Overview on Top and Single Top production

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I.: Basic facts about the top
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III: Single top production
IV: Outlook

Basic facts about top

The essential numbers:

Mass:

$$m_t = 173.07 \pm 0.52 \pm 0.72 \text{ GeV}$$

Width:

$$\Gamma = 2.0 \pm 0.5 \text{ GeV}$$

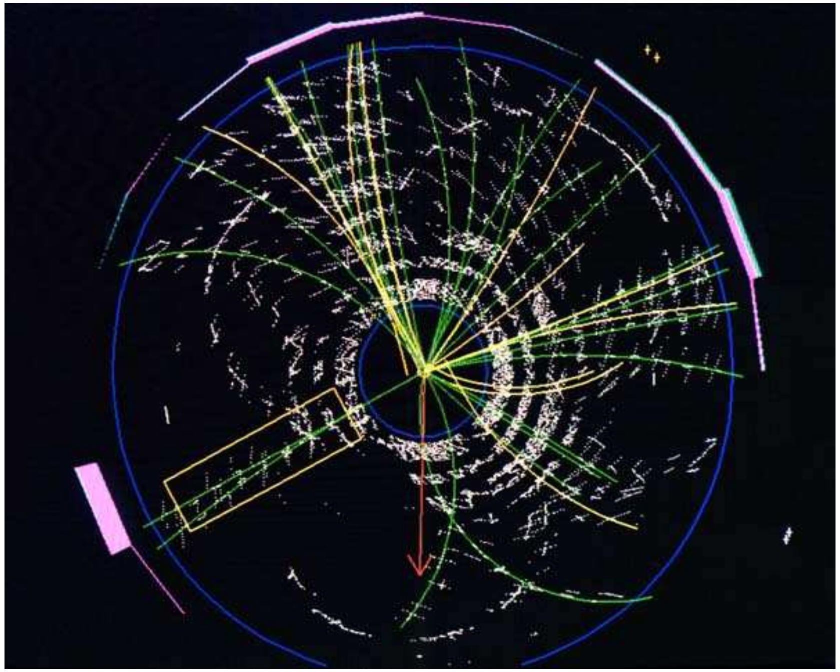
Branching fraction:

$$\frac{\Gamma(Wb)}{\Gamma(Wq)} = 0.99^{+0.09}_{-0.08} \quad \text{(pre-2011)}$$

$$= 0.90 \pm 0.04 \quad \text{(D0, 2011)}$$

$$= 1.023^{+0.036}_{-0.034} \quad \text{(CMS, 2012)}$$

Discovered at the Tevatron in 1995



A $t\bar{t}$ event from CDF.

Implications

The top quark is special:

- The large top mass sets a hard scale.
- Lifetime shorter than characteristic hadronization time scale.

⇒ Top physics is described by perturbative QCD.

- The top mass is close to the electro-weak breaking scale.

⇒ If there is new physics associated with electro-weak symmetry breaking,
top physics is a place to look for.

Theoretical aspects of the top mass

$$\mathcal{L} \quad = \quad \bar{\psi}\,(i\not{D} - m_{\text{bare}})\,\psi$$

Renormalisation:

$$m_{\text{bare}} \quad = \quad Z_m\, m_{\text{renorm}}$$

Z_m and hence m_{renorm} depend on the renormalisation scheme !

Conventional choices:

- The $\overline{\text{MS}}$-scheme: The $\overline{\text{MS}}$-mass $m_{\overline{\text{MS}}}(\mu)$ is scale-dependent.
- The on-shell-scheme: The mass m_{pole} is defined as the pole of the propagator.

In perturbation theory one can convert between different schemes !

The precision and accuracy on the top mass

With increasing experimental precision, more theoretical issues become relevant:

- The top quark is neither stable nor a colour-singlet.
  - This re-introduces non-perturbative effects
  - The pole mass is ambigous by an amount $O(\Lambda_{\mathrm{QCD}})$.

