Top Quark Interactions in Simplified Dark Matter Models

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Outline

- Top Quark Physics
  - Top Quark Production Mechanisms
- Simplified Dark Matter Models
  - Spin-0 Mediators
  - Spin-1 Mediators
- Conclusions and Outlook

Top Quark Physics

Top Quark in the SM

- First observed in 1995: Top quark pair production

  F. Abe et al., Phys. Rev. Lett. 74 (1995) 2626;

  S. Abachi et al., Phys. Rev. Lett., 74 (1995) 2632.

  Observed again in 2009: Single top quark production

  S. Abachi et al., Phys. Rev. Lett., 103 (2009) 092001;

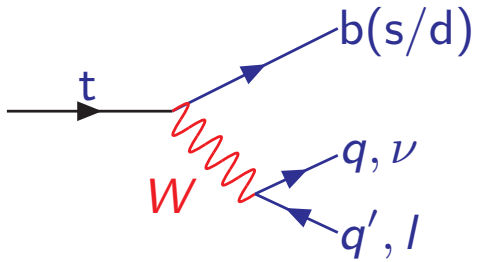
  T. A. Aaltonen et al., Phys. Rev. Lett. 103 (2009) 092002.

- It is the heaviest elementary particle in the SM ($m_t \approx 173$ GeV).

- Production ($1/m_{top}$) < Lifetime ($\tau_t \simeq 1/\Gamma_t \approx 5 \times 10^{-25}$s) < Hadronization ($\tau_{had} \simeq 1/\Lambda_{QCD} \approx 3 \times 10^{-24}$s) < Spin decorrelation (m_{top}/Λ^2).

- As a consequence, it is possible to measure t quark polarisation, spin correlations and $W^{\pm}$ boson helicity states by studying angular distributions of the decay products.

- $t \to Wb$ in the SM.



W decay	BR
$W \to l\nu$	0.32
$W \to qq'$	0.68

- It plays a very important role in the determination of the EWSB mechanism ($\lambda_t \sim 1$) and also in NP connected to the EWSB.

Some Top Quark Reviews:

W. Bernreuther, J. Phys. G35 (2008) 083001;

V. del Duca and E. Laenen, Int. J. Mod. Phys. A30 (2015) no. 35, 1530063;

U. Husemann, Prog. Part. Nucl. Phys. 95 (2017) 48-97;

M. Cristinziani and M. Mulders, J. Phys. G44 (2017) no. 6, 063001.

Top Quark Production Mechanisms

Top Quark Pair Production (at LO QCD)

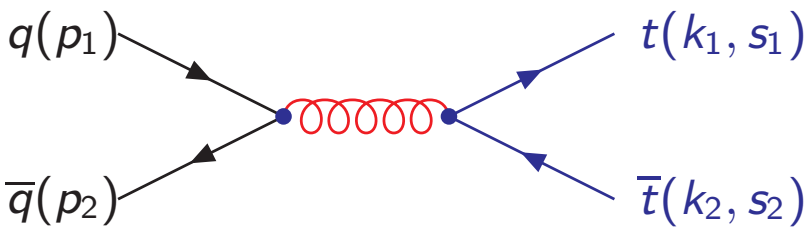
At leading order (LO) the partonic cross section for $t\bar{t}$ production is of order $\mathcal{O}(\alpha_s^2)$. The subprocesses that contribute to the cross section at this level are

M. Glück, J. F. Owens and E. Reya, Phys. Rev. D17 (1978) 2324;

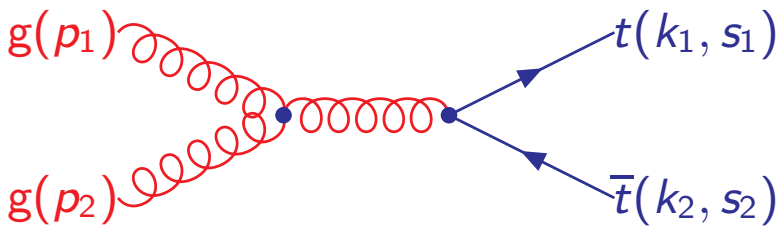
J. Babcock, D. Silvers and S. Wolfram, Phys. Rev. D18 (1978) 162;

H. Georgi et al., Ann. Phys. 114 (1978) 273.

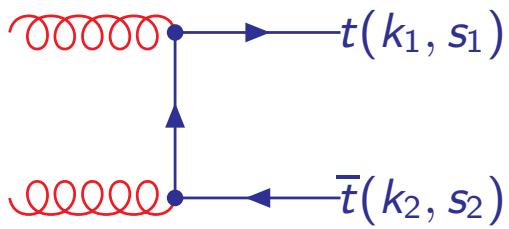
$q\bar{q}$ Annihilation



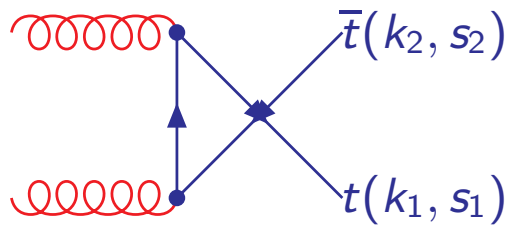
Gluon Fusion



s-channel



t-channel



u-channel

The differential cross section for the two particle scattering process can be written as

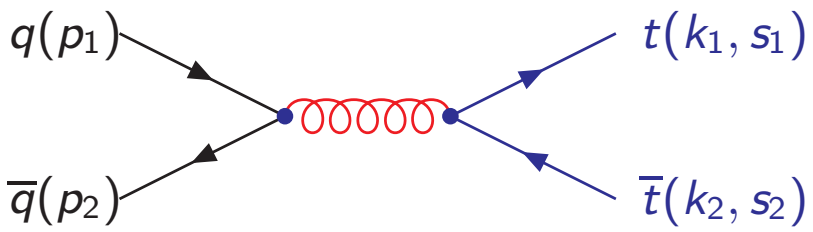
$$\frac{d\sigma}{dz} = \frac{\beta_t}{32\pi s}\overline{\sum}|\mathcal{M}(\hat{s}, m_t, z)|^2$$

with the spin and color averaged square matrix element, and where $z = \frac{\hat{u}-\hat{t}}{\hat{s}} = \cos\theta$, with θ being the scattering angle, and β_t is the top quark velocity defined by

