2m_T^2\big(1 + \cosh\Delta y\big)\ , \\
(p_1 - p_3)^2 - m^2 = & \quad -2p_1.p_3 & = -m_T^2\big(1 + e^{-\Delta y}\big)\ , \\
(p_2 - p_3)^2 - m^2 = & \quad -2p_2.p_3 & = -m_T^2\big(1 + e^{\Delta y}\big)\ .
\end{aligned}
$$

  Note that the propagators are all off-shell by a quantity of least of order m^2.

- Thus for a sufficiently heavy quark we expect the methods of perturbation theory to be applicable. It is the mass m (which by supposition is very much larger than the scale of the strong interactions Λ) which provides the large scale in heavy quark production. We expect corrections of order Λ/m
- Top quark production should be well described by perturbation theory;
- This does not address the issue of whether the charm or bottom mass is large enough to be adequately described by perturbation theory.

Heavy quark production in $O(\alpha_S^3)$

- In NLO heavy quark production m is the heavy quark mass.

$$\sigma(S) = \sum_{i,j} \int dx_1 dx_2 \; \hat{\sigma}_{ij}(x_1 x_2 S, m^2, \mu^2) F_i(x_1, \mu^2) F_j(x_2, \mu^2)$$

$$\hat{\sigma}_{i,j}(\hat{s}, m^2, \mu^2) = \sigma_0 c_{ij}(\hat{\rho}, \mu^2)$$

where $\hat{\rho} = 4m^2/\hat{s}, \bar{\mu}^2 = \mu^2/m^2, \sigma_0 = \alpha_S^2(\mu^2)/m^2$ and $\hat{s}$ in the parton total c-of-m energy squared. The coupling satisfies

$$\frac{d\alpha_S}{d\ln\mu^2} = -b_0 \frac{\alpha_S^2}{2\pi} + O(\alpha_S^3), \;\; b_0 = \frac{11N - 2n_f}{6}$$

- General form of $O(\alpha_s^3)$ result

$$c_{ij}\left(\rho, \frac{\mu^2}{m^2}\right) = c_{ij}^{(0)}(\rho) + 4\pi\alpha_S(\mu^2)\left[c_{ij}^{(1)}(\rho) + \overline{c}_{ij}^{(1)}(\rho)\ln(\frac{\mu^2}{m^2})\right] + O(\alpha_S^2)$$

Total cross sections

The lowest-order functions $c_{ij}^{(0)}$ are obtained by integrating the lowest order matrix elements

$$c_{q\overline{q}}^{(0)}(\rho) = \frac{\pi\beta\rho}{27}\left[(2+\rho)\right] ,$$

$$c_{gg}^{(0)}(\rho) = \frac{\pi\beta\rho}{192}\left[\frac{1}{\beta}\left[\rho^2 + 16\rho + 16\right]\ln\left(\frac{1+\beta}{1-\beta}\right) - 28 - 31\rho\right] ,$$

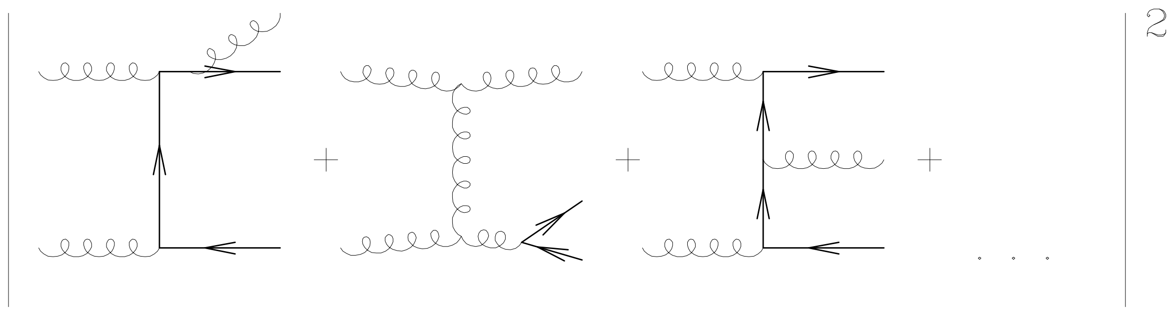
$$c_{gq}^{(0)}(\rho) = c_{g\overline{q}}^{(0)}(\rho) = 0 ,$$

and $\beta = \sqrt{1-\rho}$.

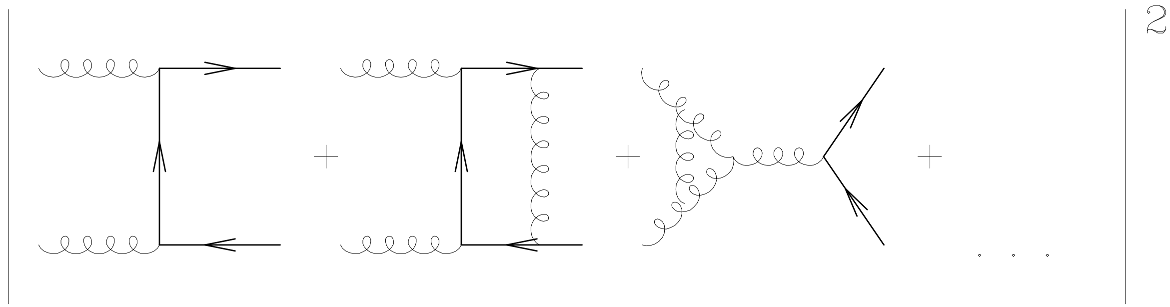
- The functions $c_{ij}^{(0)}$ vanish both at threshold ($\beta \to 0$) and at high energy ($\rho \to 0$).
- Note that the quark-gluon process is zero in lowest order, but is present in higher orders.

Next-to-leading corrections, $O(\alpha_S^3)$

- The functions $c_{ij}^{(1)}$ are also known
- Numerical calculation Nason, Dawson, Ellis (1989)
- Analytic calculation Czakon, Mitov (arXiv:0811.4119)
- $O(\alpha_s^4)$ calculation is now complete, important since at the LHC top production is a standard candle for gluon luminosity.