    Bigi, Shifman, Uraltsev, Vainshtein, ’94, Beneke, ’94, Smith, Willenbrock, ’96, Skands, Wicke, ’07

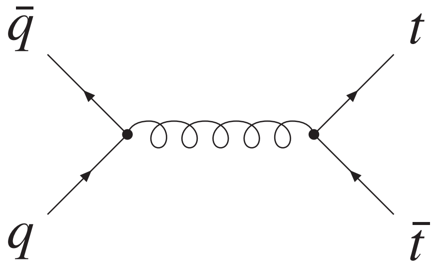
- Experimentally measured are the decay products of the top.
  - For top measurements based on reconstruction:
    The $\overline{\mathrm{MS}}$ mass distorts the Breit-Wigner shape.

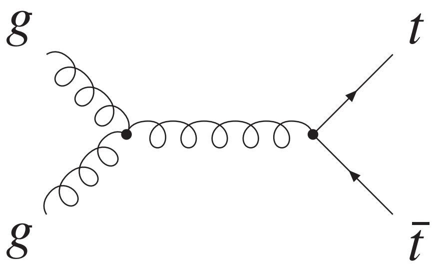
Solution: Carefully define a short-distance mass, insensitive to non-perturbative effects, and relate the experimental measurement to this short-distance mass.

Fleming, Hoang, Mantry, Stewart, ’07

Top-pair production

The leading-order Feynman diagrams:





The quark-antiquark channel dominates at the Tevatron,
while the gluon-gluon channel dominates at the LHC.

We are interested in the inclusive process

$$pp \quad \rightarrow \quad t\bar{t} + X$$

as well as the exclusive processes

$$pp \rightarrow t\bar{t} + 0 \text{ jets}, \quad pp \rightarrow t\bar{t} + 1 \text{ jet}, \quad pp \rightarrow t\bar{t} + 2 \text{ jets}, \quad \ldots$$

Status of NLO calculations

- $pp \to t\bar{t}$

  Nason, Dawson, Ellis, '88,

  Beenakker, Kuijf, van Neerven, Smith, '89,

- $pp \to t\bar{t} + 1$ jet

  Dittmaier, Uwer, S.W., '07,

  Melnikov, Schulze, '10

- $pp \to t\bar{t} + 2$ jets

  Bevilaqua, Czakon, Papadopoulos, Worek, '10

  sub-process $pp \to t\bar{t} + b\bar{b}$

  Bredenstein, Denner, Dittmaier, Pozzorini, '09,

  Bevilaqua, Czakon, Papadopoulos, Pittau, Worek, '09

$pp \to b\bar{b}W^+W^-$

Bevilaqua, Czakon, van Hameren, Papadopoulos, Worek, '10

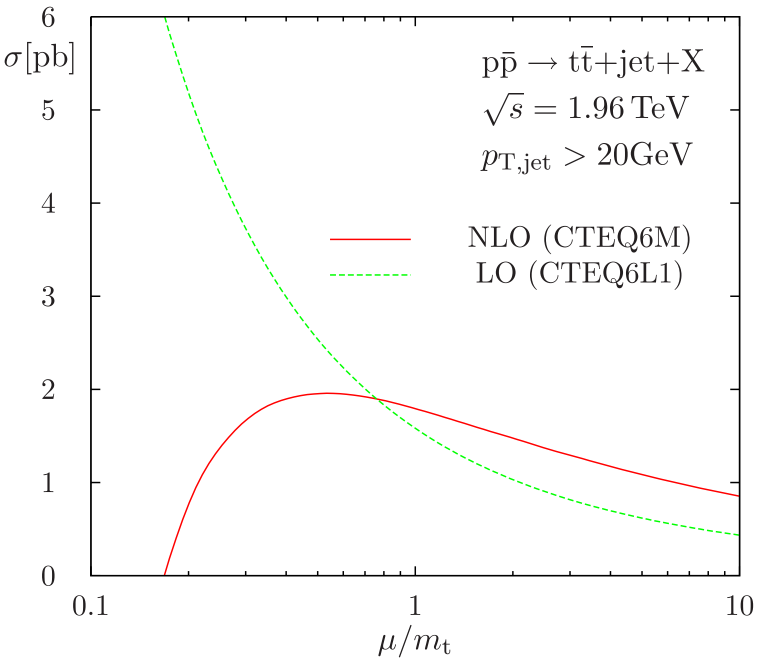
Denner, Dittmaier, Kallweit, Pozzorini, '10