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

W. Benakker, A. Denner, W. Hollik, T. Mertig, R. Sack and D. Wackeroth, Nucl. Phys. B (1994) 343

$q\bar{q}$ Annihilation

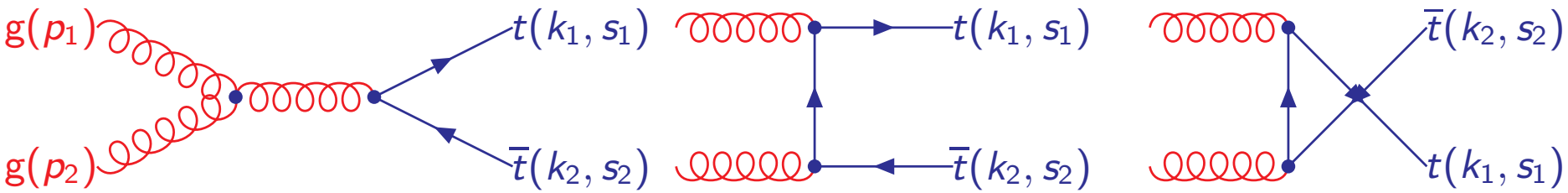


$$\overline{\sum}|\mathcal{M}_B^{q\bar{q}}|^2 = \frac{8}{9}\alpha_s^2\pi^2(2-\beta_t^2(1-z^2))$$

Integrating the differential cross section between the kinematical limits $-1 < z < 1$ we get the total cross section for the $q\bar{q}$ annihilation subprocess

$$\hat{\sigma}_B^{q\bar{q}}(\hat{s}) = \frac{4}{27}\frac{\alpha_s^2\pi\beta_t}{s}(3-\beta_t^2)$$

Gluon Fusion



s-channel **t-channel** **u-channel**

$$\overline{\sum}|\mathcal{M}_B^{gg}|^2 = \frac{\alpha_s^2\pi^2}{6}\frac{(7+9z^2\beta_t^2)}{(1-z^2\beta_t^2)^2}(1-z^4\beta_t^4+2\beta_t^2(1-z^2)(1-\beta_t^2))$$

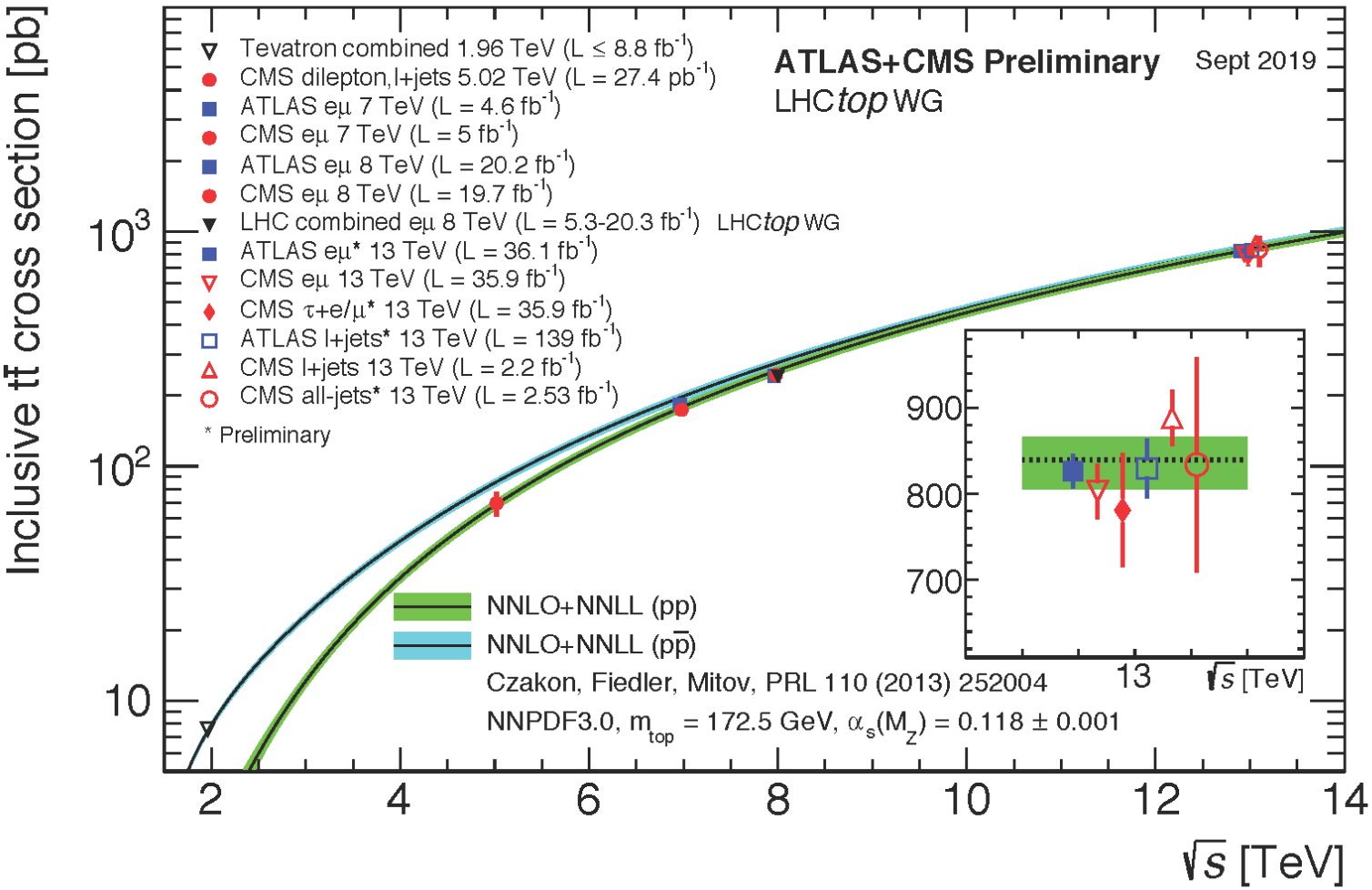
Integrating the differential cross section between the kinematical limits $-1 < z < 1$ we get the total cross section for the *gluon fusion* subprocess

$$\hat{\sigma}_B^{gg}(\hat{s}) = \frac{\alpha_s^2\pi}{96s}\left(\beta_t(-59+31\beta_t^2)+2(33-18\beta_t^2+\beta_t^4)\log\left(\frac{1+\beta_t}{1-\beta_t}\right)\right)$$

Top Quark Production at the Tevatron and LHC

	$q\bar{q} \to t\bar{t}$	$gg \to t\bar{t}$
Tevatron ($p\bar{p}$ at $\sqrt{s} = 1.96\ TeV$)	85%	15%
LHC (pp at $\sqrt{s} = 14\ TeV(\sqrt{s} = 7\ TeV)$)	10%	90%($\approx$ 80%)

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98 (2018) 030001



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

Single Top Quark Production

- The most important production process at hadron colliders is $t\bar{t}$, which is mediated by the strong interaction.
- Single top quarks (antiquarks) production is mediated by electroweak interactions.
- The single top quark signal is smaller than the $t\bar{t}$ signal and it is difficult to separate from the background.
- The single top quark production cross section is within an order of magnitude of top quark pair production.

