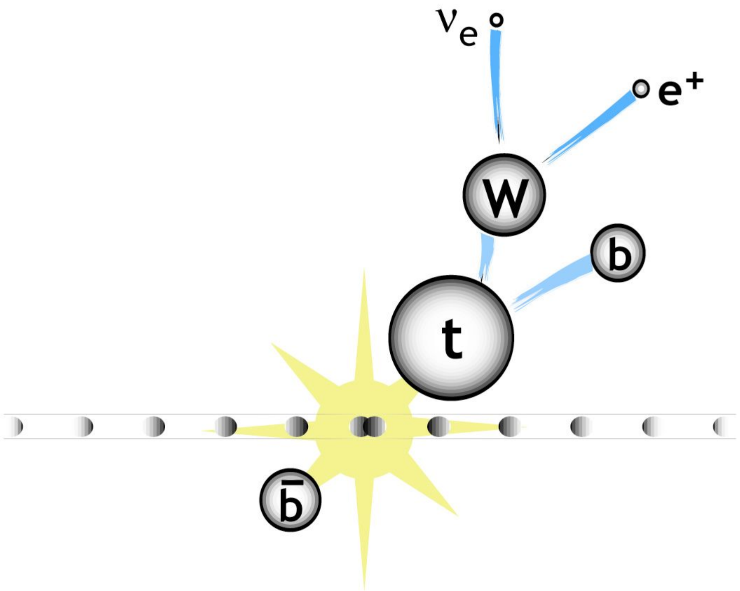
Top-Quarks am LHC: das Standardmodell auf dem Prüfstand

Challenging the Standard Model with top quarks

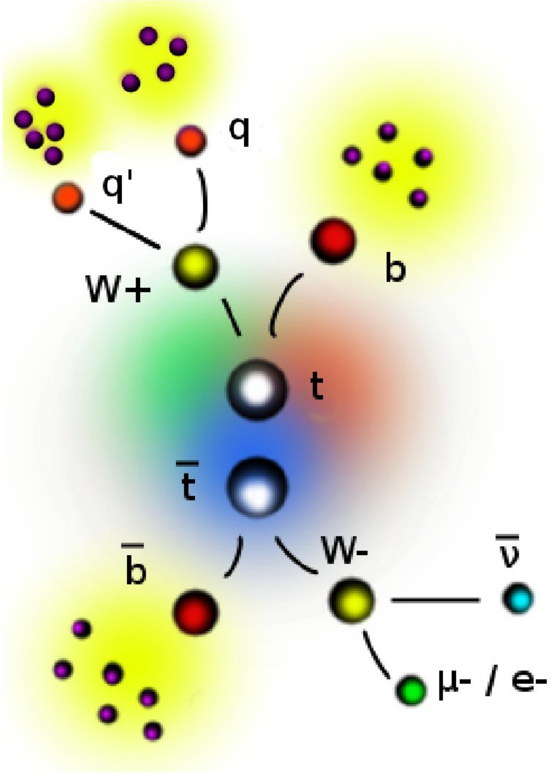
Wolfgang Wagner
Bergische Universität Wuppertal
und ATLAS-Kollaboration

Seminar am Karlsruher Institut für Technologie
14. Januar 2020

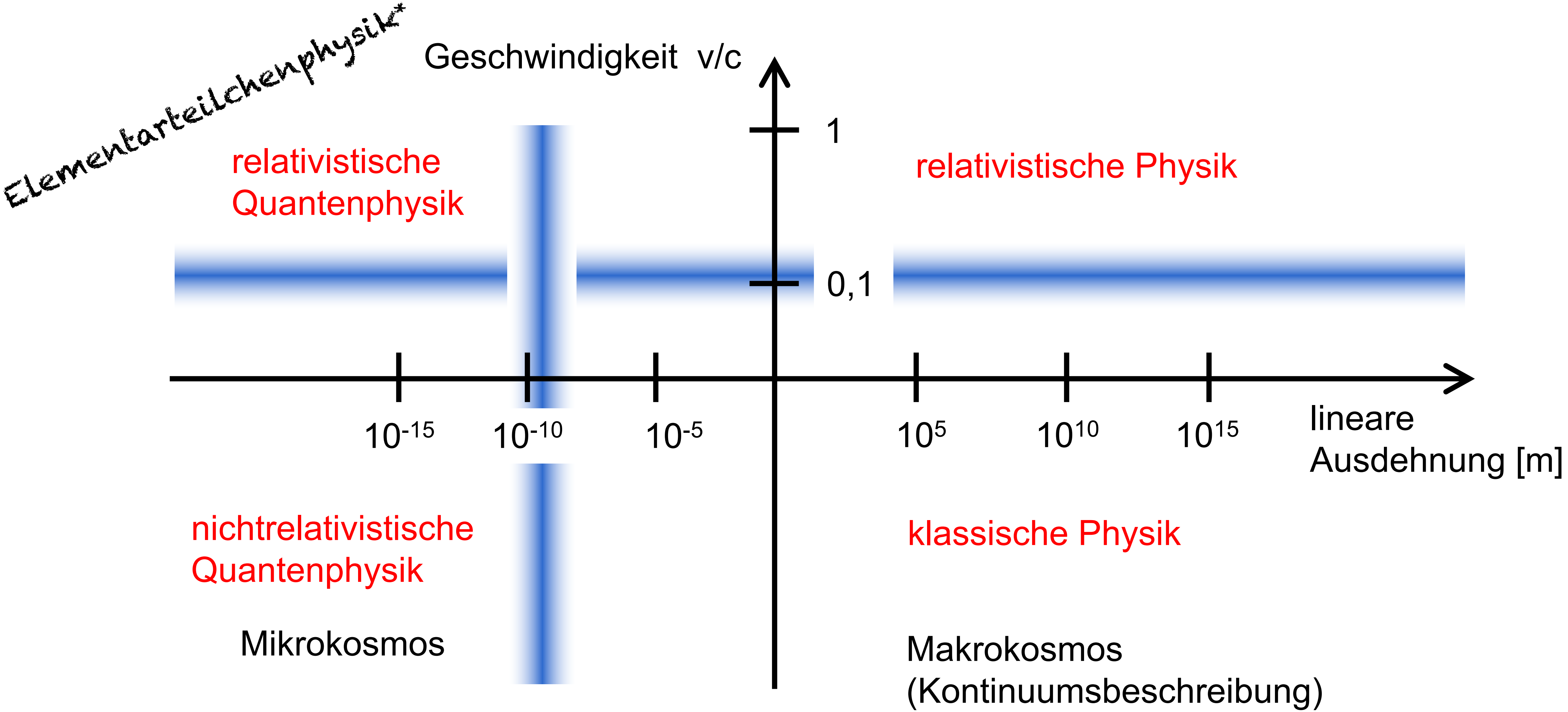


Überblick

1) Die Rolle des Top-quarks im Standardmodell (SM)
2) Der Large Hadron Collider und der ATLAS-Detektor
3) Direkte Suchen nach neuen Teilchen
4) Indirekte Suchen / Suchen nach anomalen Kopplungen
5) Präzisionsmessungen von Top-Quark-Eigenschaften



Die Elementarteilchenphysik im Kosmos der Physik



relativistische Quantenphysik

relativistische Physik

nichtrelativistische Quantenphysik

klassische Physik

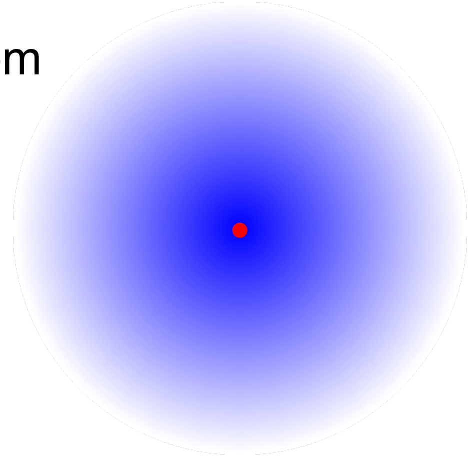
Mikrokosmos

Makrokosmos (Kontinuumsbeschreibung)

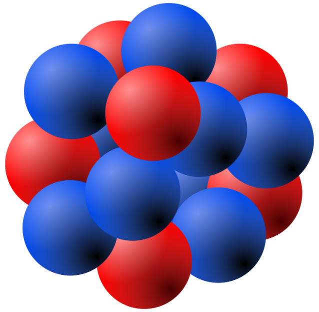
* Wichtig für das Verständnis des frühen Universums.

Streuexperimente als Weg zur subnuklearen Physik

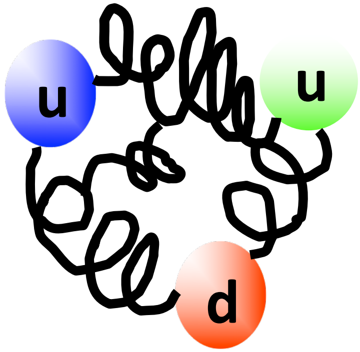
Atom



Atomkern



Proton



Quarks und Leptonen

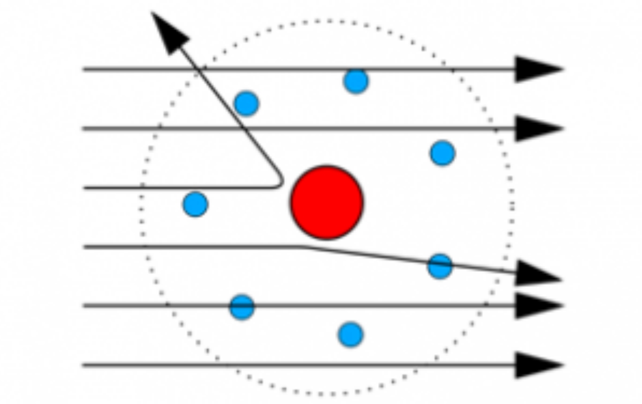
Unteilbar und strukturlos

lineare Ausdehnung [m]

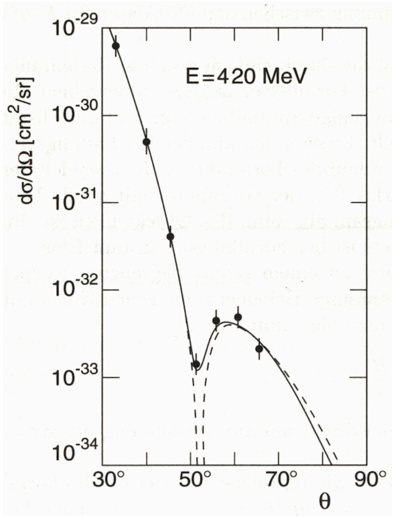
10^{-10}

10^{-15}

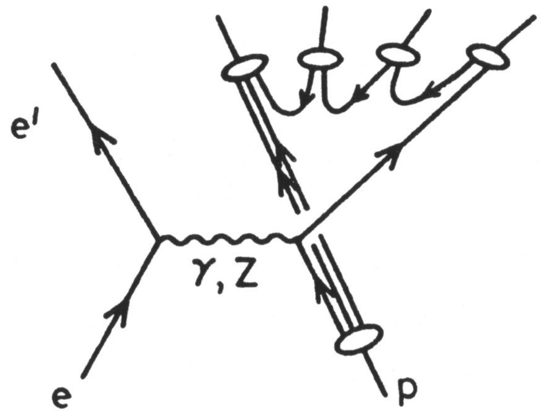
10^{-18}



Rutherforscher Streuversuch



Elastische Streuung von Elektronen an Atomkernen



Tiefinelastische ep-Streuung

Quarks and leptons

Q_{em}			
$= +\frac{2}{3}\,e$	Up	Charm	**Top**
$= -\frac{1}{3}\,e$	Down	Strange	Bottom

- „Matter fields“
- Structureless, point-like.
- Fermions, carry spin $\frac{1}{2}$

- Quarks carry electric, weak and colour charge.
- Quarks form bound states: hadrons.
- Quarks do not exist as free particles (except for the top quark).