Numerical results on $t\bar{t}+$ jet production

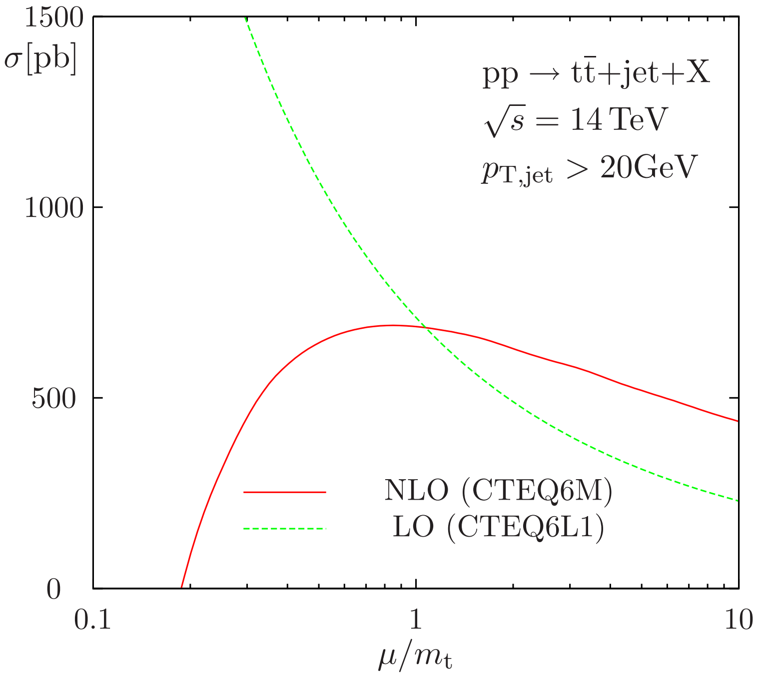
Dependence of the cross section on renormalisation and factorisation scale:

Leading order is proportional to α_s^3 !

Tevatron:



LHC:



Jet definition: $k_\perp$-algorithm with $R = 1$ applied to particles other than t or $\bar{t}$.

S. Dittmaier, P. Uwer and S.W., Phys.Rev.Lett.98:262002,2007

Status of NNLO calculations

The α_s^4-correction to $pp \to t\bar{t}$ requires

- The two-loop amplitudes $gg \to t\bar{t}$, $q\bar{q} \to t\bar{t}$

  Czakon, Mitov, Moch,

  Bonciani, Ferroglia, Gehrmann, Maitre, von Manteufel, Studerus

- The squared one-loop amplitudes $gg \to t\bar{t}$, $q\bar{q} \to t\bar{t}$

  Kniehl, Körner, Merebashvili, Rogal, ’08,

  Anastasiou, Aybat, ’08

- A method to handle the infrared divergences at NNLO,
  in particular initial state partons and massive partons.

  Bierenbaum, Czakon, Mitov,

  Boughezal, Daleo, Gehrmann, Gehrmann-De Ridder, Luisoni, Monni, Ritzmann,

  Glover, Pires

Top pair production at NNLO

Total inclusive cross section for $t\bar{t}$ production now known at NNLO.

Czakon, Fiedler, Mitov, 2013

- Two-loop integrals computed numerically
- Infrared singularities treated by sector decomposition
- Result combined with NNLL resummation, theoretical uncertainty estimated to be $\sim 3\%$

Resummation

In multi-scale problems there can be large logarithms in the perturbative expansion:

$$\alpha_s^n \ln^j \beta$$

Top-pair production in the threshold region

$$\beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$$

⇒ sum large logarithms to improve perturbation theory

In addition, Coulomb singularities of the form

$$\frac{1}{\beta^k}$$

NNLL resummation

Soft gluon resummation at next-to-next-to-leading logarithmic accuracy:

Moch, Uwer, '08,

Czakon, Mitov, Sterman, '09,

Kidonakis, '10,

Ahrens, Ferroglia, Neubert, Pecjak, Yang, '10,

Beneke, Falgari, Klein, Schwinn, '11

Can re-expand NNLL to obtain an "approximate NNLO" result.