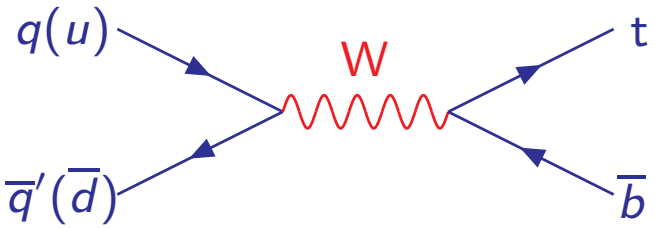
- $t \to Wb$ vertex in production and decay.
- Top is produced polarized, almost 100%.
- Cross sections are proportional to $|V_{tb}|^2$ in all channels.
- BSM physics can appear in cross sections and properties.

E. Boos and L. Dudko, Int. J. Mod. Phys. A27 (2012) 1230026;

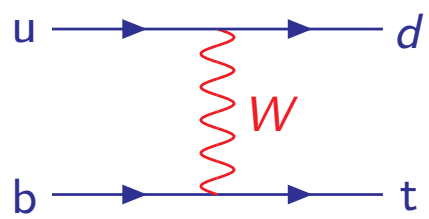
A. Giammanco and R. Schwienhorst, Rev. Mod. Phys. 90 (2018) no.3 035001;