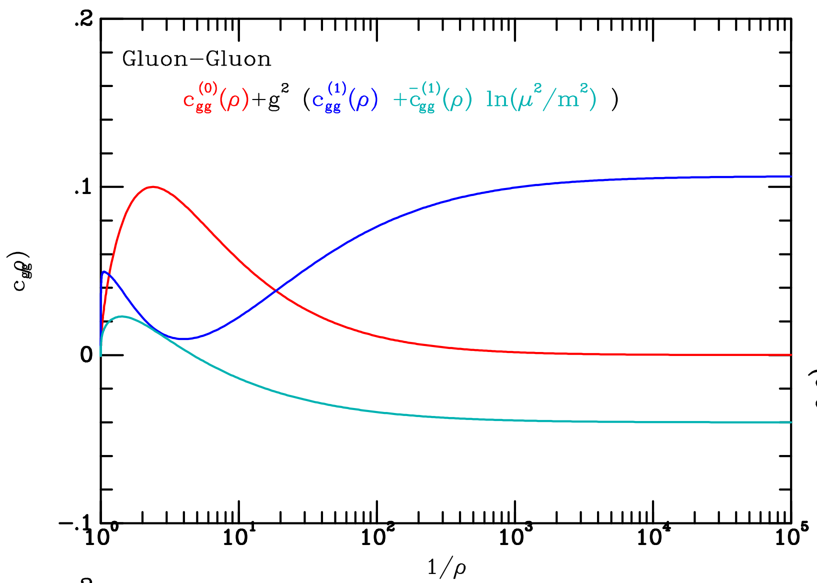
Real emission diagrams

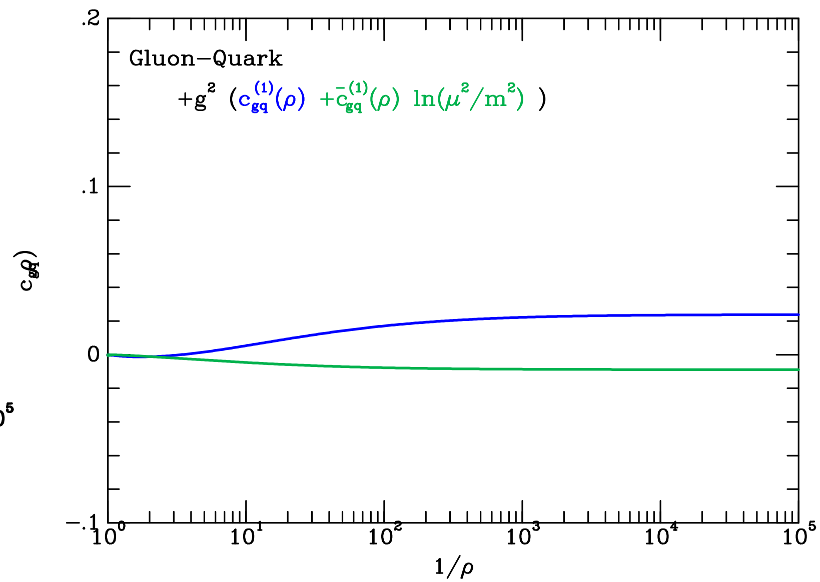


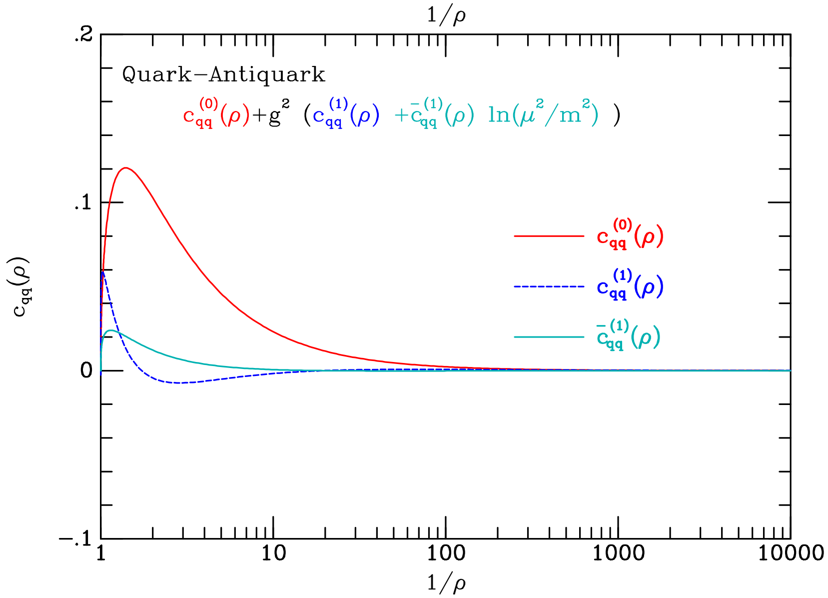
Virtual emission diagrams

Higher order functions

- In order to calculate the c_{ij} in perturbation theory we must perform both renormalization and factorization of mass singularities. The subtractions required for renormalization and factorization are done at mass scale μ.







μ dependence

- μ is an unphysical parameter. The physical predictions should be invariant under changes of μ at the appropriate order in perturbation theory. If we have performed a calculation to $O(\alpha_S^3)$, variations of the scale μ will lead to corrections of $O(\alpha_S^4)$,

$$\mu^2 \frac{d}{d\mu^2} \sigma = O(\alpha_S^4).$$

- The term $\overline{c}^{(1)}$, which controls the μ dependence of the higher-order perturbative contributions, is fixed in terms of the lower-order result $c^{(0)}$:

$$\overline{c}_{ij}^{(1)}(\rho) = \frac{1}{8\pi^2}\left[4\pi b c_{ij}^{(0)}(\rho) - \int_\rho^1 dz \sum_k c_{kj}^{(0)}(\frac{\rho}{z}) P_{ki}^{(0)}(z) + c_{ik}^{(0)}(\frac{\rho}{z}) P_{kj}^{(0)}(z)\right].$$

  In obtaining this result we have used the renormalization group equation for the running coupling

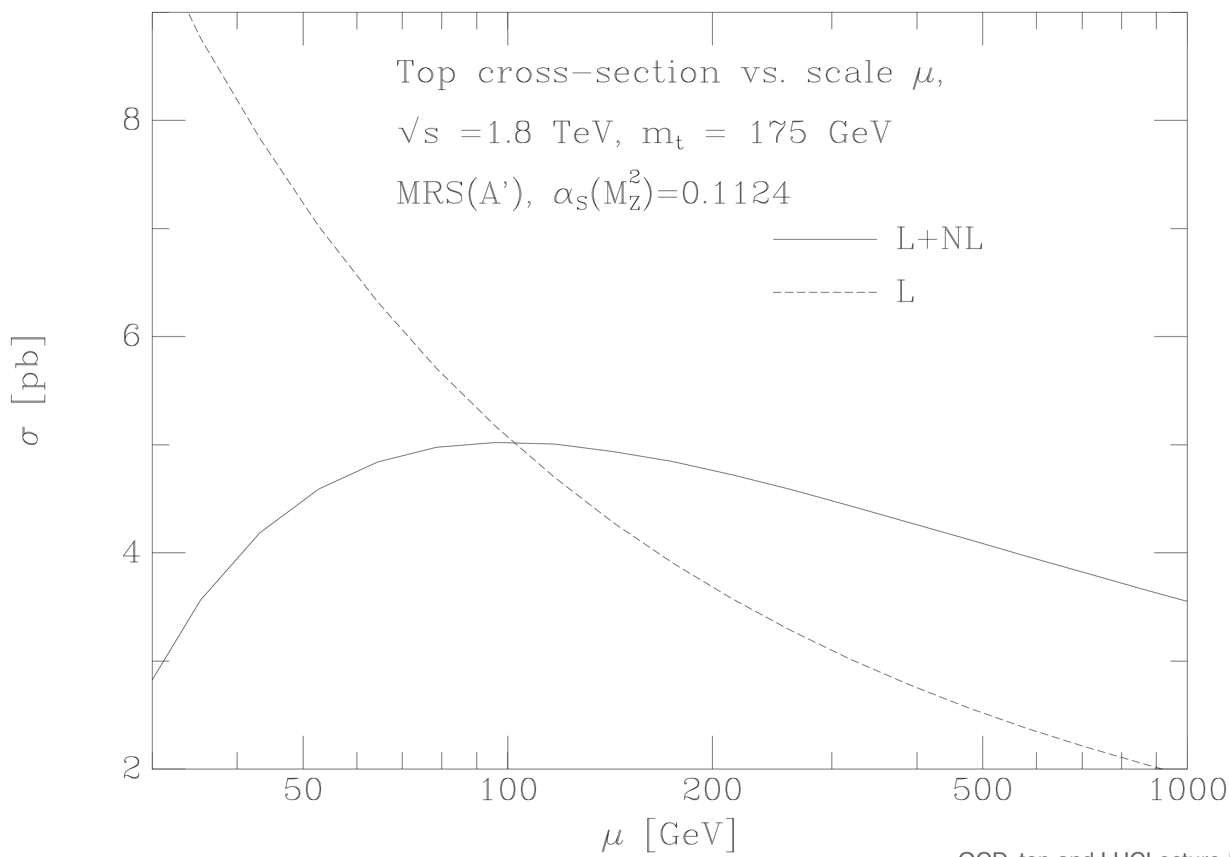
$$\mu^2 \frac{d}{d\mu^2} \alpha_S(\mu^2) = -b\alpha_S^2 + \ldots$$

  and the lowest-order form of the GLAP equation

$$\mu^2 \frac{d}{d\mu^2} f_i(x,\mu^2) = \frac{\alpha_S(\mu^2)}{2\pi} \sum_k \int_x^1 \frac{dz}{z} P_{ik}^{(0)}(z) f_k(\frac{x}{z},\mu^2) + \ldots .$$

Scale dependence

- This illustrates an important point which is a general feature of renormalization group improved perturbation series in QCD. The coefficient of the perturbative correction depends on the choice made for the scale μ, but the scale dependence changes the result in such a way that the physical result is independent of that choice. Thus the scale dependence is formally small because it is of higher order in α_S. This does not assure us that the scale dependence is actually *numerically* small for all series. A pronounced dependence on the scale μ is a signal of an untrustworthy perturbation series.