Differences between the various groups:

- Exact definition of the resummation variable.
- Resummation of soft gluons only or also Coulomb terms ?
- Which scale dependent parts are included ?

NLO with parton showers

Parton showers are exclusive and resum large logarithms at LL accuracy.

Avoid double-counting when combining NLO calculations with parton showers: MC@NLO and POWHEG.

Frixione, Webber, ’02, Nason, ’04

Convenient tool: POWHEG-BOX

Alioli, Nason, Oleari, Re, ’10.

Recent application to $pp \to t\bar{t} + 1$ jet:

Kardos, Papadopoulos, Trocsanyi, ’11

Alioli, Moch, Uwer, ’11

Spin correlations

Within the Standard Model the top decays purely through left-handed weak decay.

In dilepton channel of top-pair production:
Correlation between top and anti-top spins transferred to leptons.

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_l d\cos\theta_{\bar{l}}} = \frac{1}{4}(1 - C\cos\theta_l\cos\theta_{\bar{l}})$$

$$\begin{aligned} C(\text{D0}) &= 0.1^{+0.45}_{-0.45} \\ C(\text{CDF}) &= 0.6 \pm 0.5 \pm 0.2 \quad \text{(EPS 2011)} \\ C(\text{Theory}) &= 0.777^{+0.027}_{-0.042} \end{aligned}$$

Mahlon, Parke, ’97,   Bernreuther, Brandenburg, Si, Uwer, ’04

The forward-backward asymmetry at the Tevatron

Forward-backward or charge asymmetry in $q\bar{q} \to t\bar{t}(+\text{jets})$

Origin: Interference of C-odd with C-even parts.

$q\bar{q} \to t\bar{t}$: asymmetry appears first at NLO (Kühn, Rodrigo '98).
A_{FB} @ NLO requires NNLO $p\bar{p} \to t\bar{t}$

$q\bar{q} \to t\bar{t} + \text{jet}$: asymmetry is LO effect (Halzen, Hoyer, Kim, ' 87, Bowen, Ellis, Rainwater, '05).
A_{FB} @ NLO can be deduced from NLO $p\bar{p} \to t\bar{t} + \text{jet}$.

The asymmetry for $t\bar{t}$ at the Tevatron

Lab frame:

$$\begin{aligned} A_{FB}(\text{CDF}) &= (15.0 \pm 5.5)\,\%, \\ A_{FB}(\text{Theory}) &= (5.8 \pm 0.9)\,\%, \end{aligned}$$

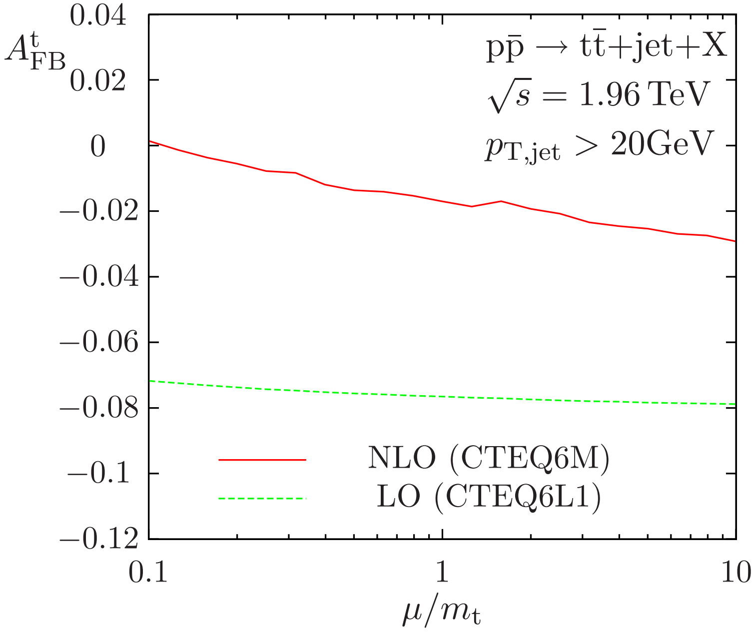
$t\bar{t}$ rest frame:

$$\begin{aligned} A_{FB}(\text{CDF}) &= (20.0 \pm 7.3)\,\%, \\ A_{FB}(\text{D0}) &= (19.6 \pm 6.5)\,\%, \\ A_{FB}(\text{Theory}) &= (8.7 \pm 1.0)\,\%, \end{aligned}$$

Theory status: LO QCD (from NLO $p\bar{p} \to t\bar{t}$)
electroweak corrections small Hollik, Kollar, '07, Bernreuther, Si, '10, Kühn, Rodrigo, '11,
soft gluon corrections small Kidonakis, '11, Ahrens, Ferroglia, Neubert, Pecjak, Yang, '11

There is a certain tension ...