Single Top Quark Production Channels

Electroweak single top quark production

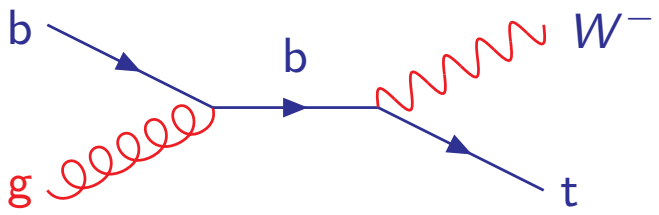


s-channel

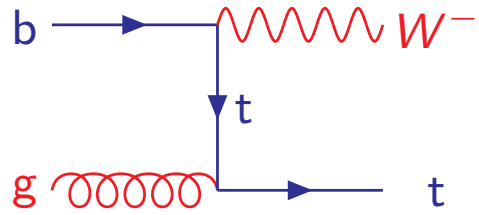


t-channel

Top - W boson

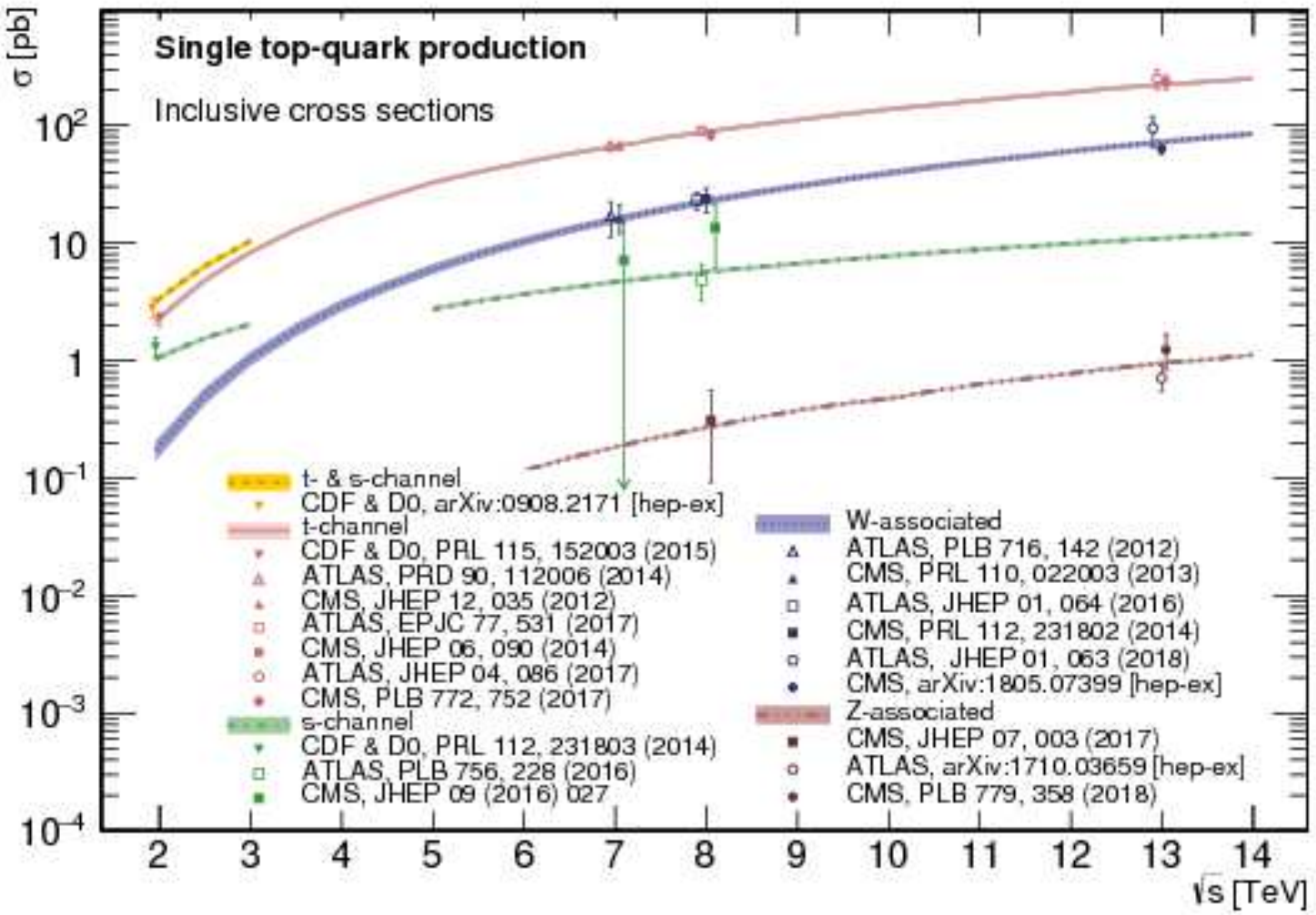


s-channel

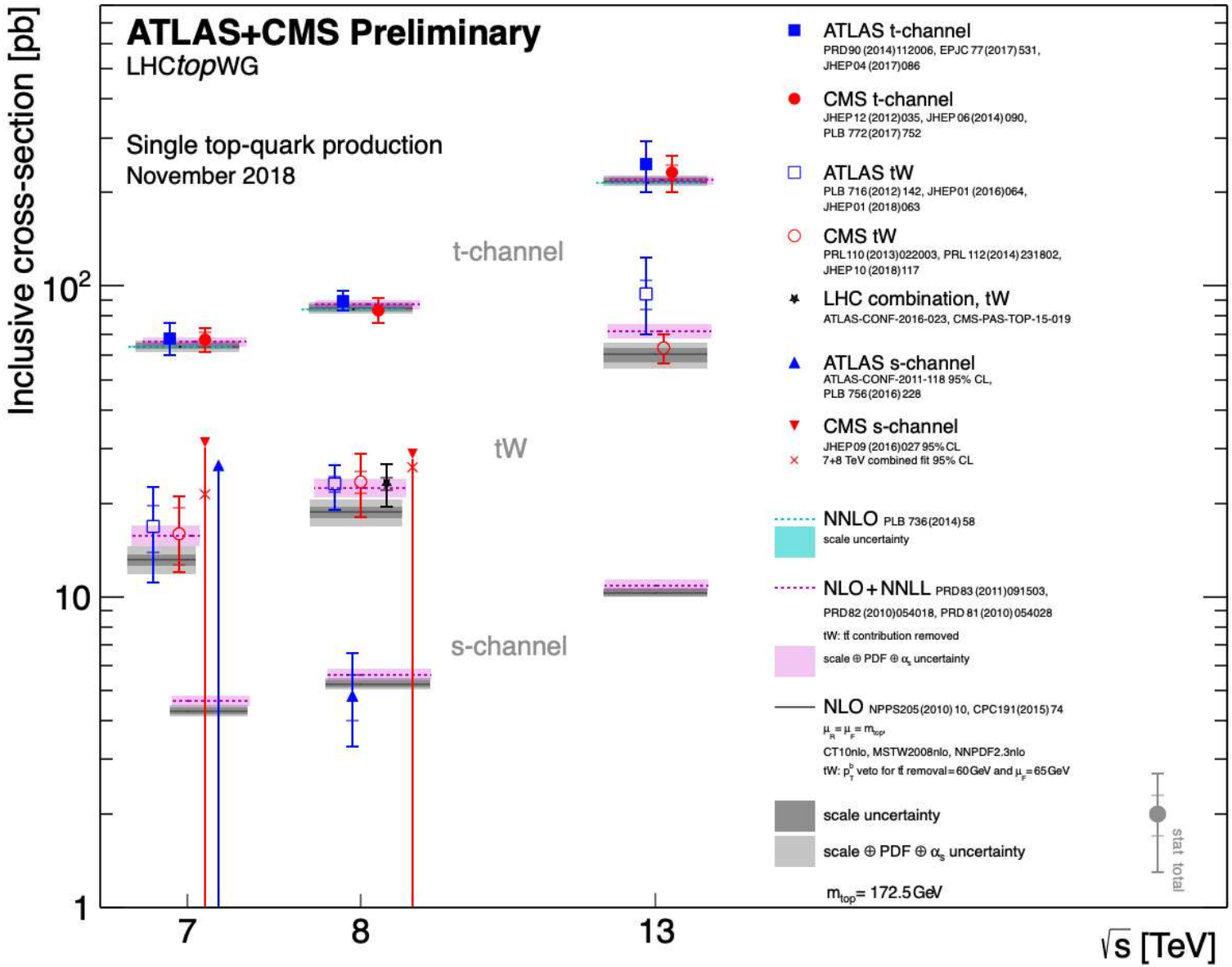


t-channel

Single Top Quark Production: Inclusive Cross Sections



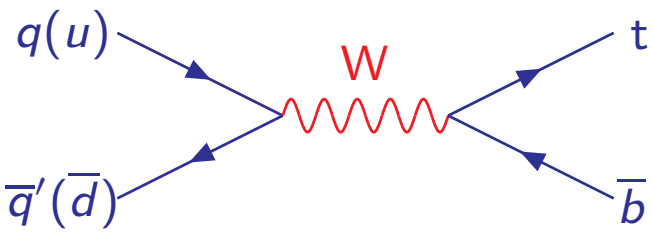
A. Giammanco and R. Schwienhorst, Rev. Mod. Phys. 90 (2018) 035001



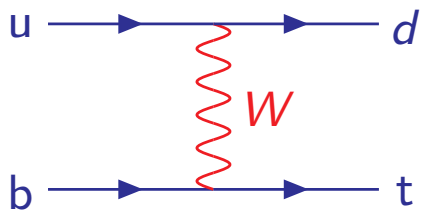
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

s-channel and t-channel: Spin Correlations

Spin correlations may appear when the top quark is highly polarized in its production and decay