Features of HO corrections

- Two features of $c_{ij}^{(1)}$ are worthy of note.
- The quark-antiquark and gluon-gluon initiated processes have a very rapid rise at threshold.

$$c_{q\bar{q}}^{(1)} \rightarrow \frac{c_{q\bar{q}}^{(0)}(\rho)}{8\pi^2}\left[-\frac{\pi^2}{6\beta}+\frac{16}{3}\ln^2\left(8\beta^2\right)-\frac{82}{3}\ln(8\beta^2)\right]$$

$$c_{gg}^{(1)} \rightarrow \frac{c_{gg}^{(0)}(\rho)}{8\pi^2}\left[\frac{11\pi^2}{42\beta}+12\ln^2\left(8\beta^2\right)-\frac{366}{7}\ln(8\beta^2)\right]$$

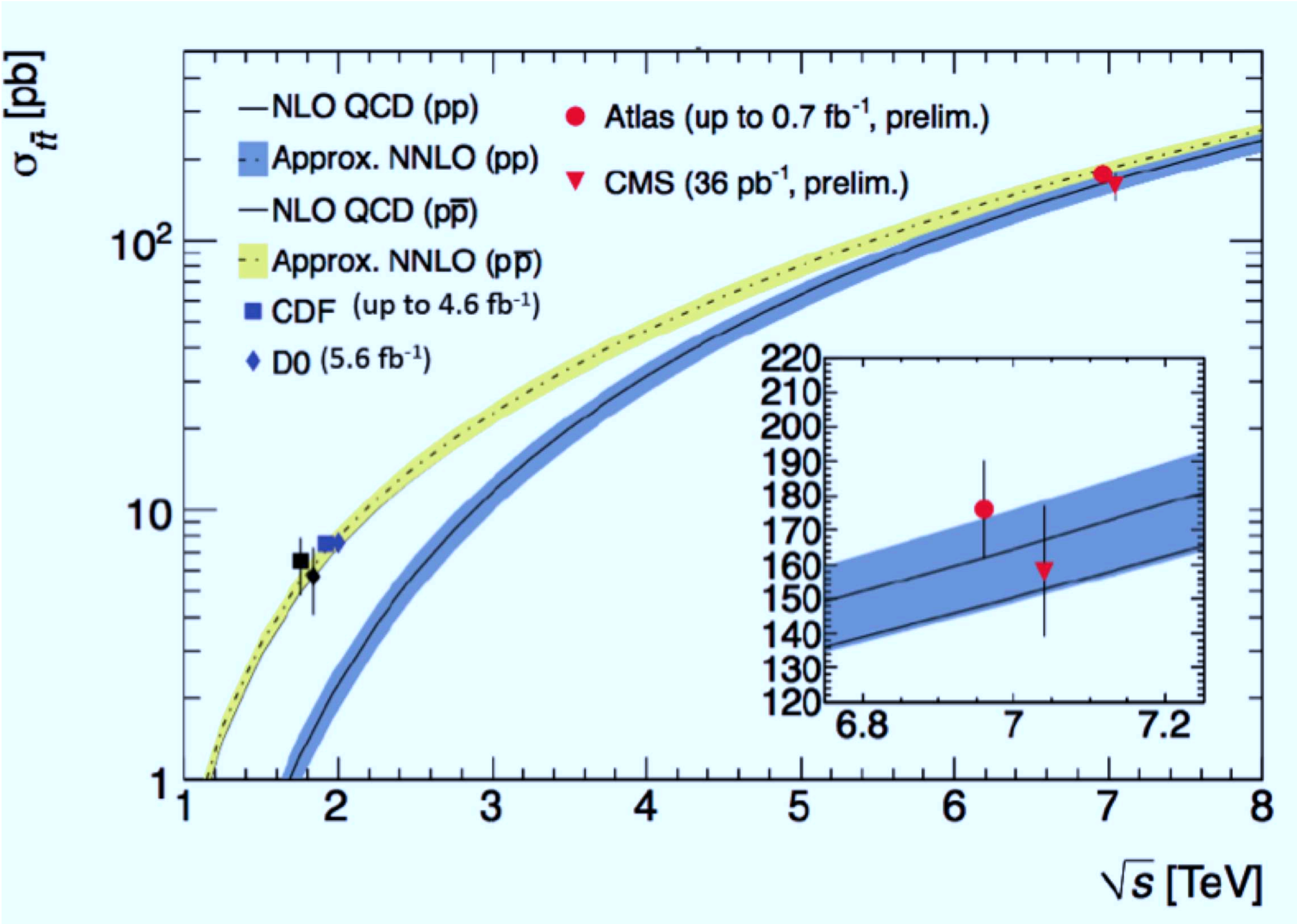
due to Coulomb $1/\beta$ singularities and to Sudakov double logarithms. Near threshold, these terms give large contributions and require special treatment, such as resummation to all orders.

- The gg and gq contributions to $c_{ij}^{(1)}$, which involve spin-one gluon exchange in the t-channel, tend to a constant value at large $\hat{s}$, where $k = \frac{7291}{16200}\frac{1}{8\pi}$

$$\begin{aligned} c_{gg} &\rightarrow 6k \sim 0.1074 \\ c_{gq} &\rightarrow \frac{4}{3}k \sim 0.02388 \end{aligned}$$

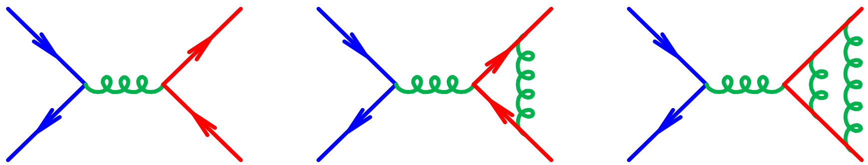
2011 total cross section results

- 9% Uncertainty at LHC!

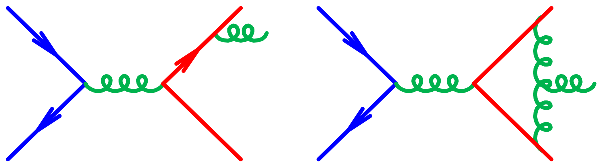


Total cross section at NNLO

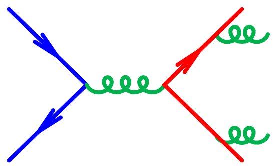
- Challenge is not only the calculation of individual diagrams, but also the assembly of pieces that individually contain infrared divergences.