The forward-backward asymmetry in $t\bar{t}+$ jet



$$\begin{aligned} \sigma^{\pm} &= \sigma(y_t > 0) \pm \sigma(y_t < 0), \\ A^{t}_{FB,LO} &= \frac{\sigma^{-}_{LO}}{\sigma^{+}_{LO}}, \\ A^{t}_{FB,NLO} &= \frac{\sigma^{-}_{LO}}{\sigma^{+}_{LO}} \left(1 + \frac{\delta\sigma^{-}_{NLO}}{\sigma^{-}_{LO}} - \frac{\delta\sigma^{+}_{NLO}}{\sigma^{+}_{LO}} \right). \end{aligned}$$

$(\mu = \mu_{ren} = \mu_{fact})$

- $A^{t}_{FB,LO} = O(\alpha_s^0)$, i.e. no dependence on μ_{ren}
  mild dependence on $\mu_{fact} \ll$ theoretical uncertainty !

- $A^{t}_{FB,NLO}$ depends on μ_{fact} and μ_{ren}
  asymmetry almost washed out by scale dependence.

Dittmaier, Uwer, S.W., ’07, Melnikov, Schulze, ’10

The charge asymmetry at the LHC

No forward-backward asymmetry in the lab frame at the LHC due to symmetric pp initial state.

But: t tend to follow initial q, while $\bar{t}$ tend to follow initial $\bar{q}$.

Initial q's tend to have a larger momentum fraction (valence-like) than initial $\bar{q}$'s (always sea quarks).

$\Rightarrow$ Rapidity distribution of t should be broader than the rapidity distribution of $\bar{t}$.

Complication: At the LHC $q\bar{q}$ initial state gives only a small fraction of the events, dominated by gg.

In view of the Tevatron results this measurement should be worth the effort !

The charge asymmetry at the LHC

Definition of the charge asymmetry:

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

LHC results:

$$\begin{aligned} A_C(\text{ATLAS}) &= (0.6 \pm 1.0)\,\%, \\ A_C(\text{CMS}) &= (0.4 \pm 1.5)\,\%, \\ A_C(\text{Theory}) &= (1.23 \pm 0.05)\,\%. \end{aligned}$$

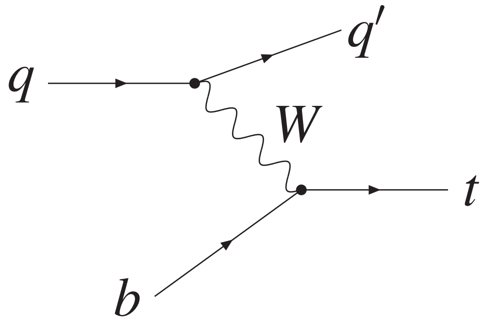
Consistent with Standard Model !

Related observables with enhanced sensitivity: incline asymmetry

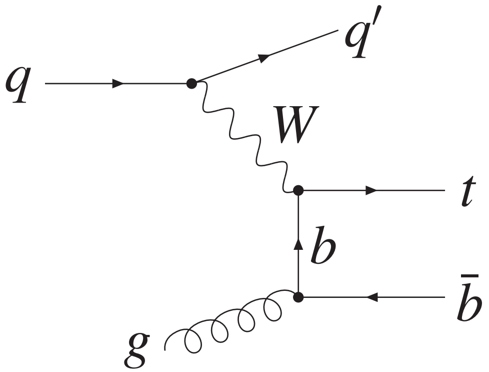
Berge, Westhoff, ’13

Single top production

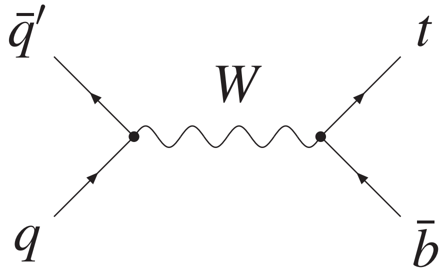
Top quark can also be produced singly by an electroweak Wtb-vertex:



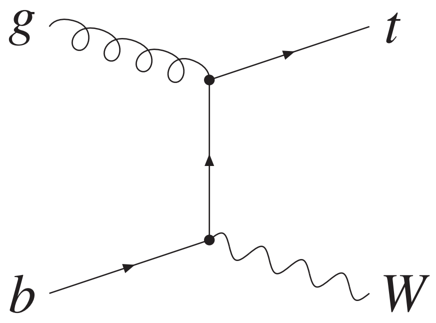
Flavour excitation



W-gluon fusion



s-channel



Associated W-production

Single top production

Physics motivation for single top production:

- Process sensitive to Wtb vertex.
  Non-standard couplings can give a hint on physics beyond SM.
- Direct measurement of CKM matrix element V_{tb}.
  Verification of unitarity of CKM matrix.
- The top quark is produced left-handed.
  Since no hadronization occurs, spin correlations survive in the final decay products.
- The flavour excitation channel can be used to extract the b-quark density.

Status of NLO calculations

- s-channel and t-channel:

  Stelzer, Sullivan, Willenbrock, '98, Harris, Laenen, Phaf, Sullivan, S.W., '02, Cao, Schwienhorst, Yuan, '04,

  Campbell, Ellis, Tramontana, '04, Campbell, Frederix, Maltoni, Tramontano, '09,

  Falgari, Giannuzzi, Mellor, Signer, '11

- Associated W-production:

  Campbell, Tramontana, '05, Frixione, Laenen, Motylinski, Webber, White, '08

- Resummation:

  Kidonakis, '10, Zhu, Li, Wang, Zhang, '10

- MC@NLO:

  Frixione, Laenen, Motylinski, Webber, '05

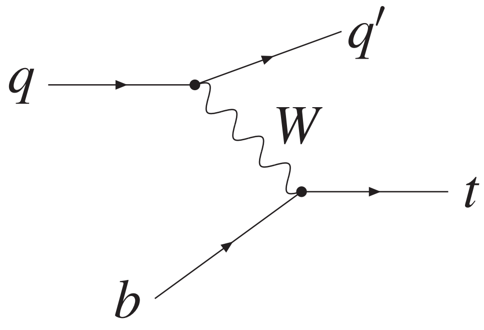
- POWHEG:

  Alioli, Nason, Oleari, Re, '09

Status of NNLO calculations

- t-channel:
  "DIS-squared" calculation,
  neglecting colour-supressed cross-talk
  between heavy- and light-quark line

  Brucherseifer, Caola, Melnikov, '14,



t-channel

The CKM matrix element V_{tb}

V_{tb} is known indirectly from unitarity

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

to a very high precision: $|V_{tb}| = 0.9990 - 0.9993$

No way to measure $|V_{tb}|$ directly to this precision !

Sideremark: From top-pair production at the Tevatron:

$$\frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.99^{+0.09}_{-0.08}$$

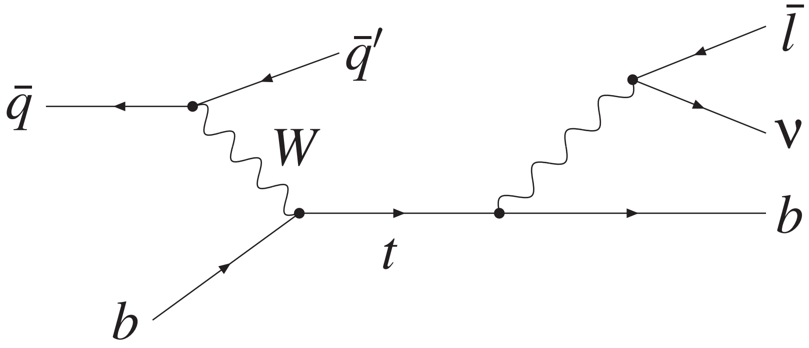
If we do not assume three generations, then it follows only

$$|V_{tb}| >> |V_{ts}|, |V_{td}|$$

Single top production: Direct measurement of $|V_{tb}|$ without any assumptions on the number of generations.