Q_{em}			
$= 0$	ν_e	ν_μ	ν_τ
$= -\,e$	Elektron	Myon	Tauon

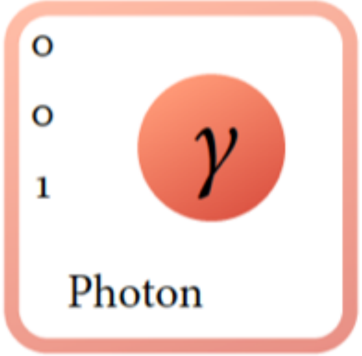
The Standard Model: a theory of interactions

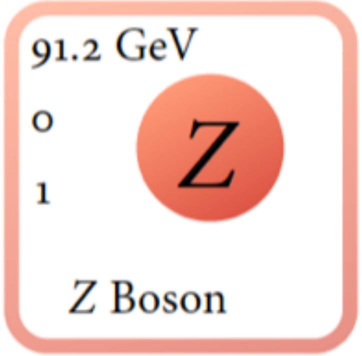
Most remarkable feature of the SM:

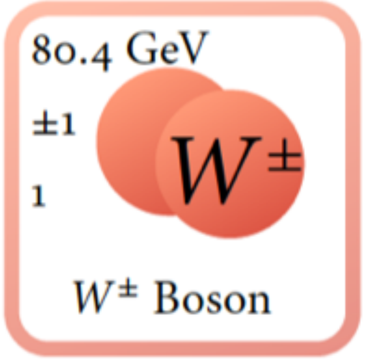
Interactions (gauge fields) are predicted / derived as a consequence of local gauge symmetry!

$$\psi \longrightarrow \exp\big(i\,\vec{\theta}(x_\mu)\cdot\vec{a}\big)\,\psi \qquad \lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \ldots$$

Gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$





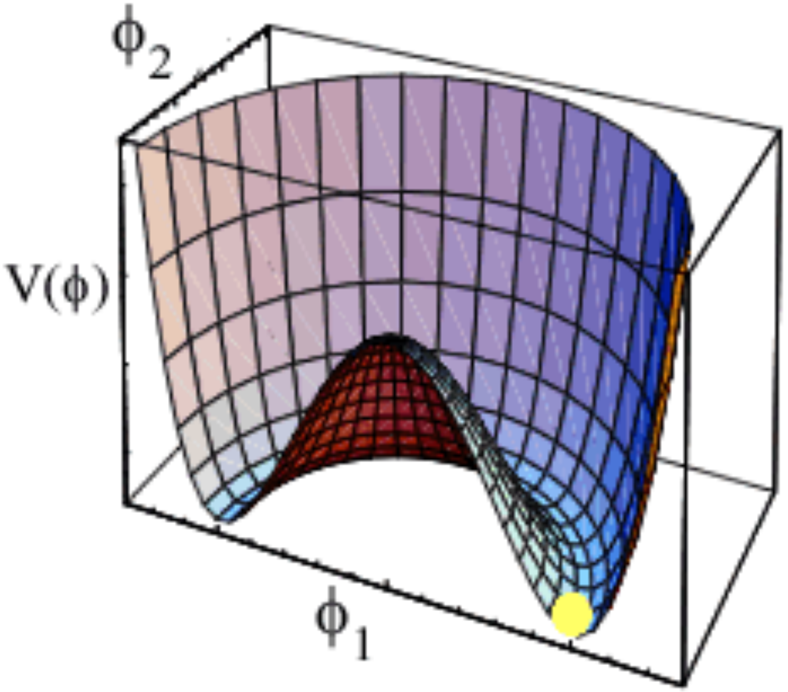


Gauge bosons mediate interactions

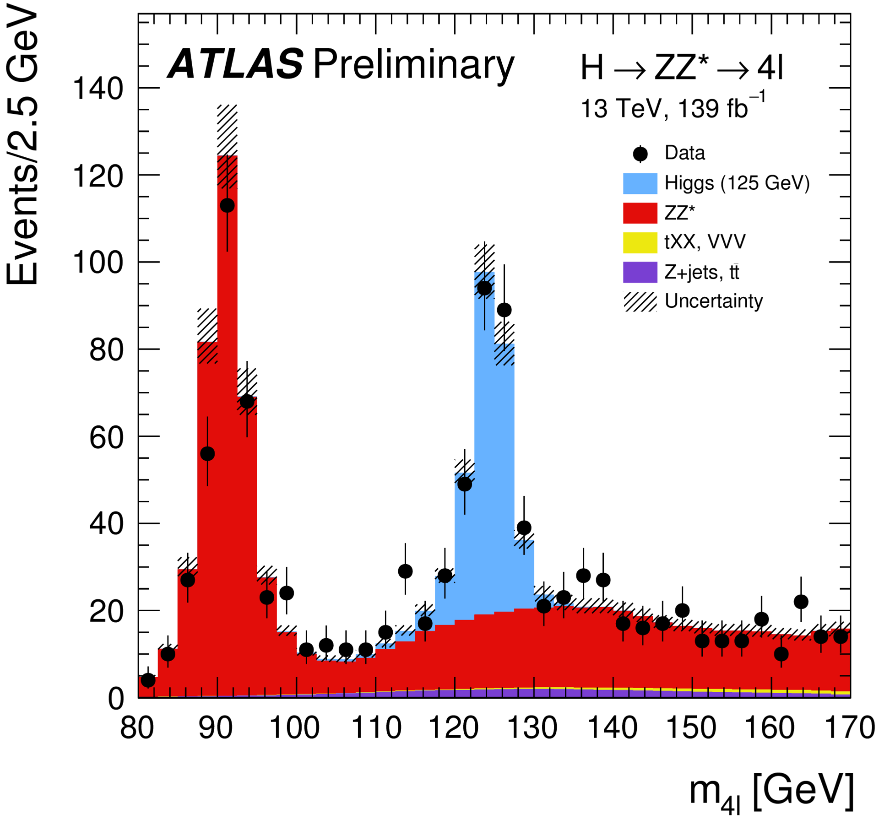
The Higgs boson

Potential of the Higgs field

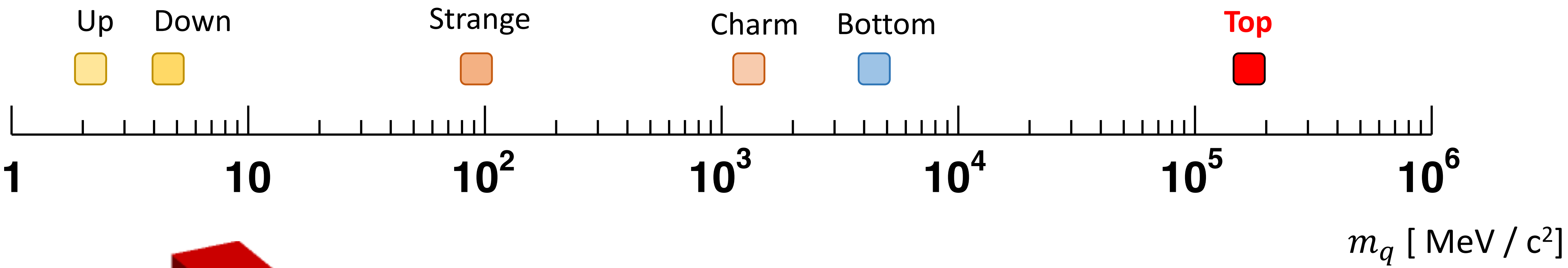
$$V(\phi) = \frac{1}{2}\mu^2\phi^\dagger\phi + \frac{1}{4}\lambda\left(\phi^\dagger\phi\right)^2$$

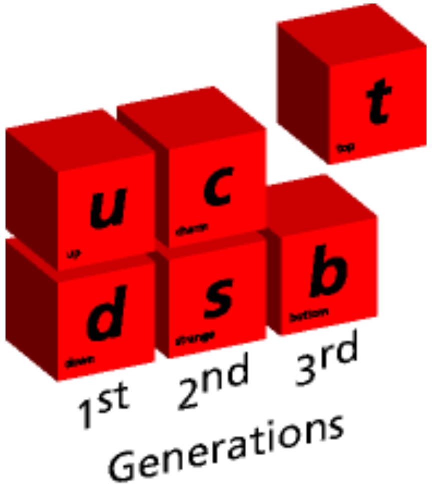


Discovery of the Higgs boson in 2012 and subsequent measurements confirm the Brout-Englert-Higgs mechanism as the source of the mass of elementary particles.



The top quark





- Weak-isospin partner of the *b*-quark.
- Charge: +2/3 e
- Spin: ½
- By far the heaviest elementary particle: $m_t = 172.7 \pm 0.5$ GeV/c²

  0,3% precision!

  → large loop corrections

- Coupling to the Higgs boson: $y_t \approx 1$

- No bound states: $$\tau_{\text{top}} \propto \left(\frac{M_W}{M_{\text{top}}}\right)^3$$

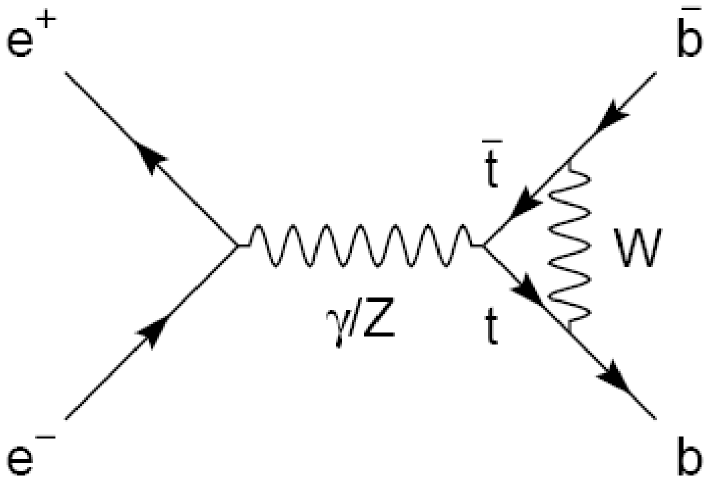
  $$\tau_{\text{top}} \approx 4.7 \cdot 10^{-25}\ \text{s}$$