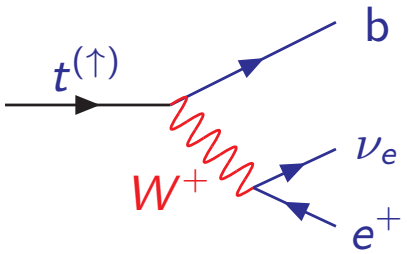
s-channel



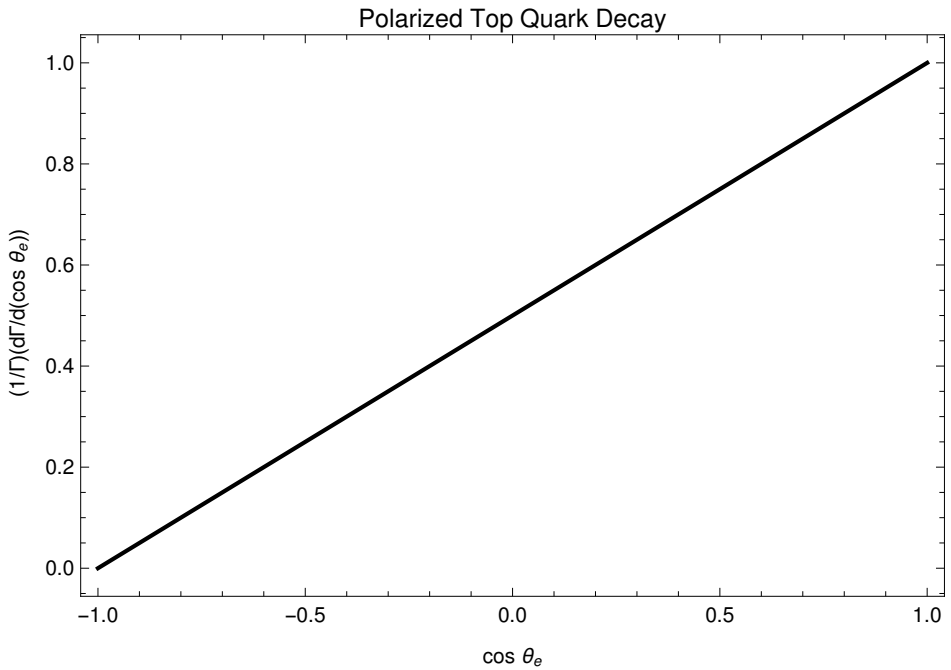
t-channel

Polarized Top Quark Decay

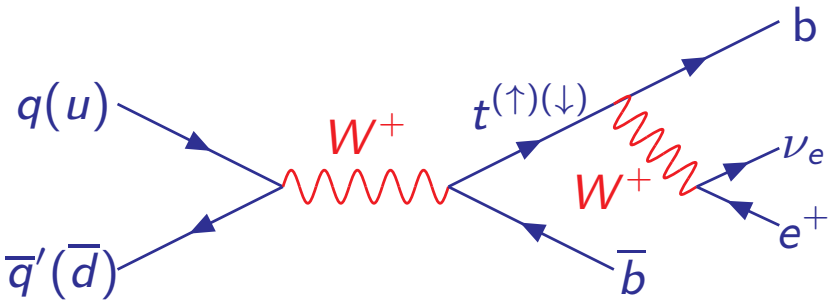
$t^{(\uparrow)} \to b\nu_e e^+$ in the SM.



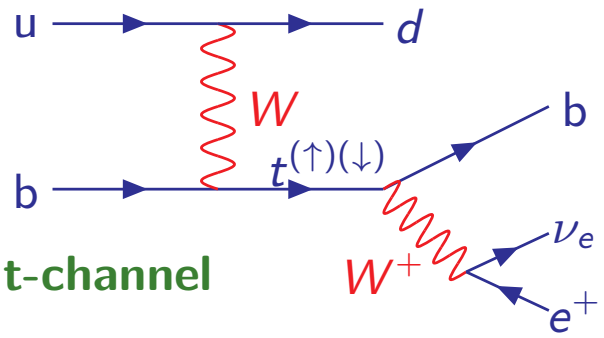
$$\frac{1}{\Gamma_T}\frac{d\Gamma_{t^{(\uparrow)}}}{d(\cos\theta_{e^+})} = \frac{1}{2}(1+\cos\theta_{e^+})$$



Single Top Quark Production and Decay



s-channel



t-channel

We define the spin asymmetry factor $A_{\uparrow\downarrow}$ as

$$A_{\uparrow\downarrow} = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

which defines the size of the observable angular correlations when there is a mixture of spin up and spin down top quarks.

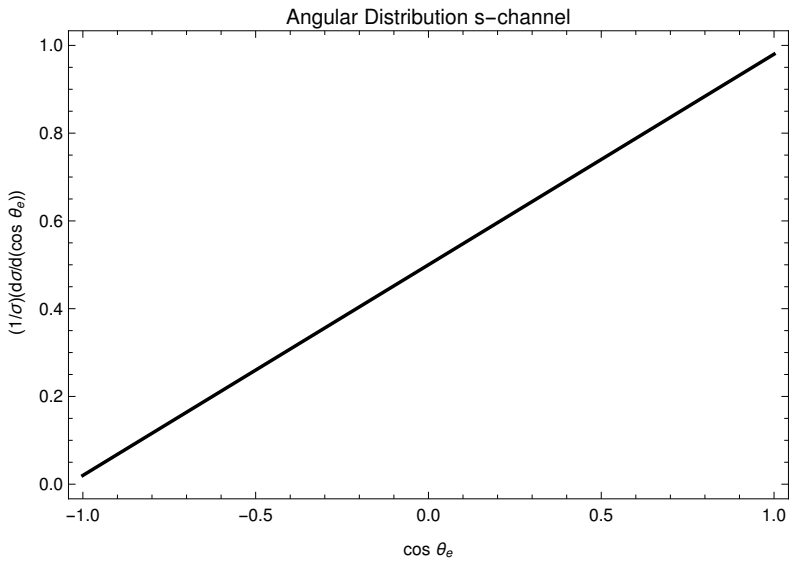
Angular distributions are linear in the cosine of the decay angles:

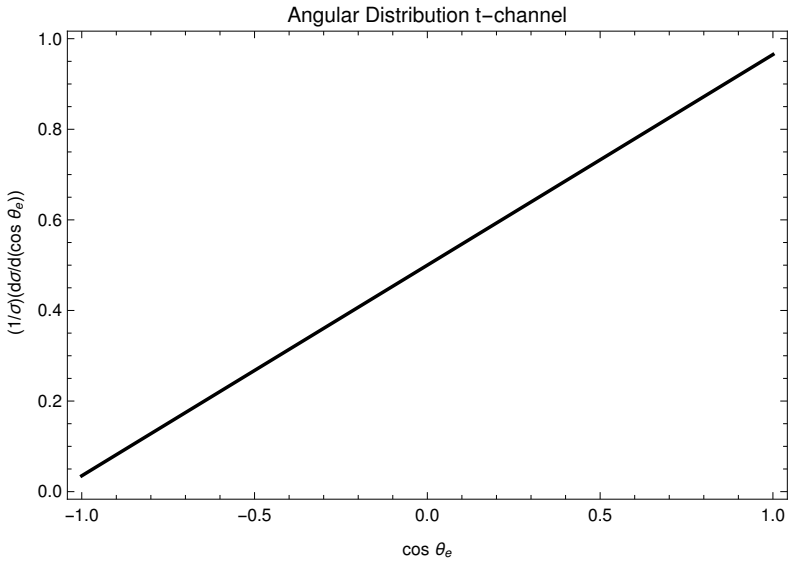
$$\frac{1}{\sigma_T}\frac{d\sigma_T}{d(\cos\theta_{e^+})} = \frac{1}{2}(1 + A_{\uparrow\downarrow}\cos\theta_{e^+})$$