Spin correlations

At the electroweak Wtb-vertex the top quark is produced left-handed.



Since no hadronization occurs, spin correlations survive in the final decay products.

Of particular importance is the angle between the lepton $\bar{l}$ and the light-quark jet $\bar{q}'$.

Jezabek, Kühn, ’94

Mahlon, Parke, ’97

van der Heide, Laenen, Phaf, S.W., ’00

Angular correlations

In W-gluon fusion or flavour excitation the top quark is highly polarized along the direction of the $\bar{d}$-quark. In addition the u-quark density is the largest among the quark densities. Look at the quantity

$$a = \frac{1}{2}\left(1+\cos\theta_{q\bar{l}}\right)$$

where $\theta_{q\bar{l}}$ is the angle between the light quark jet and the charged lepton.

In the rest frame of the top:

$$\frac{d\sigma}{da} = \sigma\left(2Pa+(1-P)\right),$$

The slope of this distribution is given by

$$2P_{\mathrm{signal}}\sigma_{\mathrm{signal}}+2P_{\mathrm{background}}\sigma_{\mathrm{background}}$$

Outlook: $t\bar{t}$ in association with multiple jets at NLO

LHC experiments measure top pair production in association with several jets.

NLO predictions available for $t\bar{t}+0$ jets, $t\bar{t}+1$ jet and $t\bar{t}+2$ jets.

Higher jet multiplicities ? Can use numerical approach:

$$\begin{aligned}
\langle O\rangle^{\mathrm{NLO}}_{\mathrm{real}} &= \int\limits_{n+1} \left(O_{n+1}\, d\sigma^{\mathrm{R}} - O_n\, d\sigma^{\mathrm{A}}\right) \\
\langle O\rangle^{\mathrm{NLO}}_{\mathrm{virtual}} &= \int\limits_{n+\mathrm{loop}} \left(O_n\, d\sigma^{\mathrm{V}}_{\mathrm{bare}} - O_n\, d\sigma^{\mathrm{L}}\right) \\
\langle O\rangle^{\mathrm{NLO}}_{\mathrm{insertion}} &= \int\limits_{n} \left(O_n\, d\sigma^{\mathrm{V}}_{\mathrm{CT}} + O_n \int\limits_{\mathrm{loop}} d\sigma^{\mathrm{L}} + O_n \int\limits_{1} d\sigma^{\mathrm{A}} + O_n\, d\sigma^{\mathrm{C}}\right)
\end{aligned}$$

D. Mediger, J. Pečovnik, S.W., work in progress

Outlook: Analytic two-loop integrals with massive particles

Several two-loop integrals relevant to top physics are currently not known analytically.

Which functions with which arguments appear in the evaluation of these integrals?

Polylogarithms:

$$\text{Li}_m(x) = \sum_{j=1}^{\infty} \frac{x^j}{j^m}$$

Multiple polylogarithms:

$$\text{Li}_{m_1,m_2,...,m_k}(x_1,x_2,...,x_k) = \sum_{j_1>j_2>...>j_k>0}^{\infty} \frac{x_1^{j_1}}{j_1^{m_1}} \cdot \frac{x_2^{j_2}}{j_2^{m_2}} \cdot ... \cdot \frac{x_k^{j_k}}{j_k^{m_k}}$$

Elliptic polylogarithms:

$$\text{ELi}_{n;m}(x;y;q) = \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} \frac{x^j}{j^n} \frac{y^k}{k^m} q^{jk}$$

S. Bloch, P. Vanhove, ’13; L. Adams, Ch. Bogner, S.W., ’14

Summary

- Top physics is a very active field in theory.
- Top mass is very close to the electroweak symmetry breaking scale.
- The value of the top mass is essential for many precision measurements.
- Angular distributions are very interesting:
  - Spin correlations in top-pair production and single top.
  - Charge asymmetry at Tevatron and LHC.