⋆ examples of $2 \to 2$ diagrams



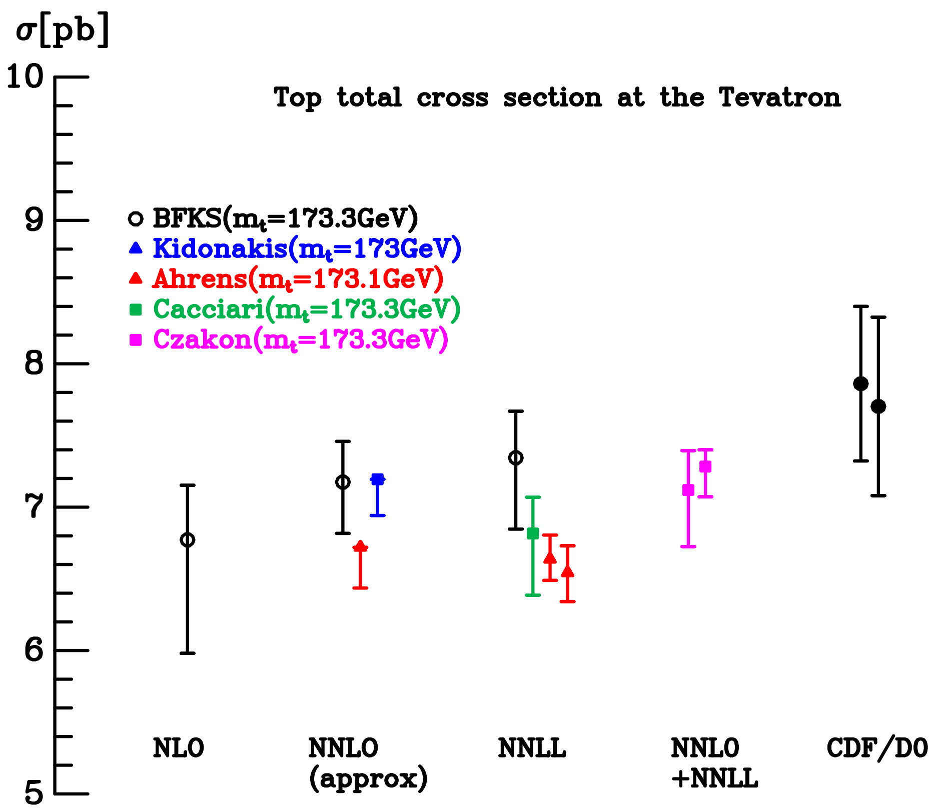
⋆ examples of $2 \to 3$ diagrams



⋆ examples of $2 \to 4$ diagrams

- In different regions of phase space lead to singularities of the matrix elements.
- Overlapping divergences are treated by partitioning phase space so that in each sector of phase space only on particle can become soft, only two definite partons collinear.

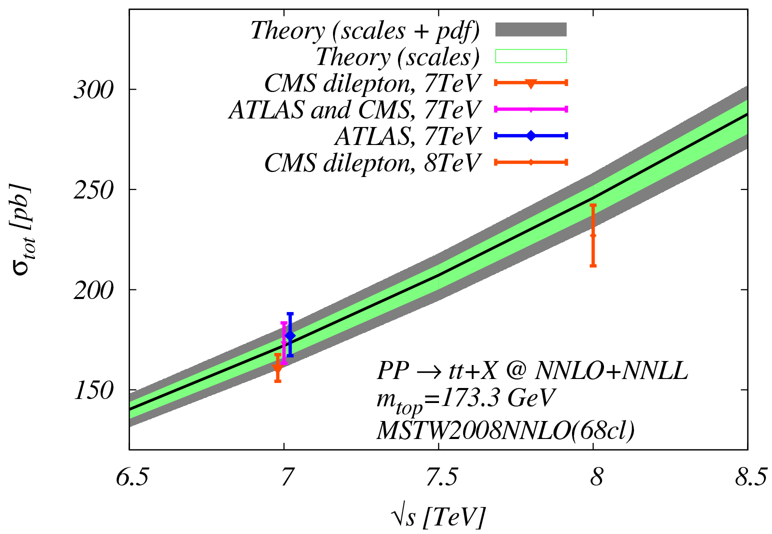
tt Total cross section at NNLO



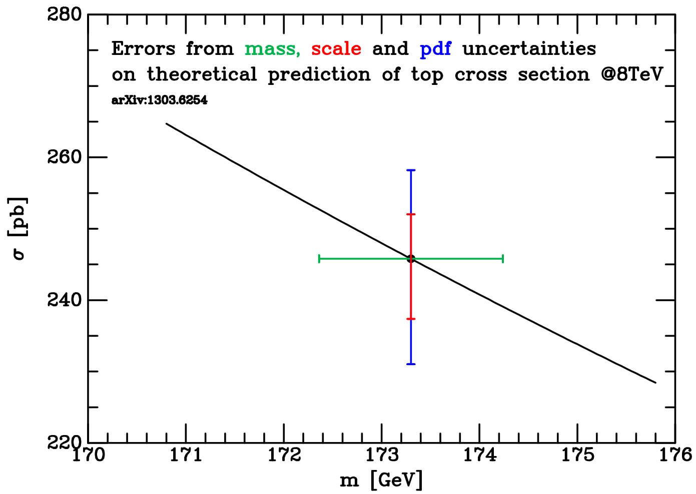
- Significant differences between approximate NNLO and NNLL calculations
- NNLL calculations sum $\alpha_S \ln^2 \beta$
- A real honest NLLO calculation is now available for the total cross section, (Czakon, Fiedler and Mitov, 1303.6254).

Comparison with data and error budget @NNLO

- Within experimental and theoretical errors, data is in good agreement with theoretical result.

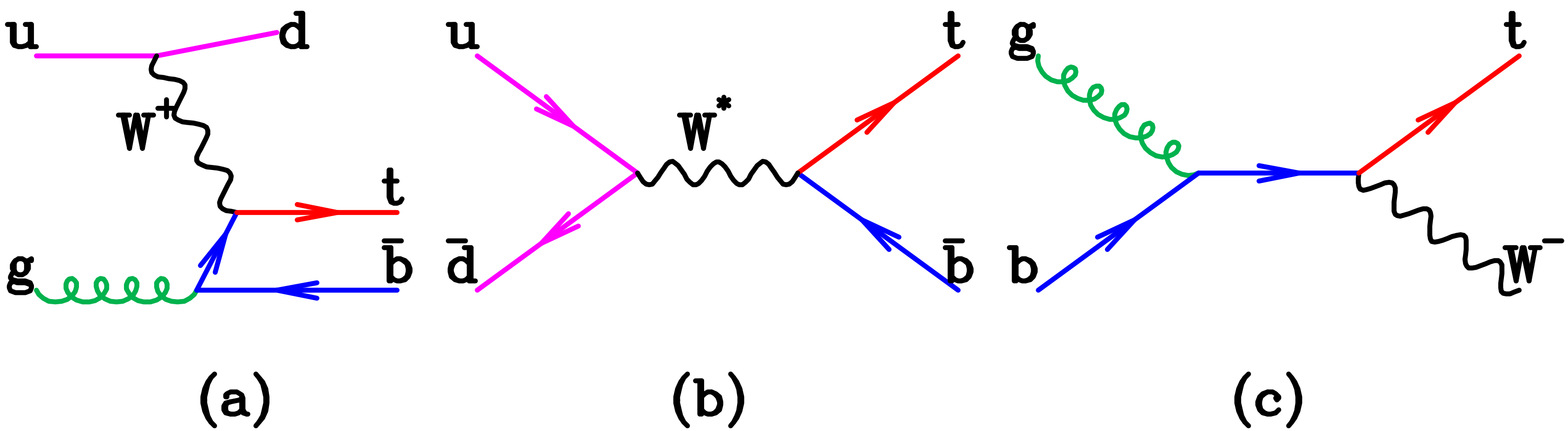


- After inclusion of NNLO, errors in top total cross section from error in mass, errors in PDF and errors in scale uncertainty are of the same order of magnitude.