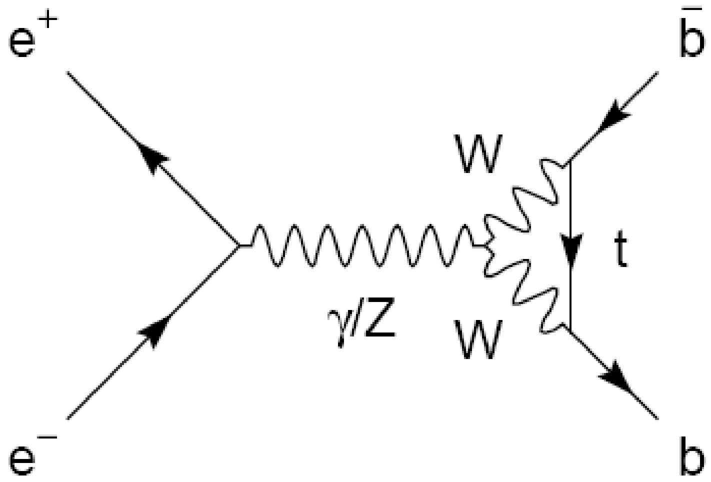
⇒ Top quark decays as a quasi free particle

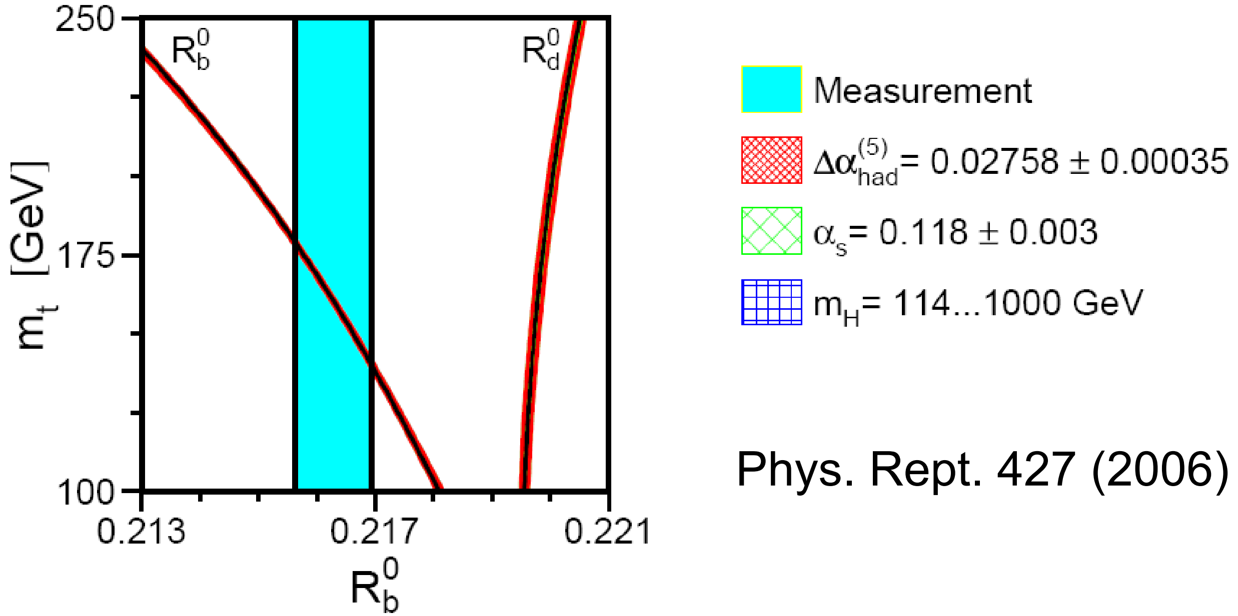
⇒ Spin information and polarisation are accessible

(Spin decorrelation time: 10^{-21} s for hadrons)

Top-quarks in loops: Corrections to $Z \to b\bar{b}$





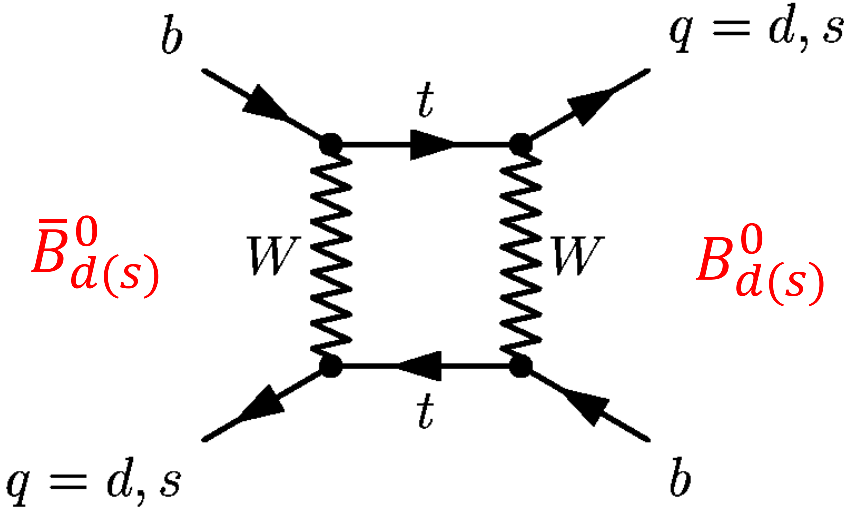


Phys. Rept. 427 (2006) 257

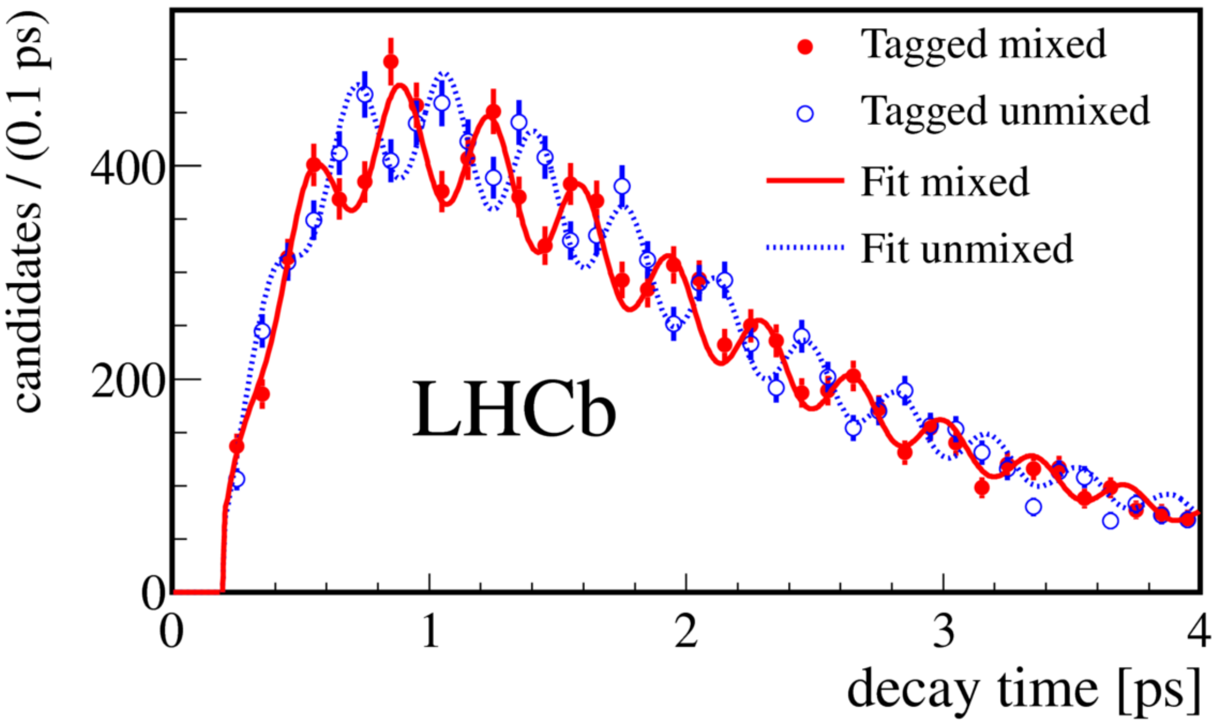
$$R_b^0 = \frac{\Gamma_{b\bar{b}}}{\Gamma_{\text{had}}}$$

The parameter R_b^0 depends strongly on the top-quark mass.

Top-quarks in loops: $B^0_{d(s)} - \bar{B}^0_{d(s)}$ mixing



- Loops with top-quarks lead to main contribution.
- If all quark masses were degenerate, the amplitudes would cancel each other.



Tagged mixed =
different flavour at production and decay

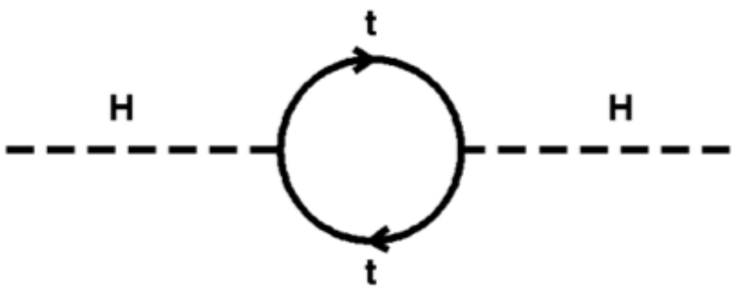
Tagged unmixed =
same flavour at production and decay

The top-quark and the Higgs boson

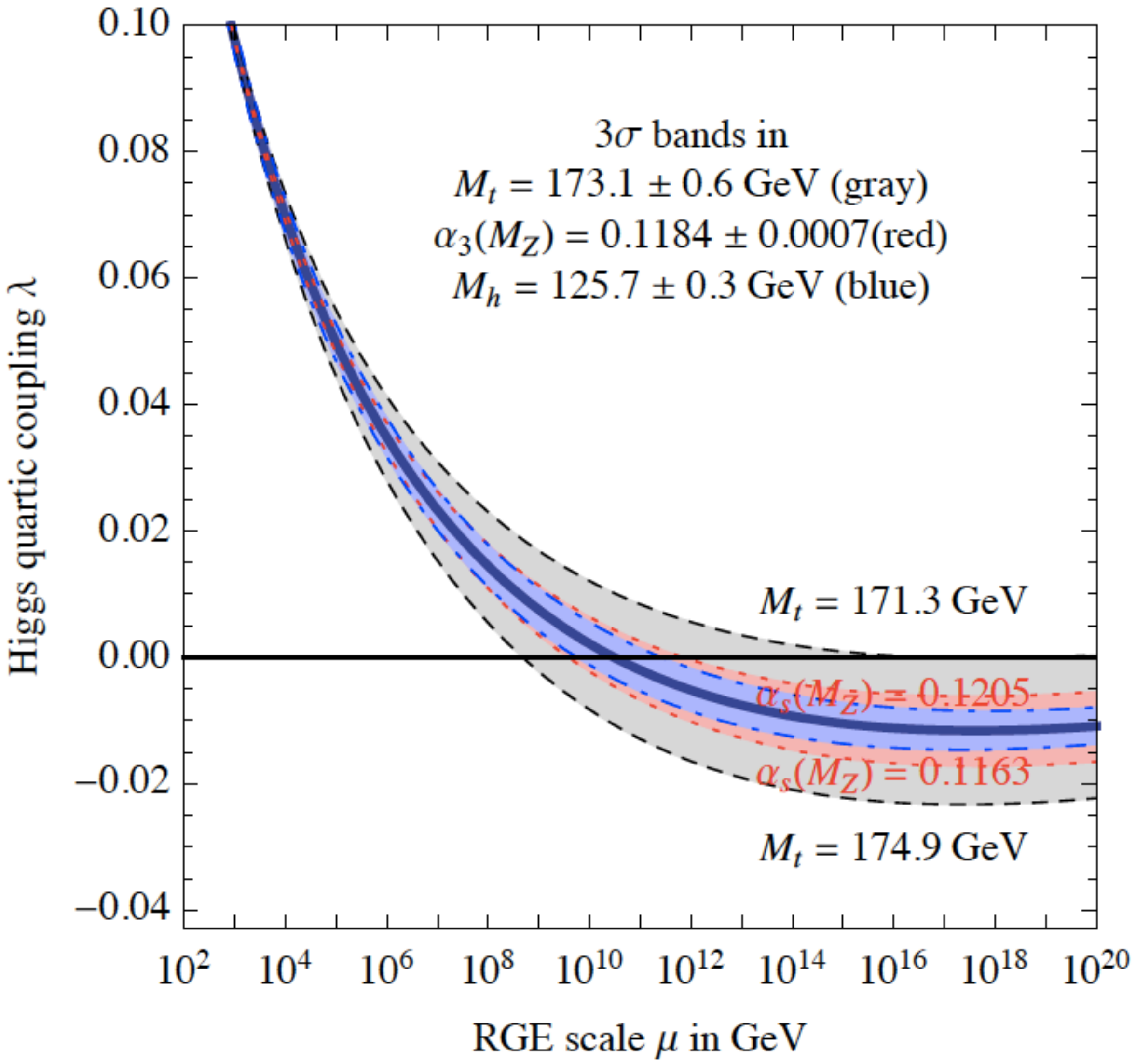
$$V(\phi) = \frac{1}{2}\mu^2\phi^\dagger\phi + \frac{1}{4}\lambda\left(\phi^\dagger\phi\right)^2$$