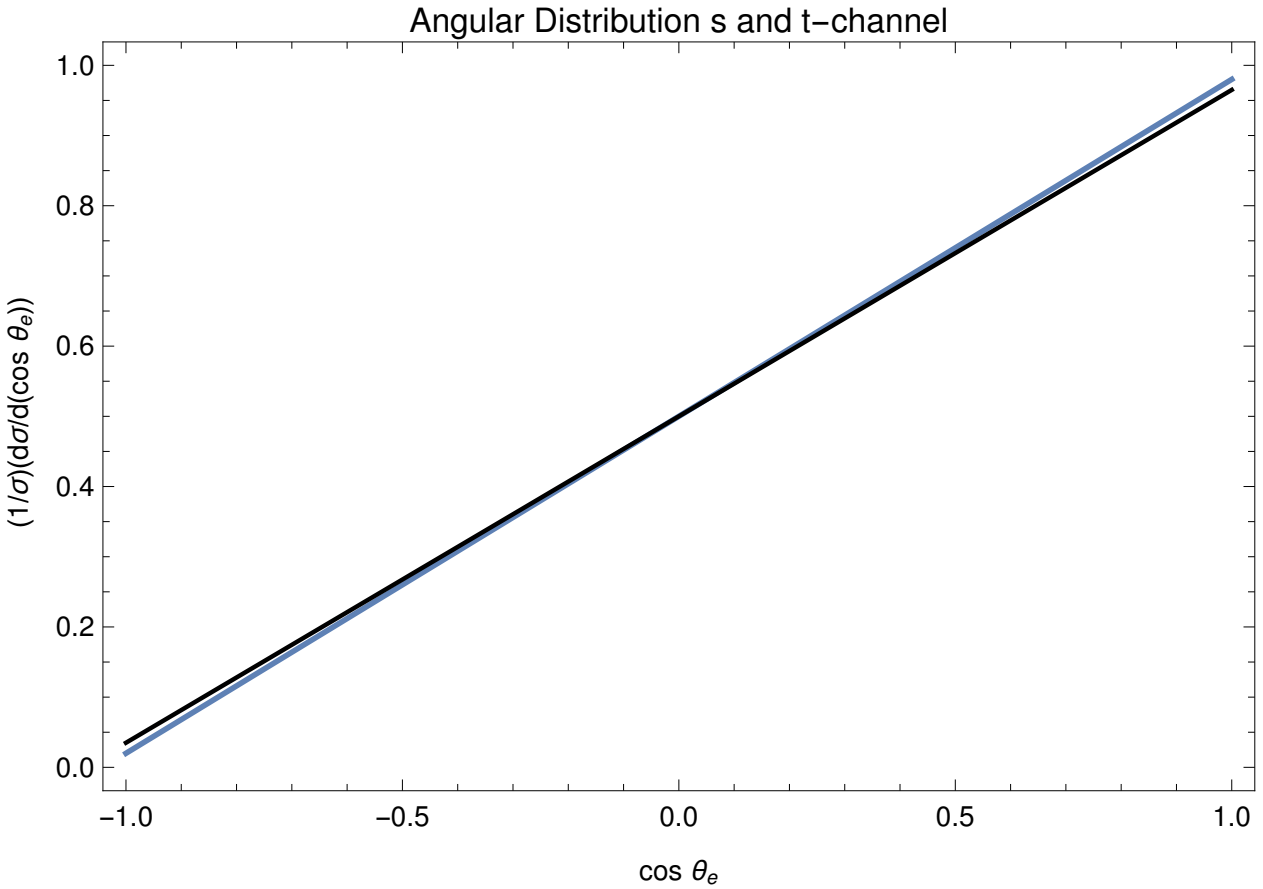
G. Mahlon, arXiv:hep-ph/0011349v1

For the s-channel, θ_{e^+} is the angle between the momenta of the outgoing positron and the incoming $\overline{d}$ ($A_{\uparrow\downarrow} = 0.96$).

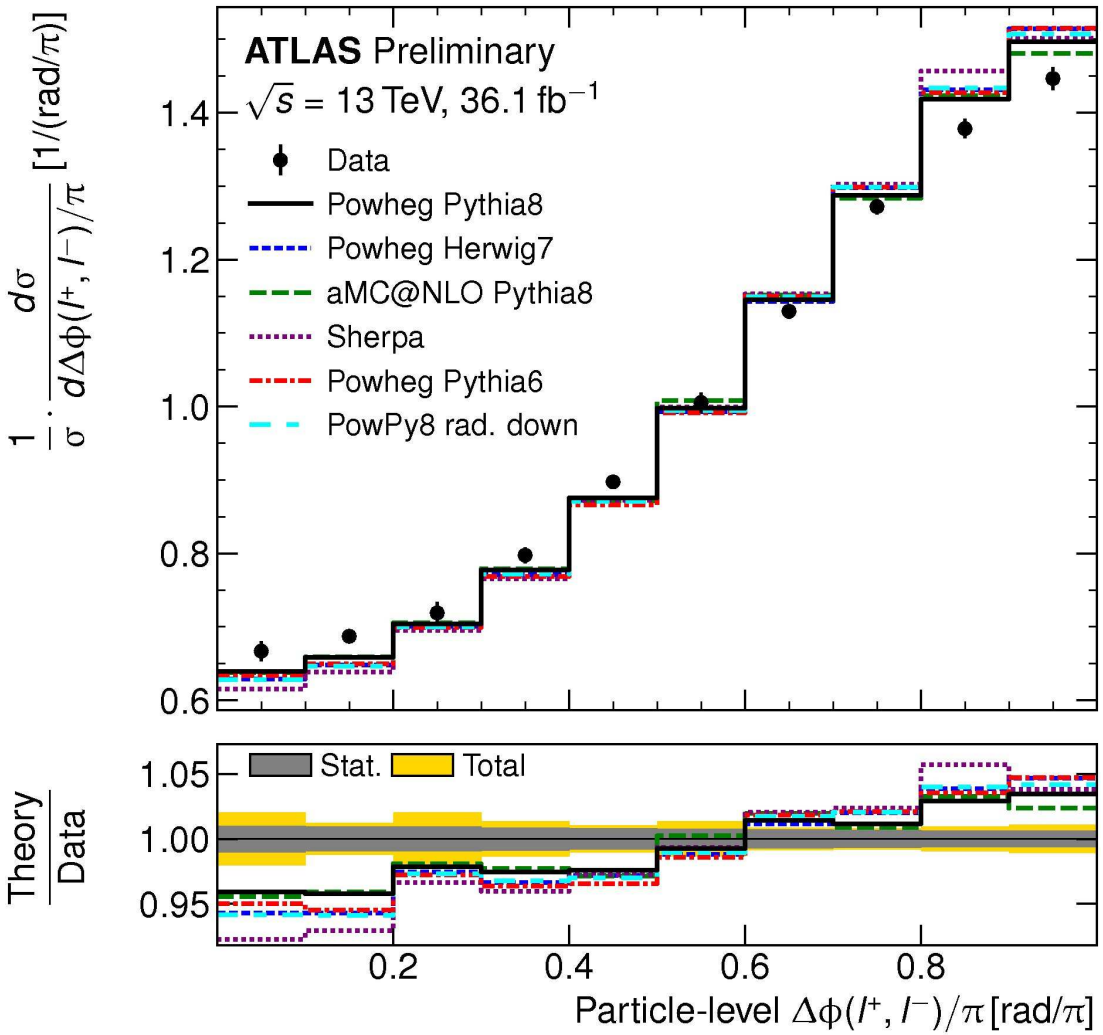
For the t-channel, θ_{e^+} is the angle between the momenta of the outgoing positron and the outgoing d quark ($A_{\uparrow\downarrow} = 0.93$).