Single Top production

- As well as pair-producing the top quark via the strong interaction, a top quark can be produced singly via the weak interaction.
- There are three such mechanisms, which provide different probes of both the physics of the top quark and possible new physics beyond the SM.



(a) This is the t-channel process

(b) This is the s-channel process, which is sensitive to V_{tb}

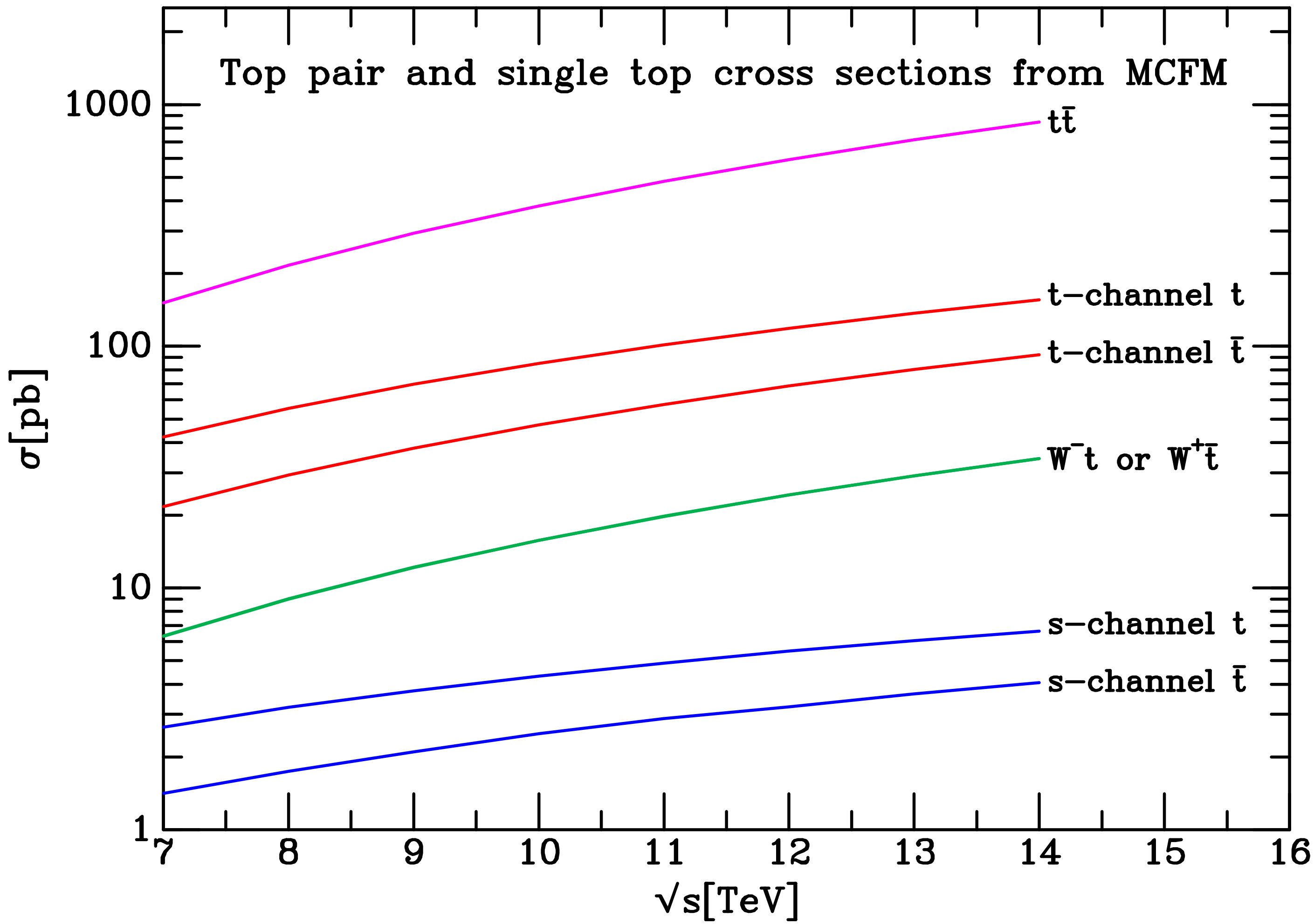
(c) This is the $W - t$ process.

Approximate Top production rates

	Tevatron	LHC@7	LHC@8	LHC@13	LHC@14
$t\bar{t}$ production	7pb	170pb	240pb	780pb	930 pb
s-channel single top	0.5pb	2.8pb	3.4pb	6.5pb	7.1 pb
t-channel single top	1.0pb	44pb	57pb	141pb	163 pb
Wt single top	0.07pb	6pb	9pb	28pb	34 pb

- Single top rates are for top, (not antitop)
- Wt rates are cut-dependent (and are very small at Tevatron)
- s-channel single top rates are very small at LHC

Top production rates



- NLO values for the top cross sections vs $\sqrt{s}$ calculated using MCFM.
- The cross sections are evaluated at factorization and renormalization scale $m_t = 173.2$ GeV using the CTEQ6M parton distributions.

Information about V_{tb} from top decay?

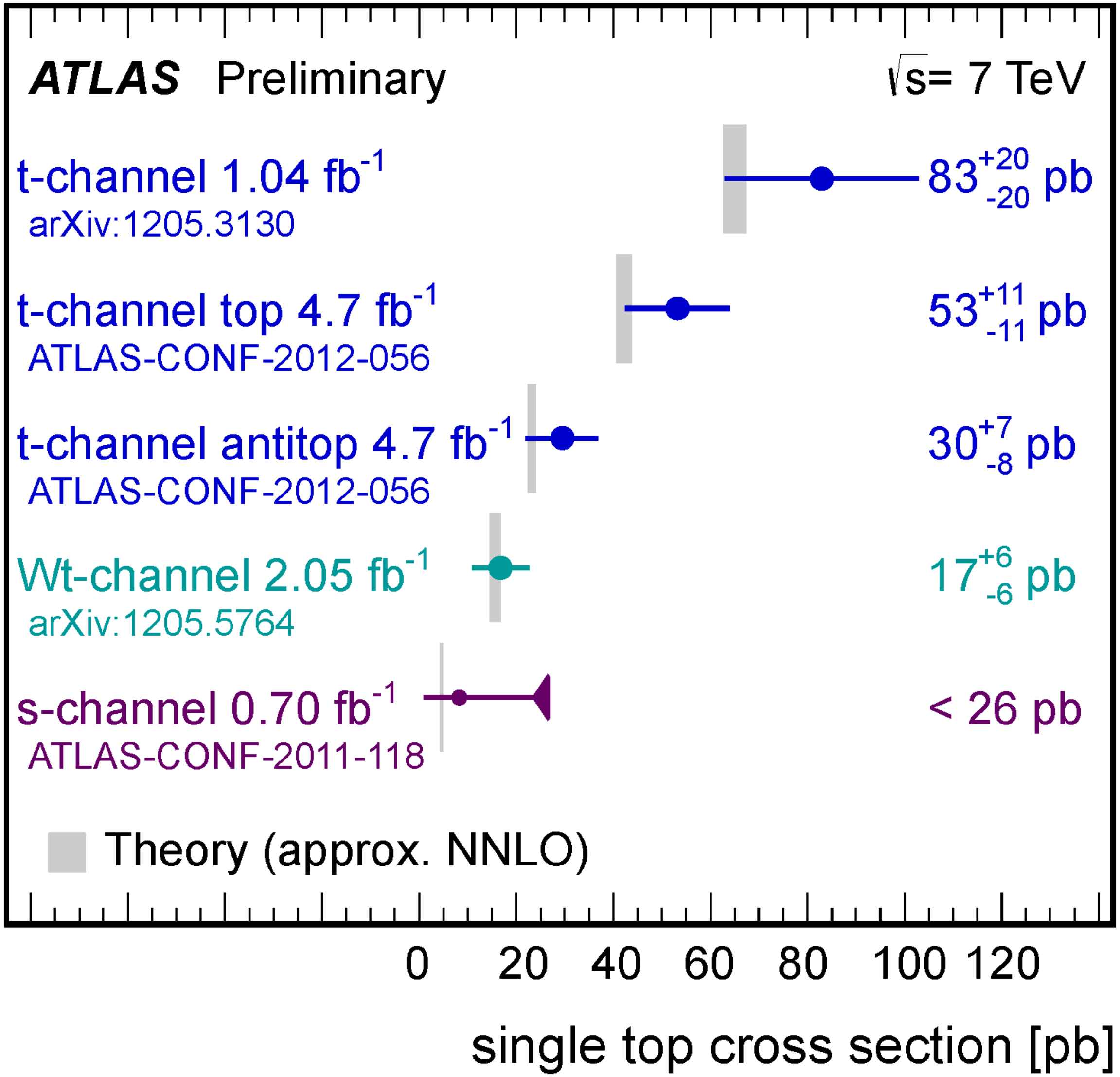
$$\frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.94^{+0.31}_{-0.24}$$