$$\lambda = \lambda(q^2)$$

- The Higgs self-coupling λ is not a constant.
- Loop corrections ⟶ dependence on momentum scale μ
- Main contributions from top-quark



Top-quark loops contribute to the Higgs propagator.

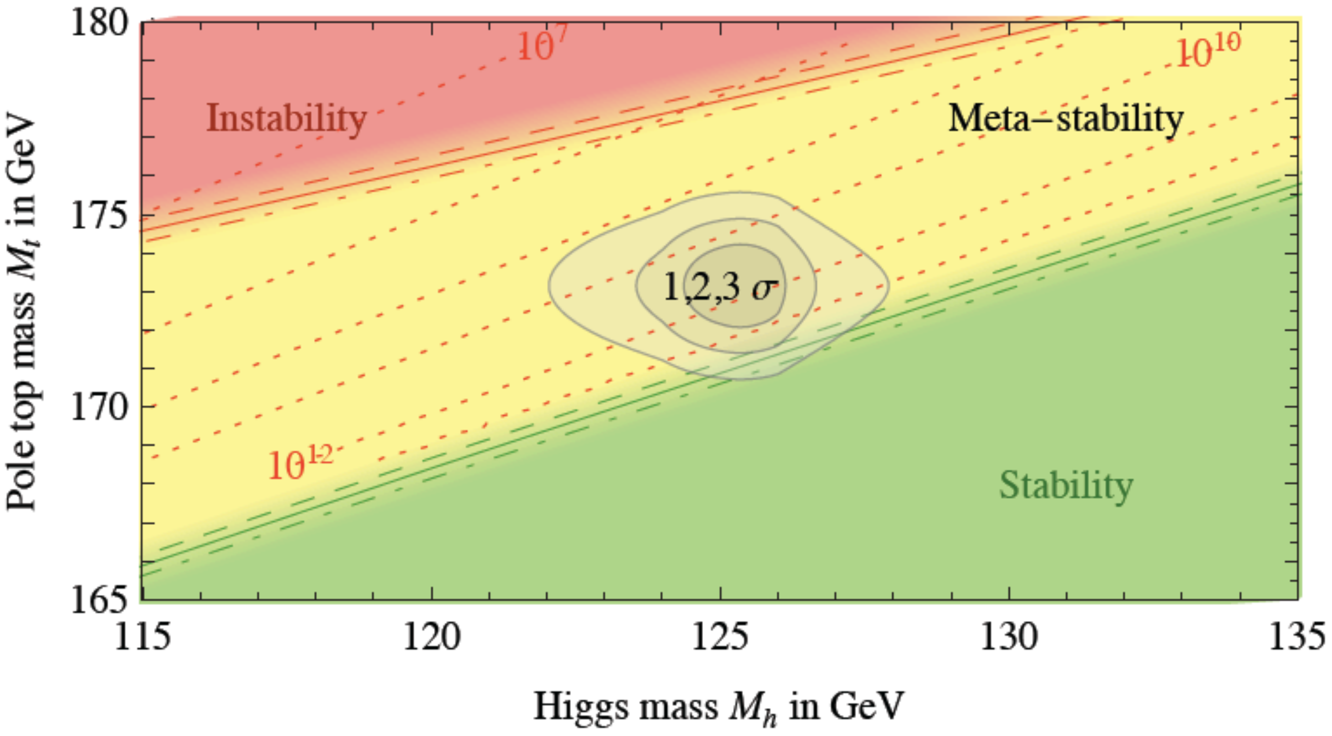


Vacuum stability

- Condition for absolute stability of the potential: $\lambda(q^2) > 0$

$$M_H \geqslant 129.2 + 1.8 \times \left(\frac{m_t^{\text{pole}} - 173.2\ \text{GeV}}{0.9\ \text{GeV}}\right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0\ \text{GeV}$$

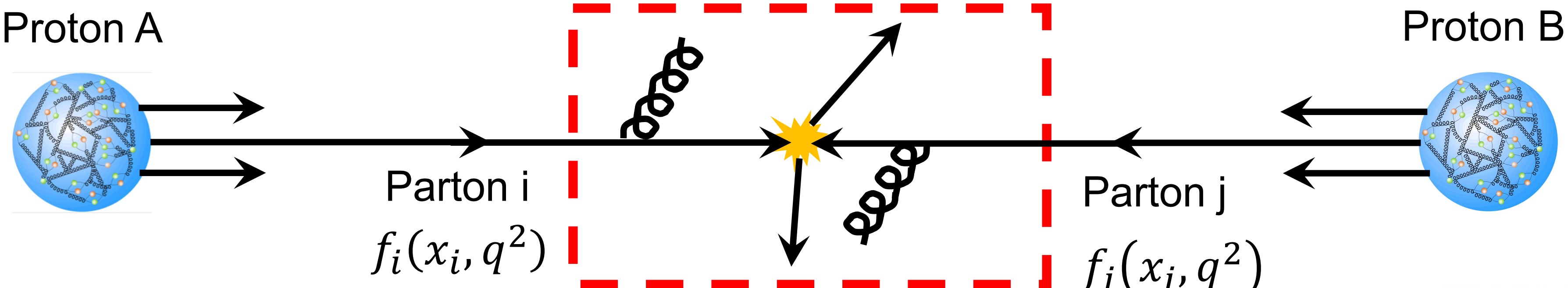
Degrassi et al., JHEP 1208 (2012) 098, arXiv:1205.6497 [hep-ph] .



Top-quark mass is important parameter (value and uncertainty).

High-p_T interactions in proton-proton collisions …

… described in the parton model



Partonic interaction

(hard process)

Proton A

Proton B

Parton i

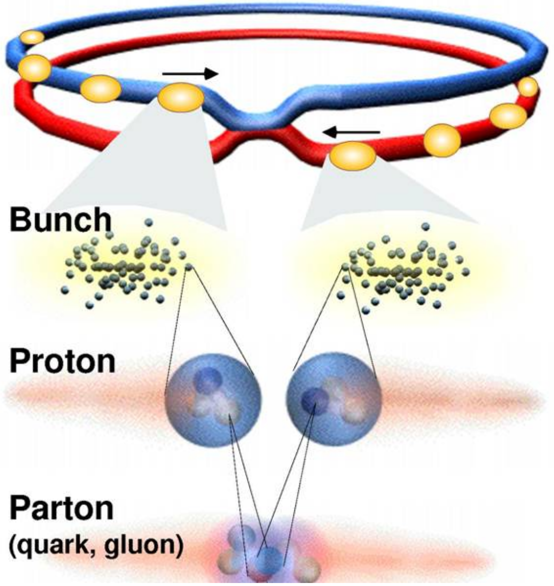
$f_i(x_i, q^2)$

Parton j

$f_j(x_j, q^2)$

Parton distribution functions

Perturbative regime
(asymptotic freedom)



Factorisation theorem

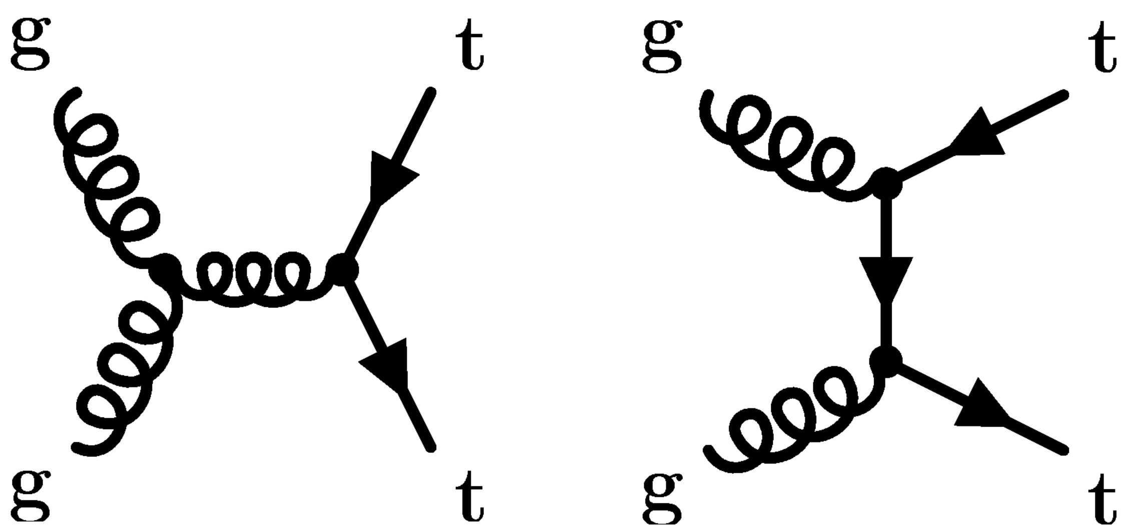
Partonic cross-section

$$\sigma(pp \to XY) = \sum_{i,j} \int d\hat{s}\, \mathcal{L}_{ij}(\hat{s}; s, \mu_f) \cdot \hat{\sigma}_{ij}(ij \to XY;\ \hat{s};\ \mu_f)$$

With $\mathcal{L}_{ij}(\hat{s}; s, \mu_f) = \frac{1}{s} \int_{\hat{s}}^{s} f_{i/A}\left(\frac{\tilde{s}}{s}\right) f_{j/B}\left(\frac{\hat{s}}{\tilde{s}}\right) \frac{1}{\tilde{s}}\, d\tilde{s}$ Parton luminosity