Angular Distribution s and t−channel
1.0
0.8
0.6
0.4
0.2
0.0
(1/σ)(dσ/d(cos θe))
−1.0
−0.5
0.0
0.5
1.0
cos θe

Top Quarks as Probes of New Physics



ATLAS Collaboration. Jul 5, 2018. ATLAS-CONF-2018-027

Simplified Dark Matter Models

Dark Matter

- The nature of the dark matter (DM) is a fundamental open question in physics.
- Its discovery is an important goal of the LHC.
- Potential interactions between DM and SM particles.
- A viable DM candidate must be:
  - electrically neutral
  - stable
  - weakly interacting
  - decay lifetime larger than the age of the Universe

Dark Matter

- DM is invisible at the LHC: Experimental signature of DM production at colliders is an event with a visible final state object recoiling against E_t^{miss} associated with DM.

- Simplified Models have few assumptions about DM and a minimal particle content.

  D. Pinna et al., Phys. Rev. D96 (2017) 035031;

  P. Pani and G. Polesello, Phys. Dark Univ. 21 (2018) 8;

  CMS Collaboration. 2018. CMS-PAS-EXO-18-010.

- Associated production of DM with top quarks may affect the spin correlations.

Simplified Dark Matter Models: Spin-0 Mediators

The Lagrangian with the interactions between SM particles and DM (χ, Dirac fermions) mediated by a massive electrically neutral scalar or pseudoescalar φ, is given by

$$\mathcal{L}_{\varphi} \supset g_{\chi}\varphi\overline{\chi}\chi + \frac{g_{\upsilon}\varphi}{\sqrt{2}}\sum_{f}(y_f\overline{f}f)$$

$$\mathcal{L}_{A} \supset ig_{\chi}A\overline{\chi}\gamma^5\chi + \frac{ig_{\upsilon}A}{\sqrt{2}}\sum_{f}(y_f\overline{f}\gamma^5 f)$$

where $y_f = \sqrt{2}m_f/\upsilon$ are the Yukawa couplings, with $\upsilon = 246$ GeV, g_{χ} is the DM mediator coupling and g_{υ} is the fermion mediator coupling. Minimal set of four free parameters (with MFV): m_{χ}, m_{φ}, g_{χ} and g_{υ}.

D. Pinna et al., Phys. Rev. D96 (2017) 035031;

D. Abercrombie et al., arXiv:1507.00966;

M. R. Buckley, D. Feld and D. Goncalves, Phys. Rev. D91 (2015) 015017.

The decay width of the scalars is

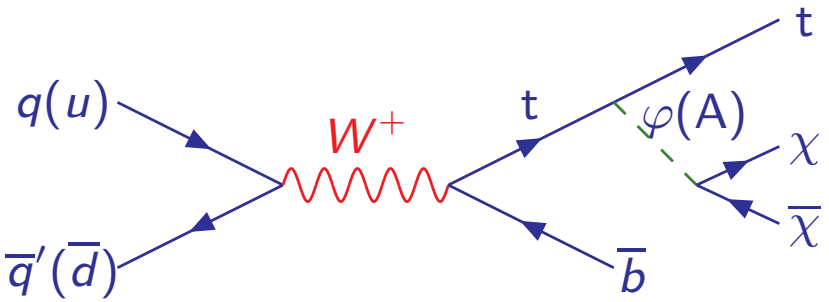
$$\Gamma_\varphi = \frac{g_\chi^2 m_\varphi}{8\pi}\left(1-\frac{4m_\chi^2}{m_\varphi^2}\right)^{n/2} + \sum_f \frac{g_\upsilon^2 y_f^2 m_\varphi}{16\pi}\left(1-\frac{4m_f^2}{m_\varphi^2}\right)^{n/2}$$

D. Pinna et al., Phys. Rev. D96 (2017) 035031;

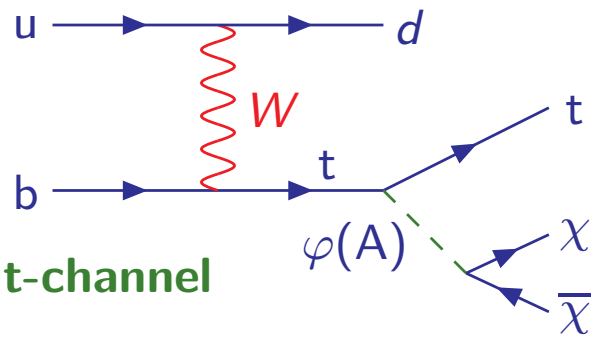
D. Abercrombie et al., arXiv:1507.00966;