If we assume just three generations of quarks, unitarity of the CKM matrix implies that the denominator is equal to one, so that we can extract

$$|V_{tb}| = 0.97^{+0.16}_{-0.12}$$

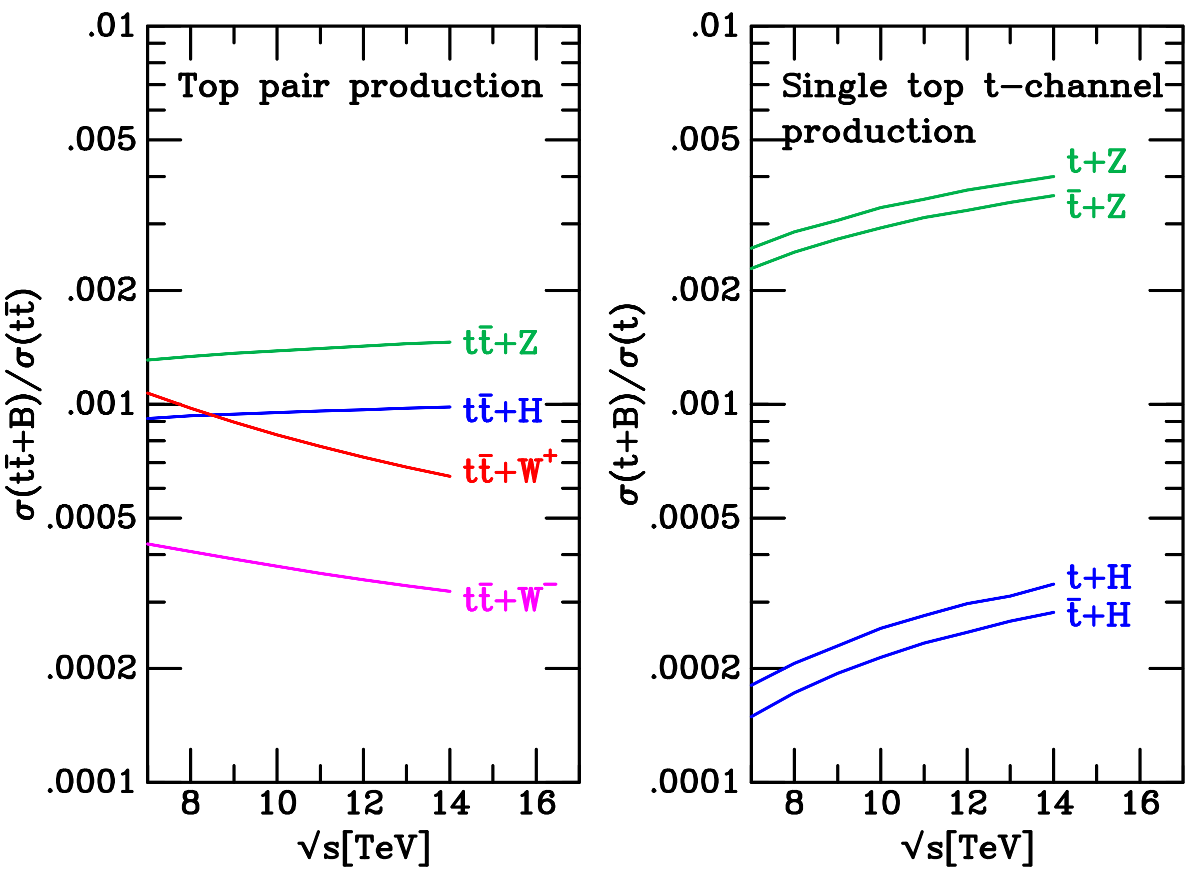
- But assuming unitarity we know already that $V_{tb} = 0.9990 - -0.9993$.
- The current CDF measurement shows that $|V_{tb}| \gg |V_{td}|, |V_{ts}|$.
- For a real measurement of V_{tb} we must look at the electroweak production of a top quark.

Results from ATLAS



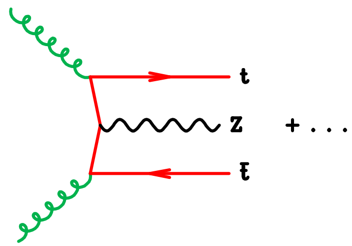
Production of bosons in association with top

- All the information on the top quark is still rather limited and crude
- One top quark pair in ~ 1000 will have an associated vector boson
- ~ 2 per mil of single tops will have an associated Z boson in the SM.
- ~ 2 per 10,000 of single tops will have an associated Higgs boson in the SM.

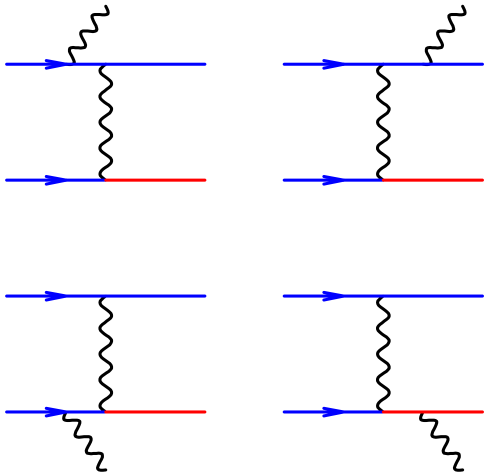


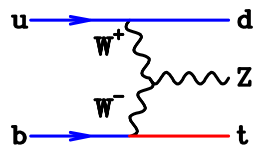
Production of Z associated with top

- Currently very little experimental information.
- In association with a top pair