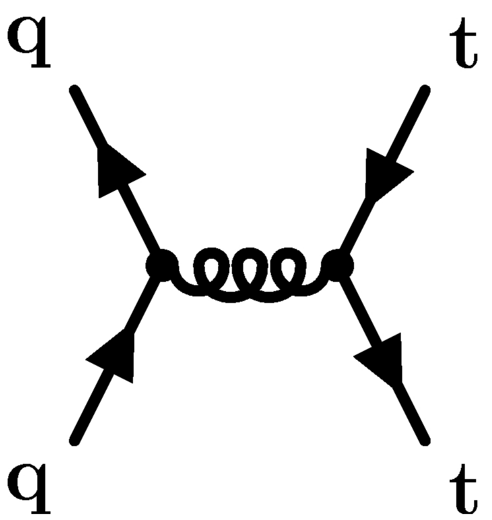
Top-quark-antiquark pair production

Gluon-gluon fusion



~90%

Quark-antiquark annihilation



~10%

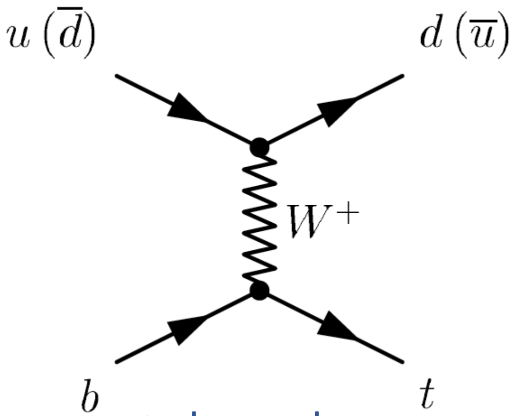
At the LHC at
$\sqrt{s} = 13$ TeV

Total cross-section: $\sigma = 832\,^{+20}_{-30}\,(\text{scale}) \pm\ 35$ (PDF and α_s) pb

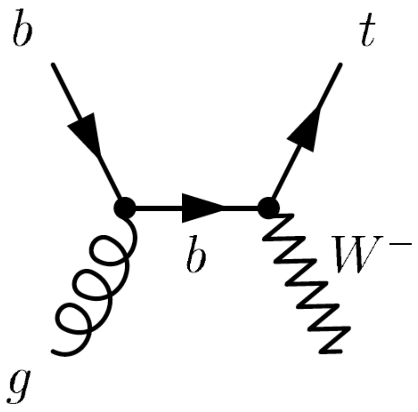
Relative uncertainty = 5.5%

... and more partonic top-quark processes

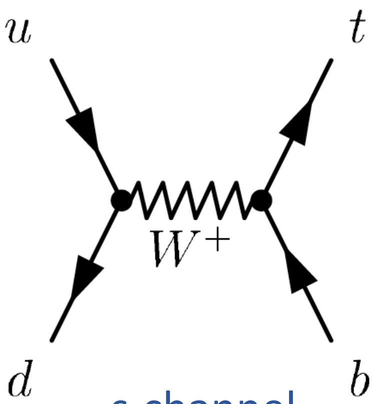
Single top-quark production



t-channel
(*tq* production)

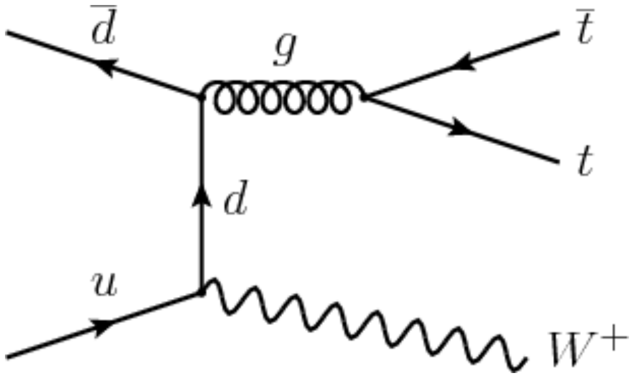


tW production

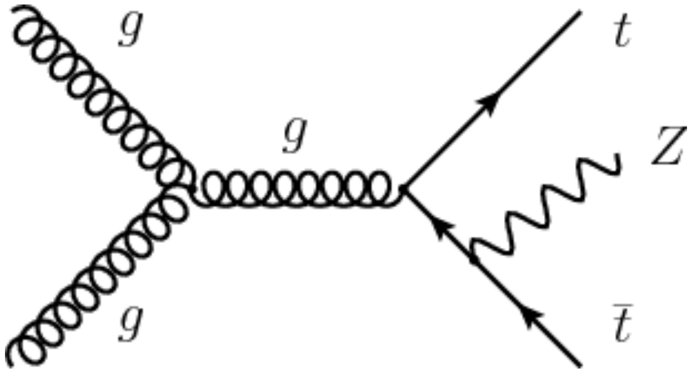


s-channel
($t\bar{b}$ production)

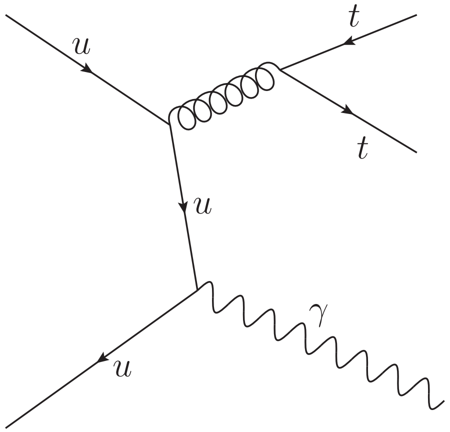
$t\bar{t}+W$ production



$t\bar{t}+Z$ production

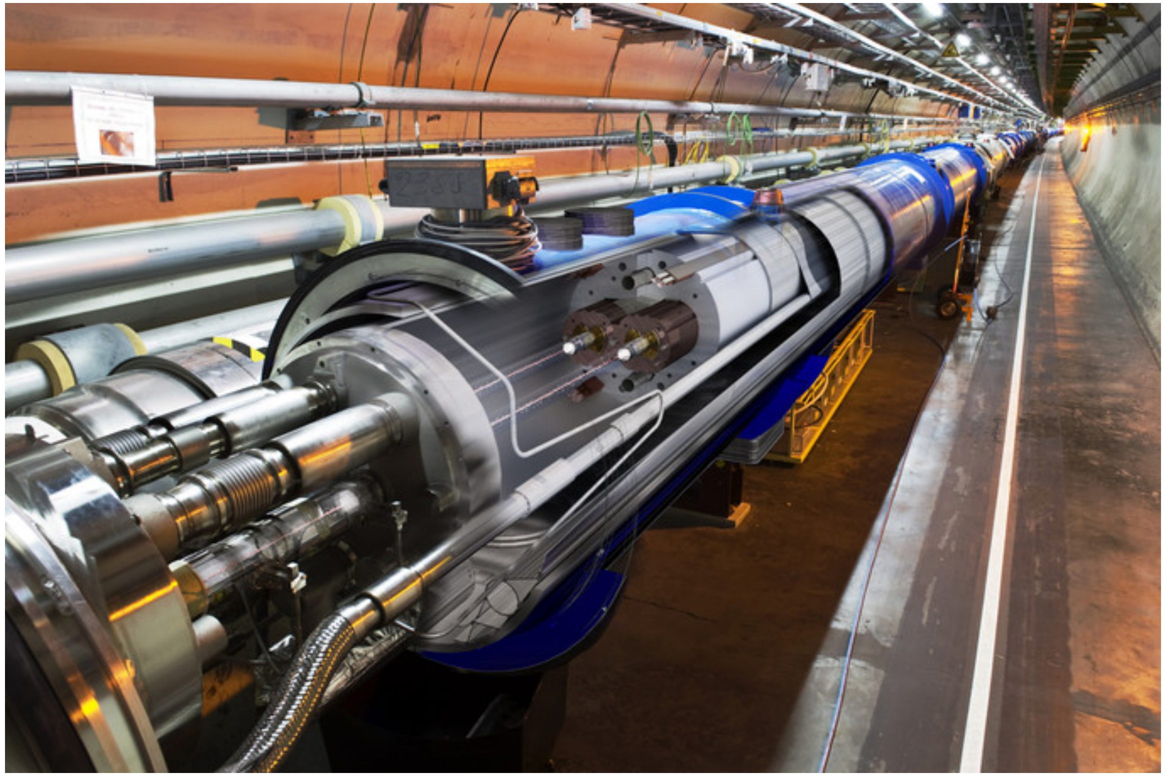


$t\bar{t}+\ \gamma$ production

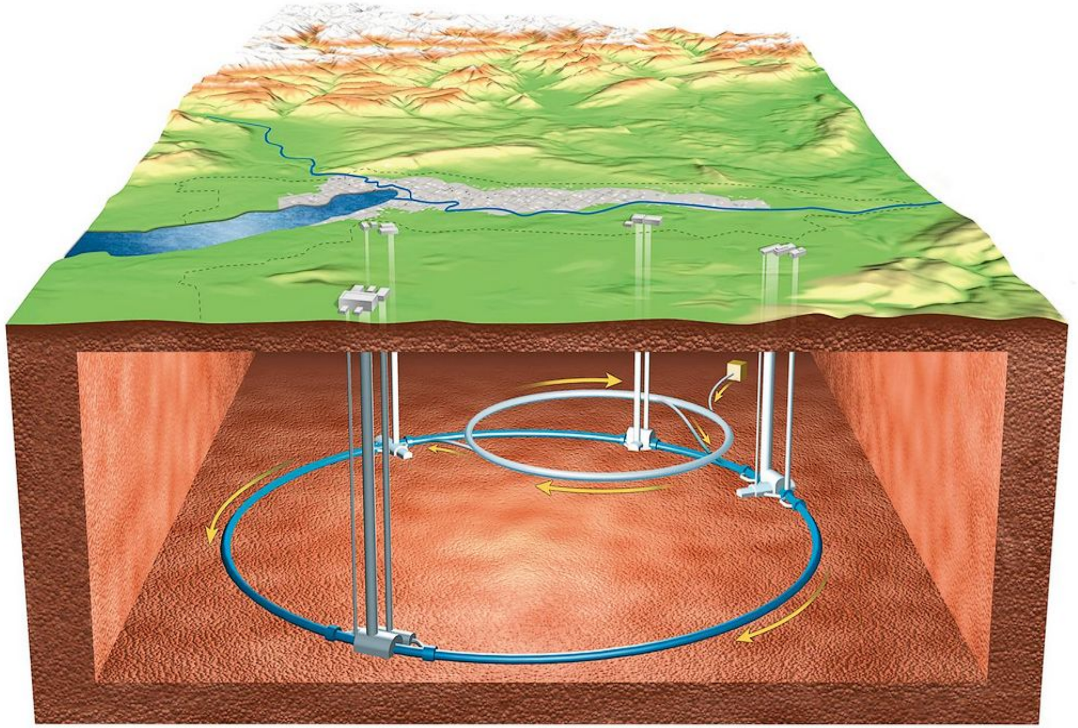


Chapter 2

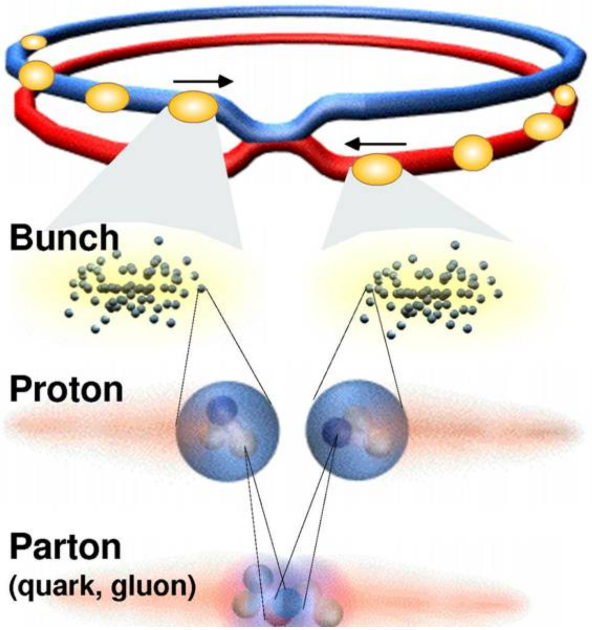
The Large Hadron Collider and the ATLAS detector