M. R. Buckley, D. Feld and D. Goncalves, Phys. Rev. D91 (2015) 015017.

Dark Matter and Single Top Quark Production

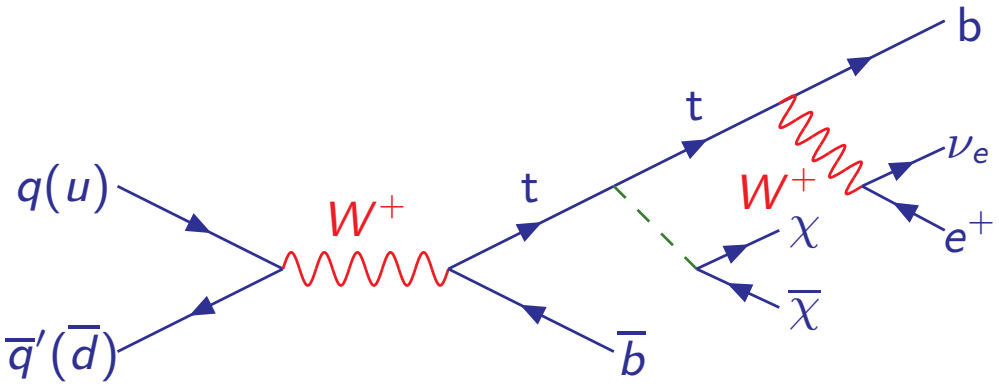


s-channel

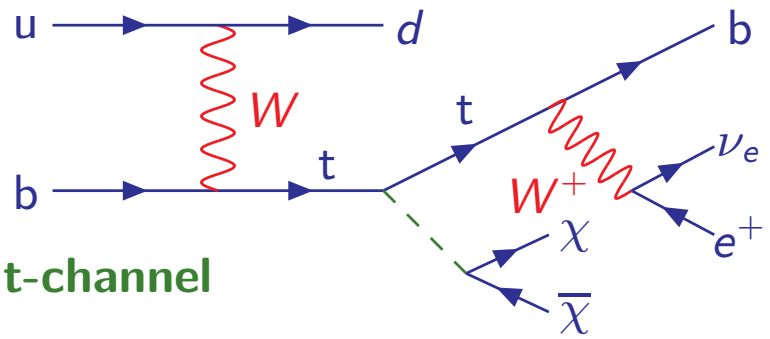


t-channel

Dark Matter and Single Top Quark Production and Decay



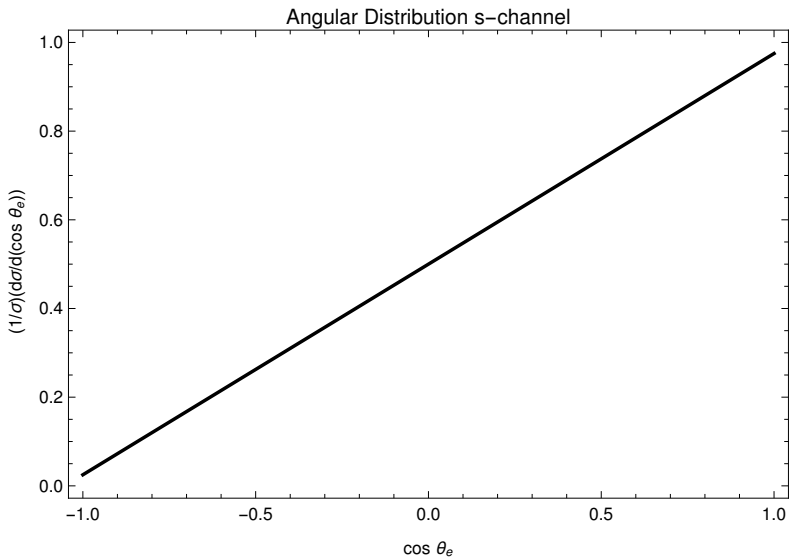
s-channel

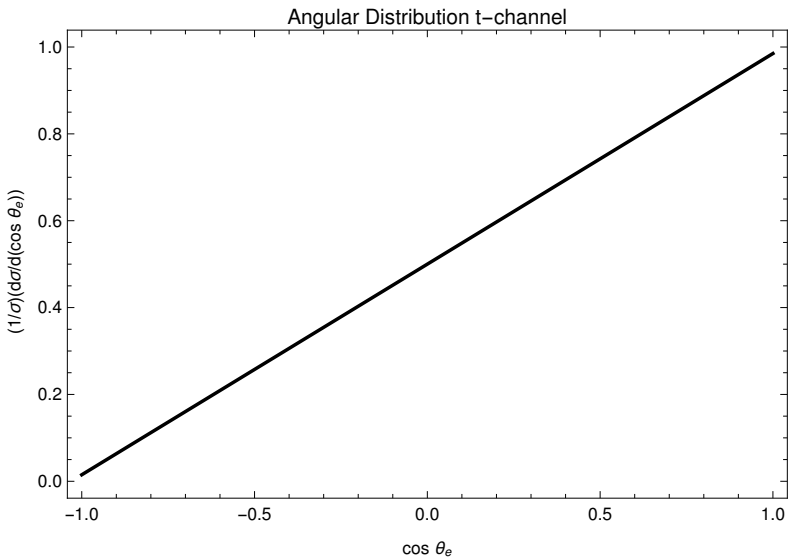


t-channel

For the s-channel, θ_{e^+} is the angle between the momenta of the outgoing positron and the incoming $\overline{d}$.

For the t-channel, θ_{e^+} is the angle between the momenta of the outgoing positron and the outgoing d quark.





Simplified Dark Matter Models: Spin-1 Mediators

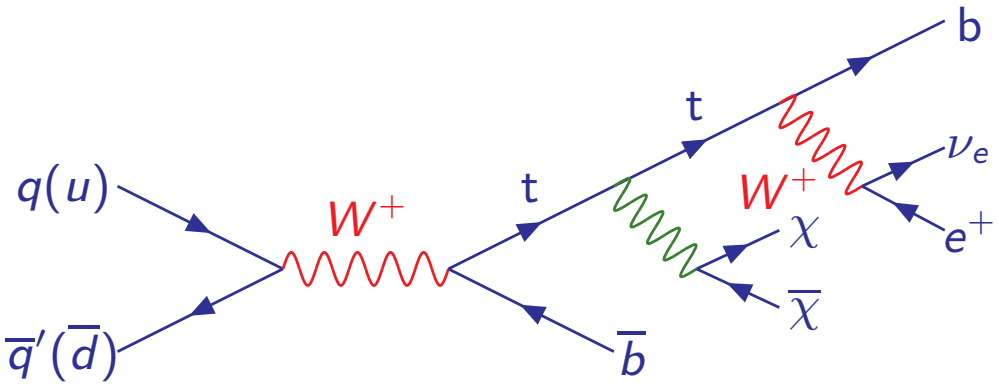
The Lagrangian with the interactions between SM particles and DM (χ, Dirac fermions) mediated by a spin-1 particle, is given by

$$\mathcal{L}_V \supset V_\mu \overline{\chi}\gamma^\mu(g_\chi^V - g_\chi^A)\chi + \sum_{f=q,l,\nu} V_\mu \overline{f}\gamma^\mu(g_f^V - g_f^A\gamma_5)f\,,$$

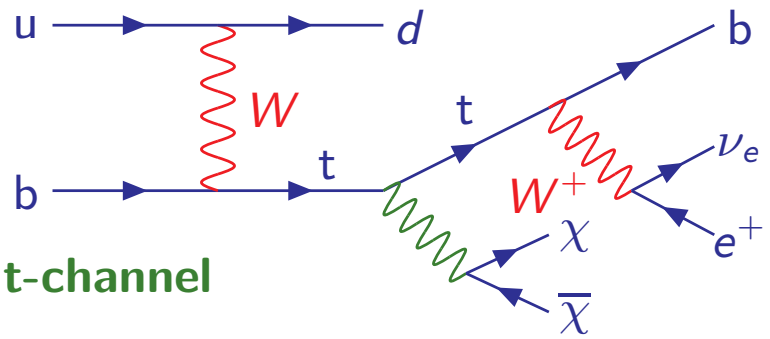
Minimal set of six free parameters (with MFV): m_χ, M_V, g_χ^V, g_u^V, g_d^V and g_l^V.

J. Abdallah et al., Phys. Dark. Univ. 9-10 (2015) 8-23.

Dark Matter and Single Top Quark Production and Decay



s-channel



t-channel

Conclusions and Outlook

- A detailed MC study is needed to study in detail effects that could be observed.
- A detailed study of the spin correlations in DM production in association with a single top quark at the LHC is in progress.