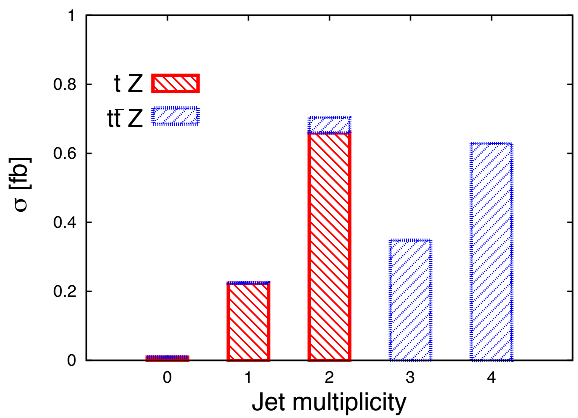
- In association with a single top

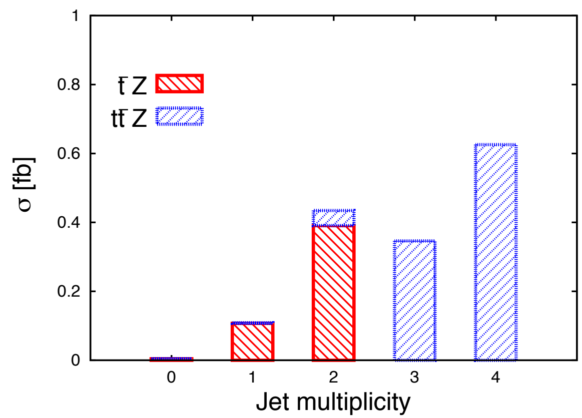




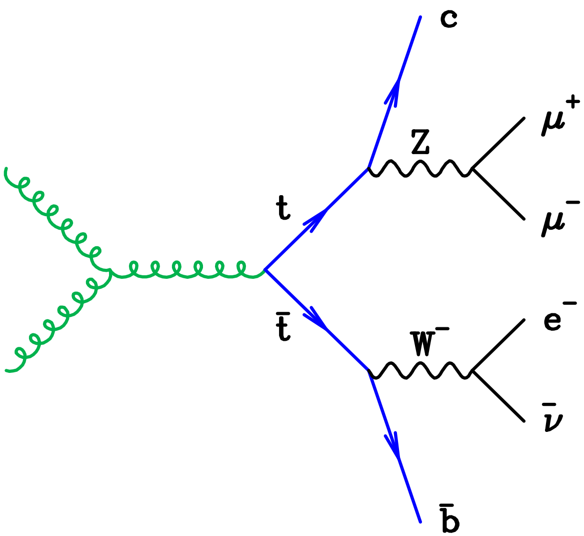
- ttZ and tZ cross sections are comparable

Comparison of $t\bar{t}Z$ and $tZ, \bar{t}Z$



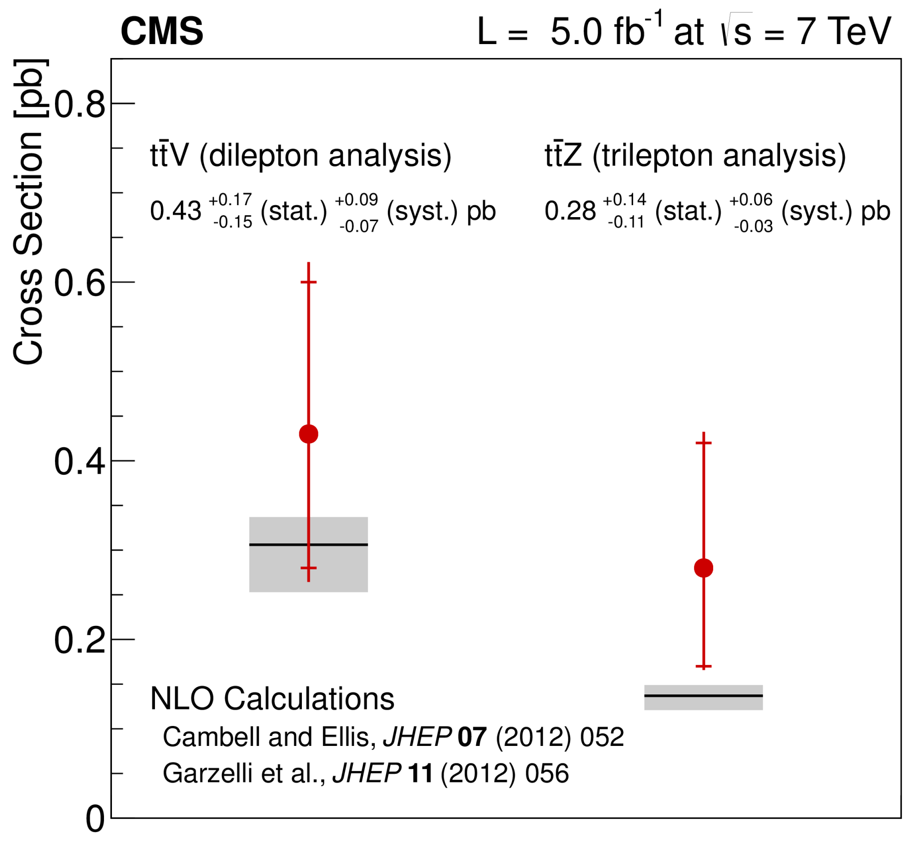


- Single top +Z also of concern for searches for non standard top decays.
- non standard top decays produce the same signature of Z +top + jet.



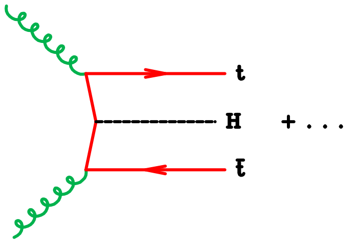
Measurement from CMS

- arXiv:1303.3239
- Analyzed in trilepton channel ($t\bar{t}Z$) and dilepton channel ($t\bar{t}Z$,$t\bar{t}W$)
- Evidence for these channels rather than observation, (signal observed with ~ 3 standard deviations).
- At least three jets with $p_T > 20$ GeV of which at least one is b-tagged.

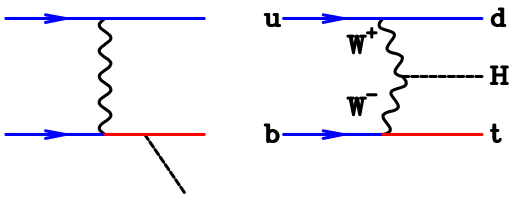


Production of H associated with top

- Currently very little experimental information.
- In association with a top pair, decay modes $b\bar{b}, \tau\tau, \gamma\gamma$.

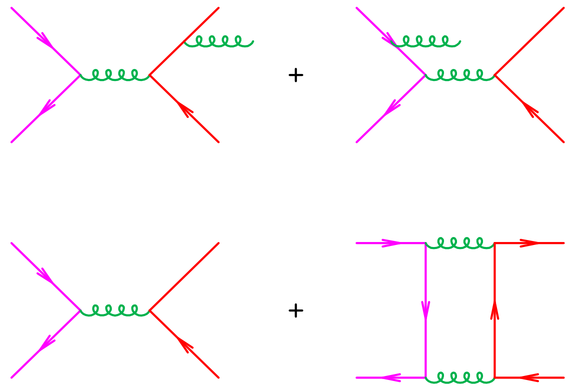


- In association with a single top

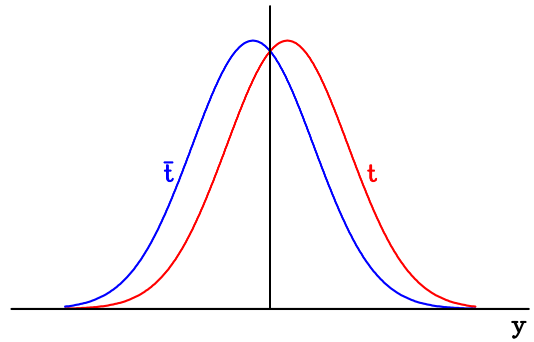


- Single top tH cross sections strongly suppressed by destructive interference in the SM.

Asymmetry in top production



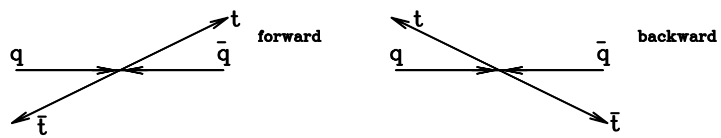
- At the Tevatron (i.e. in $p\bar{p}$ collisions), there is a forward-backward asymmetry that appears first at order α_S^3, from both real and virtual diagrams of the type shown.