Der Large Hadron Collider (LHC)

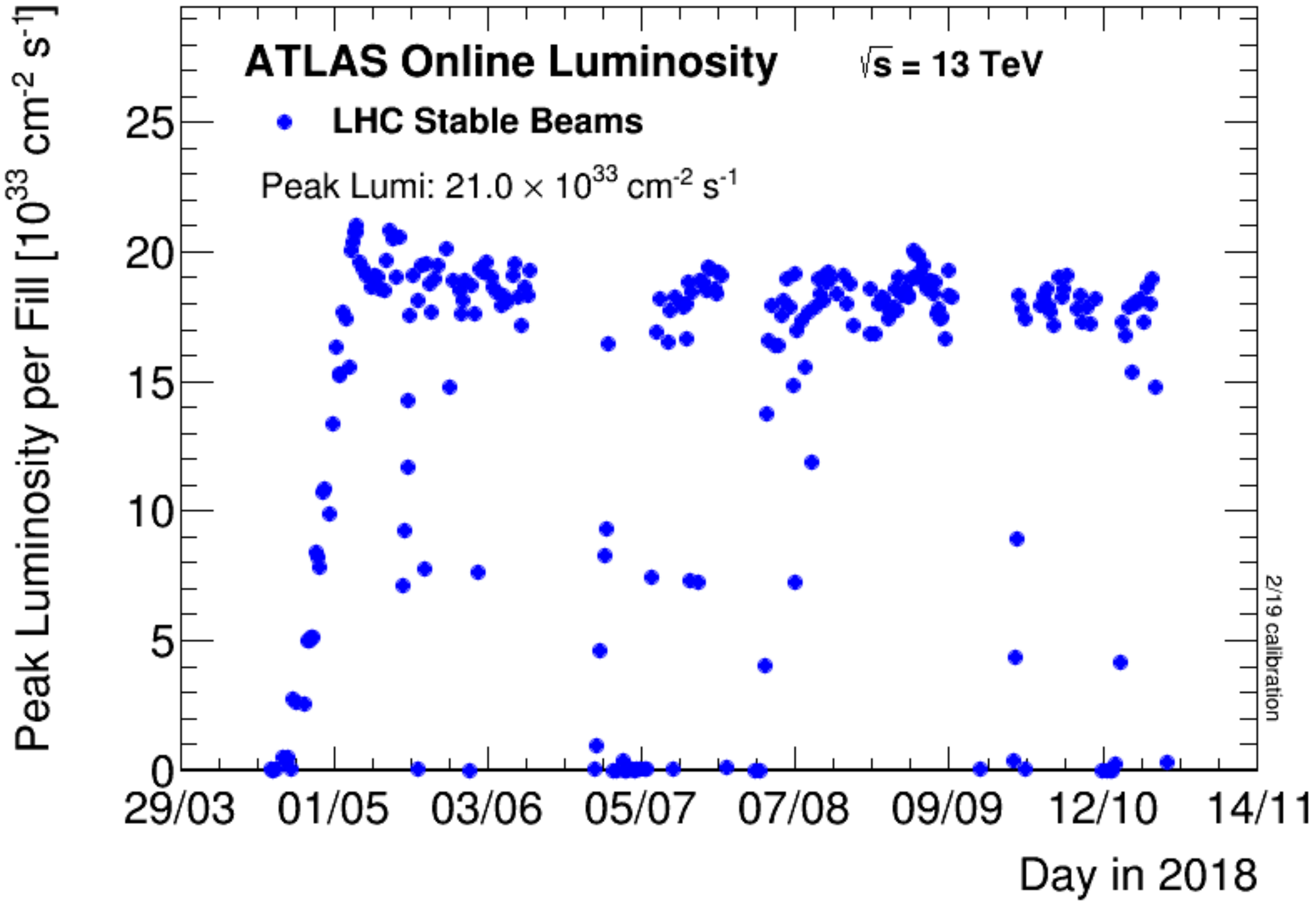


- Der leistungsstärkeste Beschleuniger der Welt:
  im Tunnel am CERN mit 27 km Umfang
- Zwei gegenläufige Protonenstrahlen machen
  10.000 Runden / Sekunde
- Kollisionen an 4 Punkten mit Rekordenergie von 13 TeV



- Jeder Strahl hat ca. 2500 Protonenpakete
- 100 Milliarden Protonen pro Paket
  (klingt viel, aber 1 mol = 6 • 10^{23})

Peak luminosity in 2018



$$\frac{dN}{dt} = {\color{red}L} \cdot \sigma$$

L: Luminosity

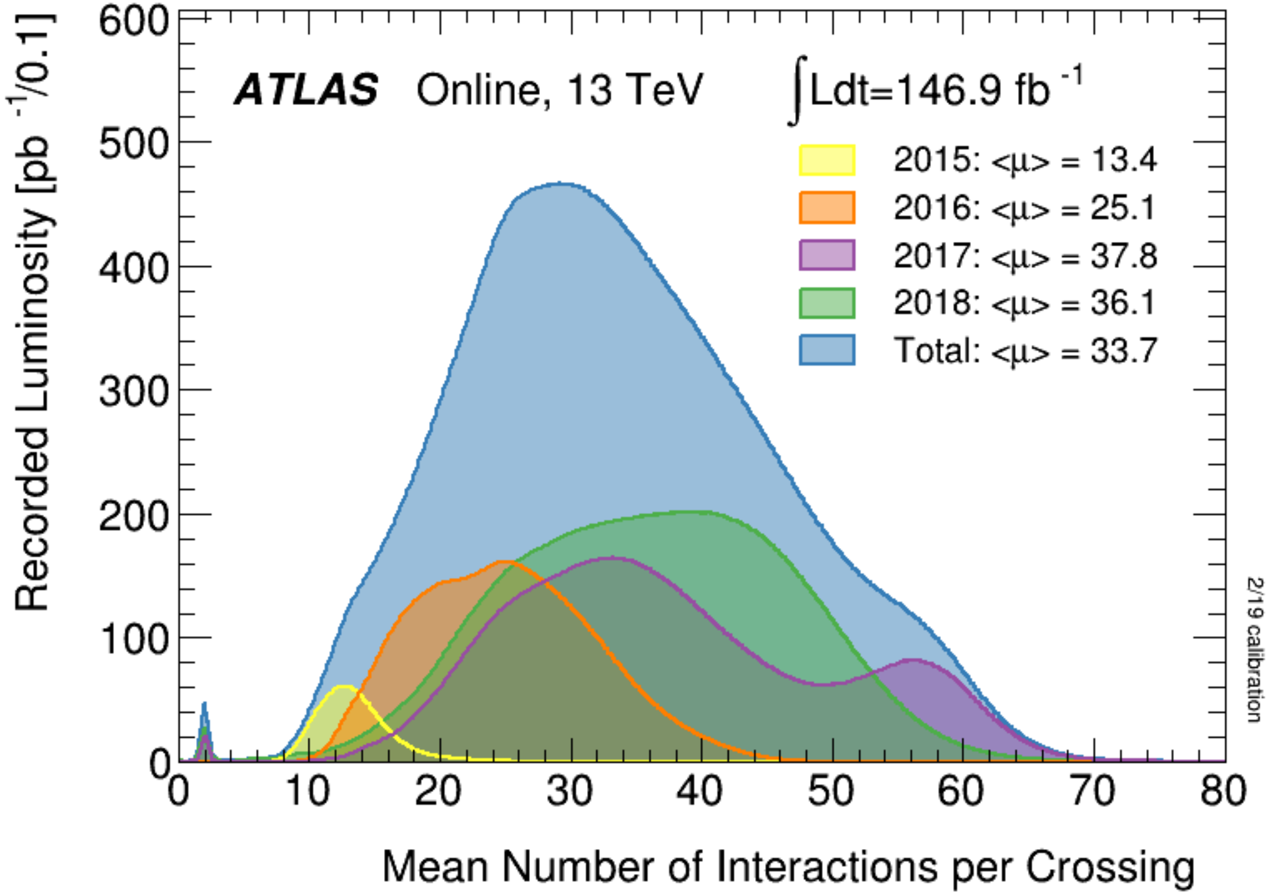
σ: Cross section

Units: cm^{-2} s^{-1}

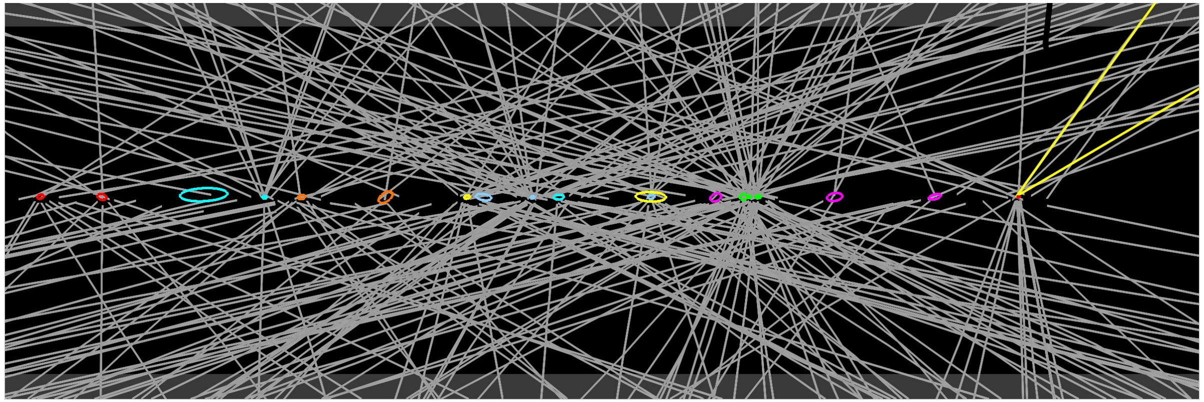
Same units as a particle current density.

Design value exceed by a factor of two!!!