- Asymmetries can be defined both at the parton level and for the charged leptons.

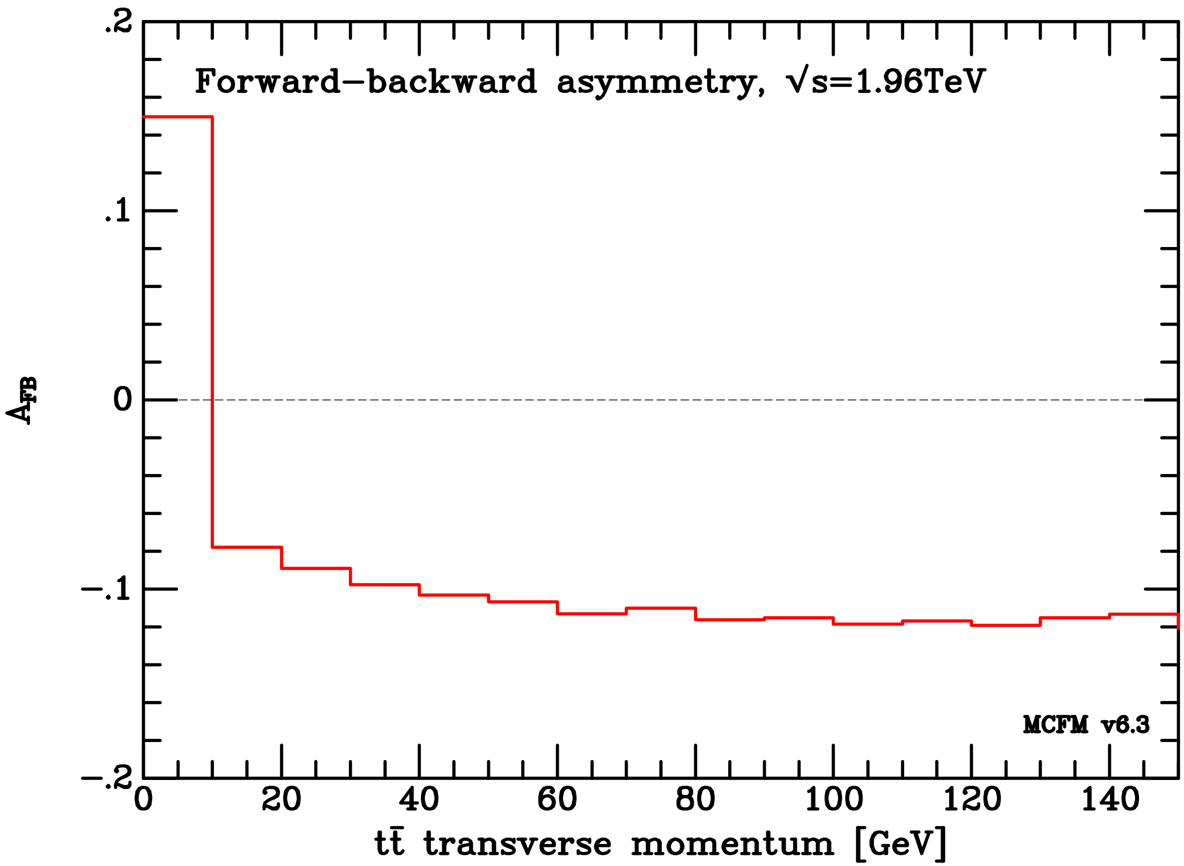
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{(\Delta y > 0) + N(\Delta y < 0)}$$

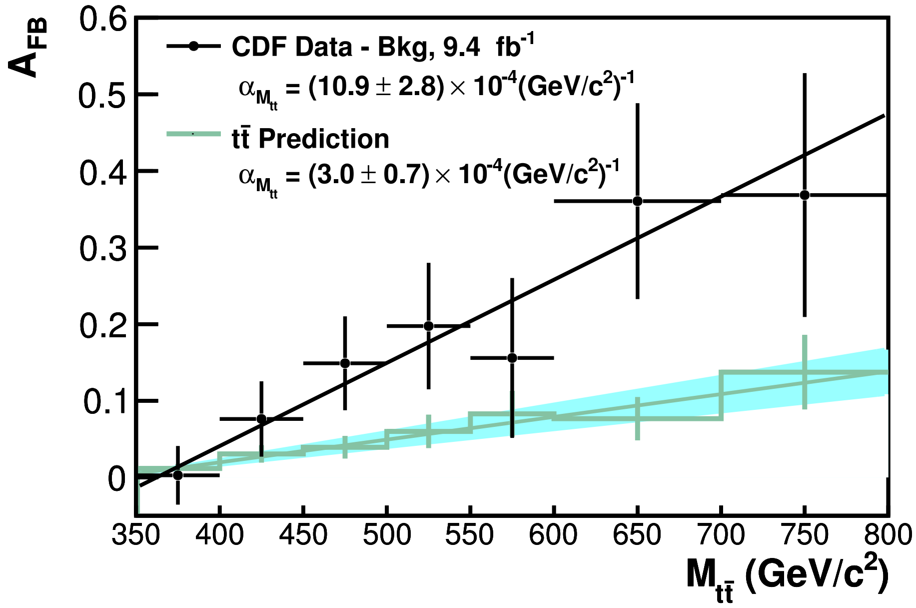
$$A^l_{FB} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$



Asymmetry vs transverse momentum

- Real radiation diagrams lead to a negative asymmetry.
- Virtual radiation diagrams lead to a positive asymmetry.



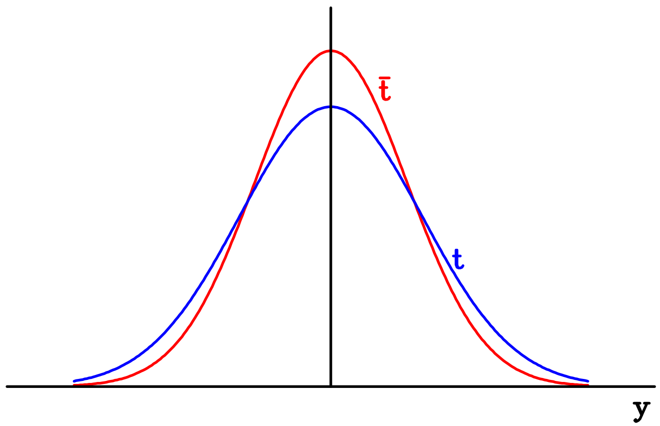


- CDF finds parton level result for $A_{FB} = 16.4 \pm 4.7\%$ (stat + syst), arXiv:1211.1003.
- CDF finds that the asymmetry grows as a function of mass as predicted by the standard model, but with a larger slope.
- D0 finds $A_{FB} = 9.2 \pm 3.7\%$ compared to MC@NLO $A_{FB} = 2.4 \pm 0.7\%$, but with no statistically significant excess at large m_{tt} or large Δy (arXiv:1110.2062).

Asymmetry at LHC

- No forward backward asymmetry at LHC, (pp machine!)

$$A_c = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)},$$
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



- ATLAS:
  $A_c = 0.029 \pm 0.018$(stat.) $\pm\, 0.014$(syst.)
- CMS: Corrected:
  $A_c = 0.004 \pm 0.010$(stat.) $\pm\, 0.011$(syst.)
- Theory: (Kühn, Rodrigo):
  $A_c = 0.0115 \pm 0.0006$

Recap

- Top will be exquisitely studied at the LHC.
- Top decays before it has time to hadronize; no top mesons.
- Top production is perturbatively calculable because of the large mass of the top.
- Single top production rate are substantial and give sensitivity to V_{tb}.
- Associated production of vector bosons $Z, H, gamma, jet$ will give information about the top couplings.