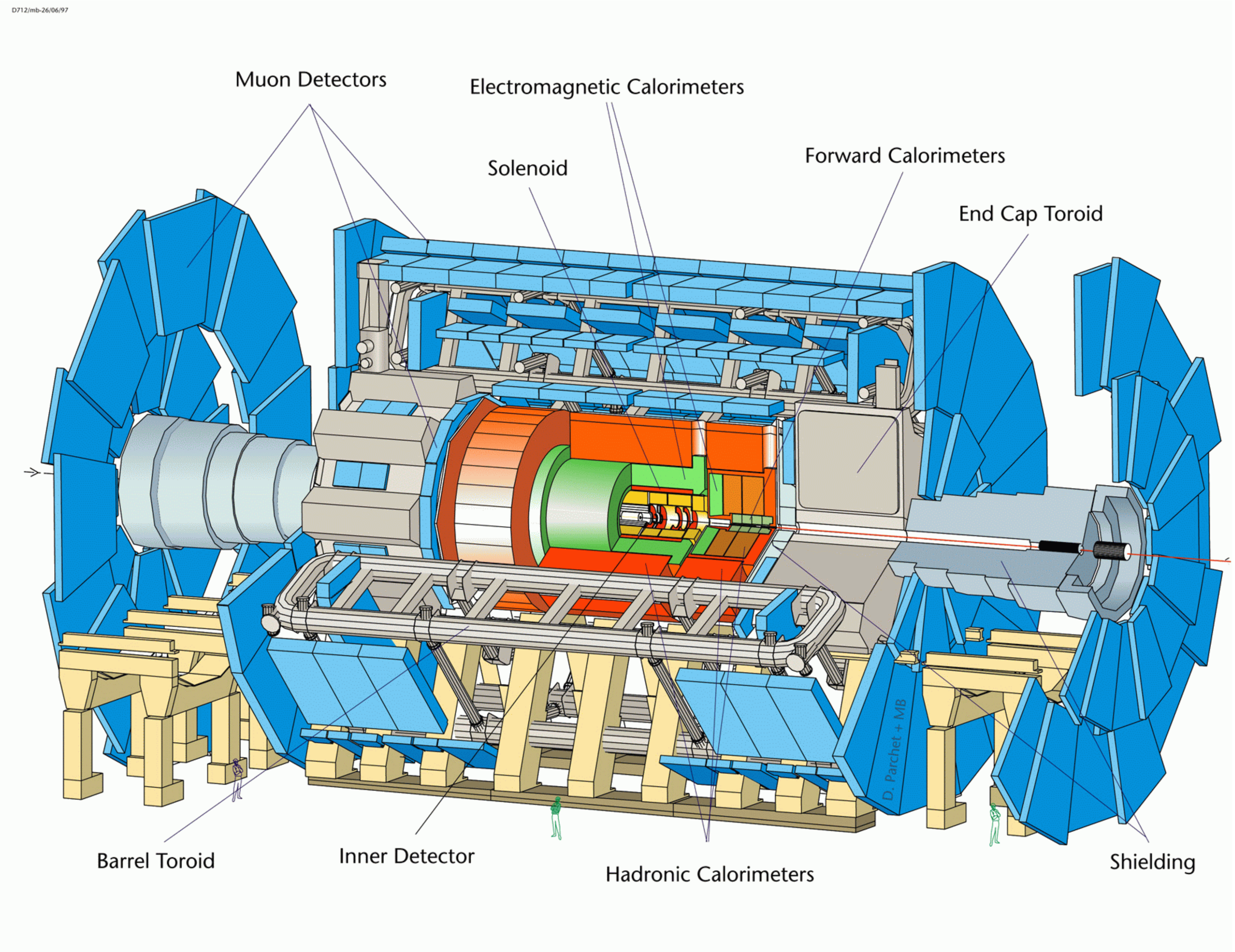
Number of pp interactions per bunch crossing



- Integrated luminosity „good for physics“ = 139 fb^{-1}
- Pile-up: proton-proton collisions at the same bunch crossing



The ATLAS detector



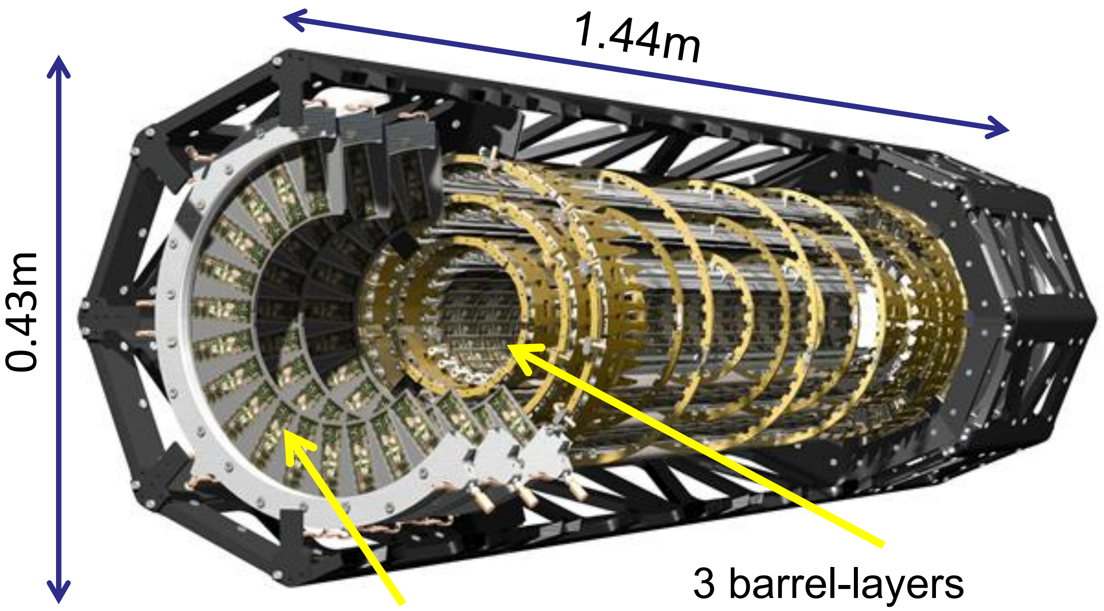
46 m long and 24 m high

Main components (= sub-detectors)

- Inner detector
  ⟶ tracks of charged particles
- Calorimeters
  ⟶ photons
  ⟶ electrons
  ⟶ hadronic jets (quarks and gluons)
- Muon system
  ⟶ muons
- Magnet systems
  ⟶ bending of charged particles

The ATLAS Pixel detector

- 3 to 4 precise track hits up to |η|< 2.5:
  - RΦ resolution: 10 μm
  - η (or z) resolution: 115 μm
- 92 million pixel cells

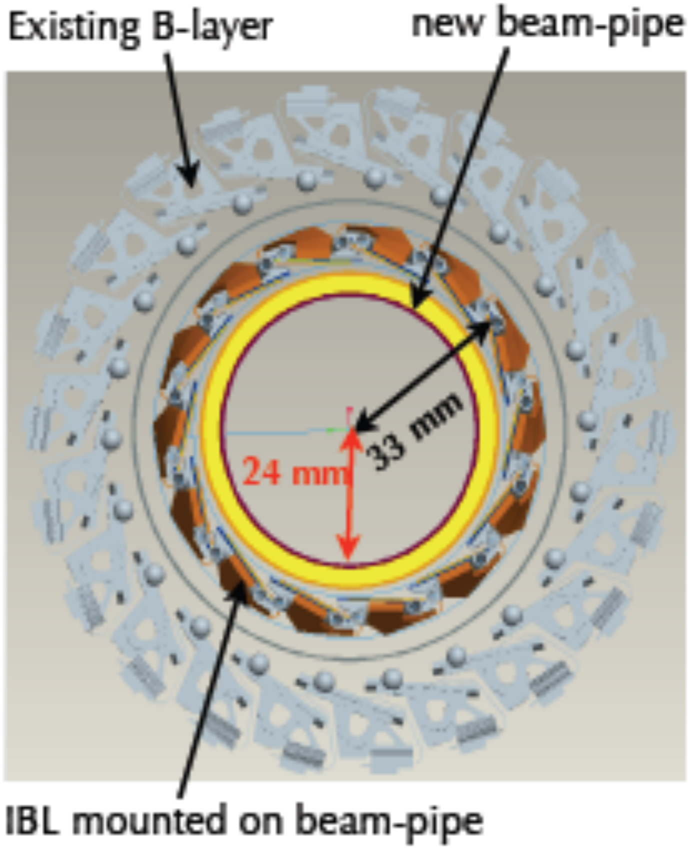


3 end-cap discs

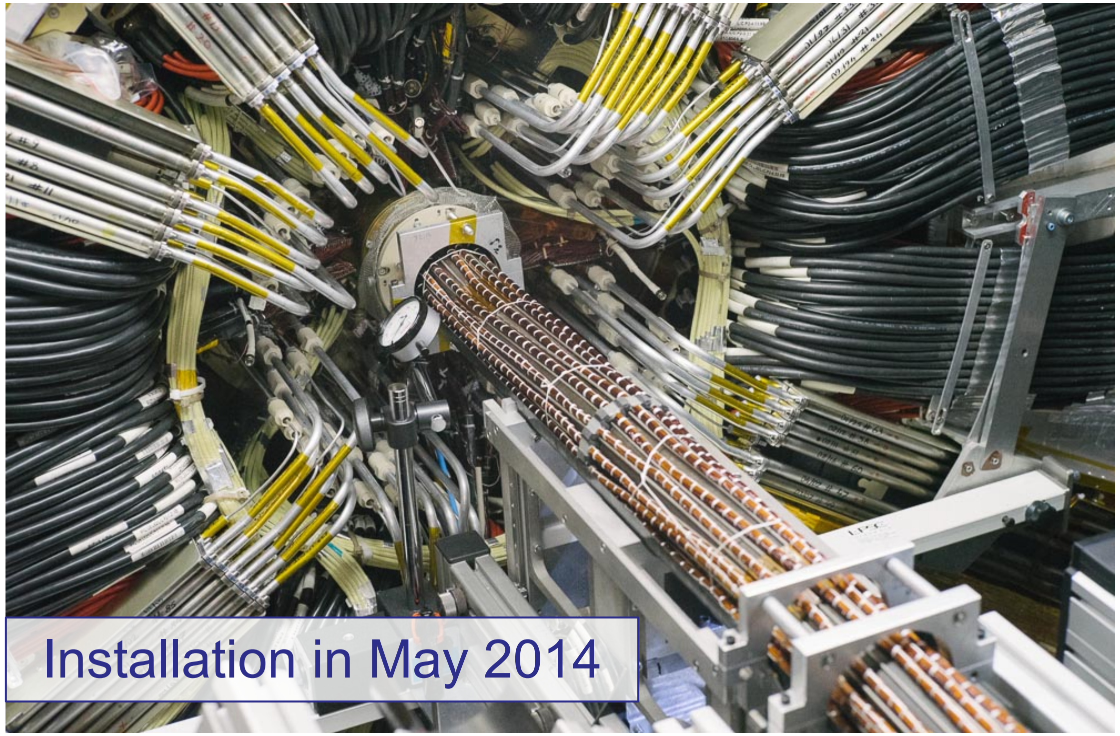
3 barrel-layers
(original installation)

- 4th layer installed in 2014.
- Radiation hard up to 2.4 × 10^{16} p/cm^2

The ATLAS IBL Collaboration, *Production and Integration of the ATLAS Insertable B-Layer*, Journal of Instrumentation (JINST) 13 (2018) T05008, arXiv: 1803.00844.

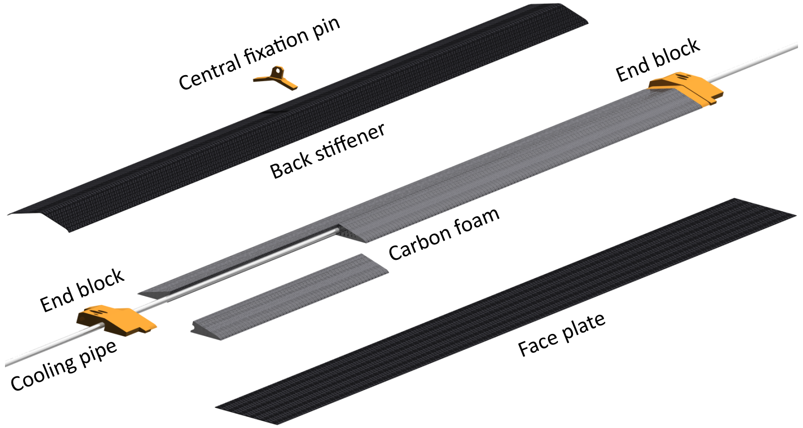


The Insertable B-Layer (IBL)

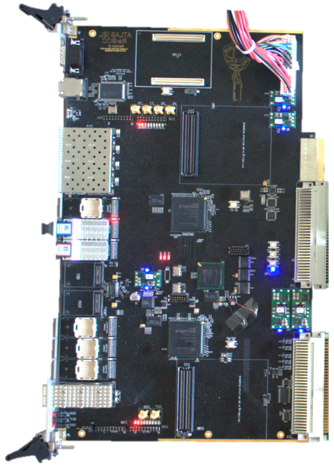

Installation in May 2014

Designed and produced with vital contributions of the Wuppertal HEP group:

1) Mechanical support structures made of carbon fibre compounds



2) Readout and data acquisition system



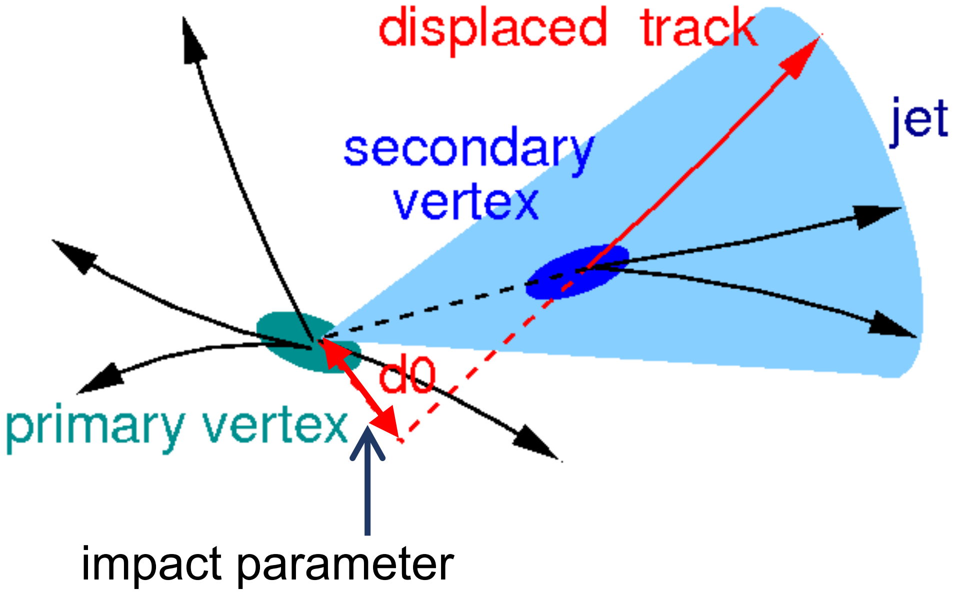
3) Monitoring and control system

Secondary vertex reconstruction

- Important for top quark ($\mathcal{B}(t \to Wb) \approx 1$) and Higgs boson physics
  Identification of
  - b-quark jets
  - τ leptons
- Long liftetime: τ (b-Hadron) ≈ 1.5 ps → cτ ≈ 450 μm
  τ (τ-Lepton) ≈ 0.3 ps

Requirement of a secondary vertex:

→ strong reduction of the W + jets background in top-quark events



Impact parameter resolution is limited by multiple scattering:

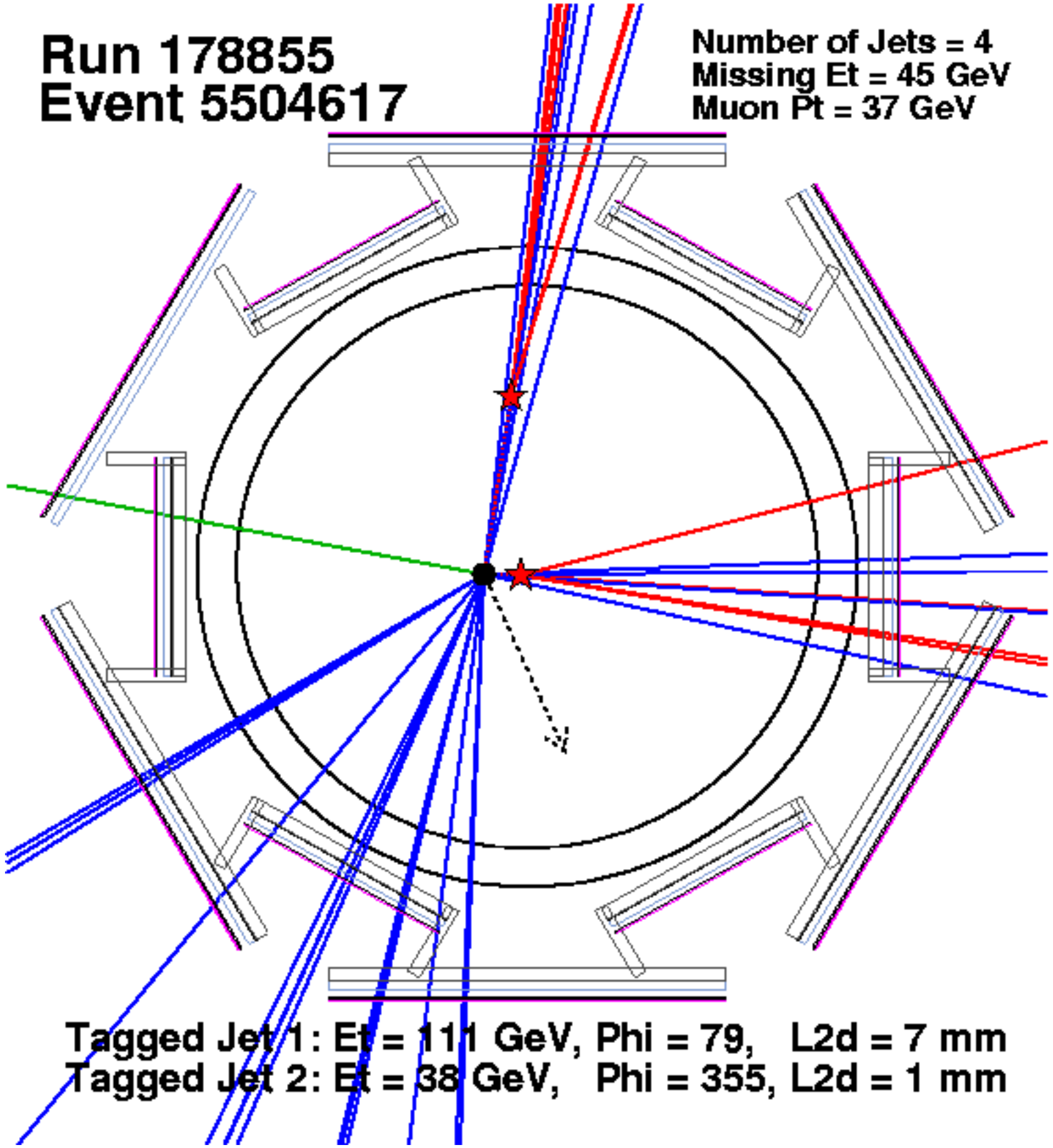
$\propto \sqrt{\frac{x}{X_0}}$ Amount of material

$\propto L$ Distance of the first measurement layer

Top-quark-antiquark pair candidate event …

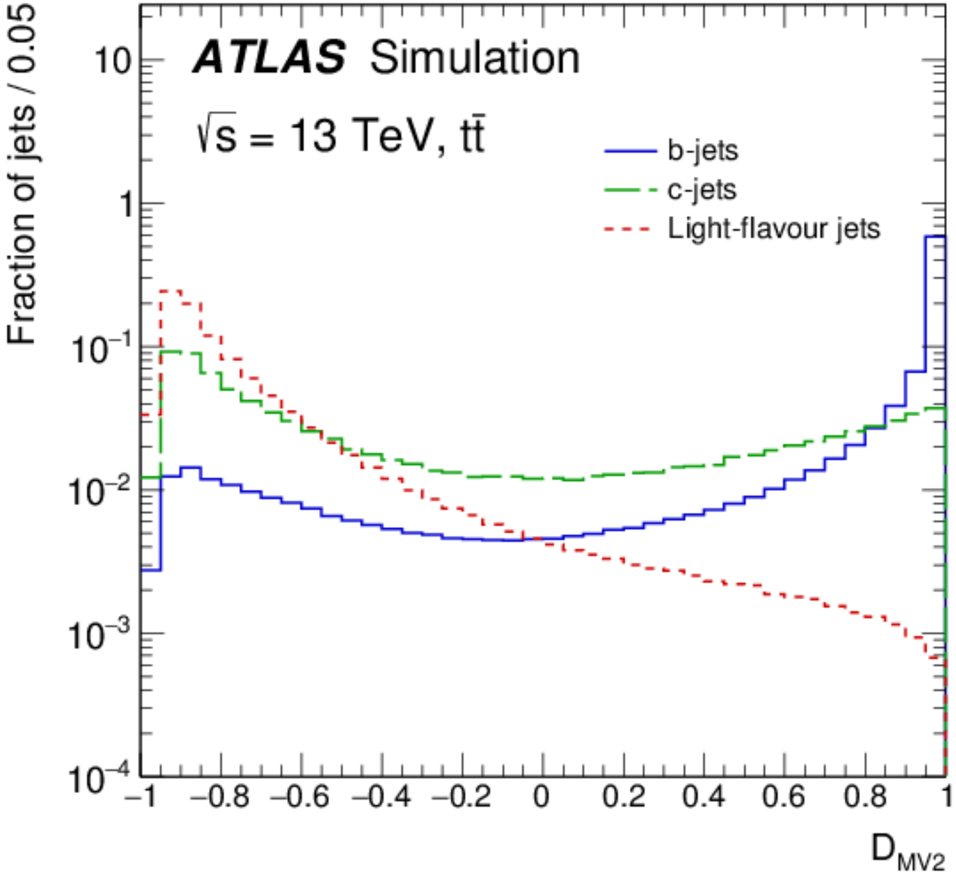
… with two reconstructed secondary vertices

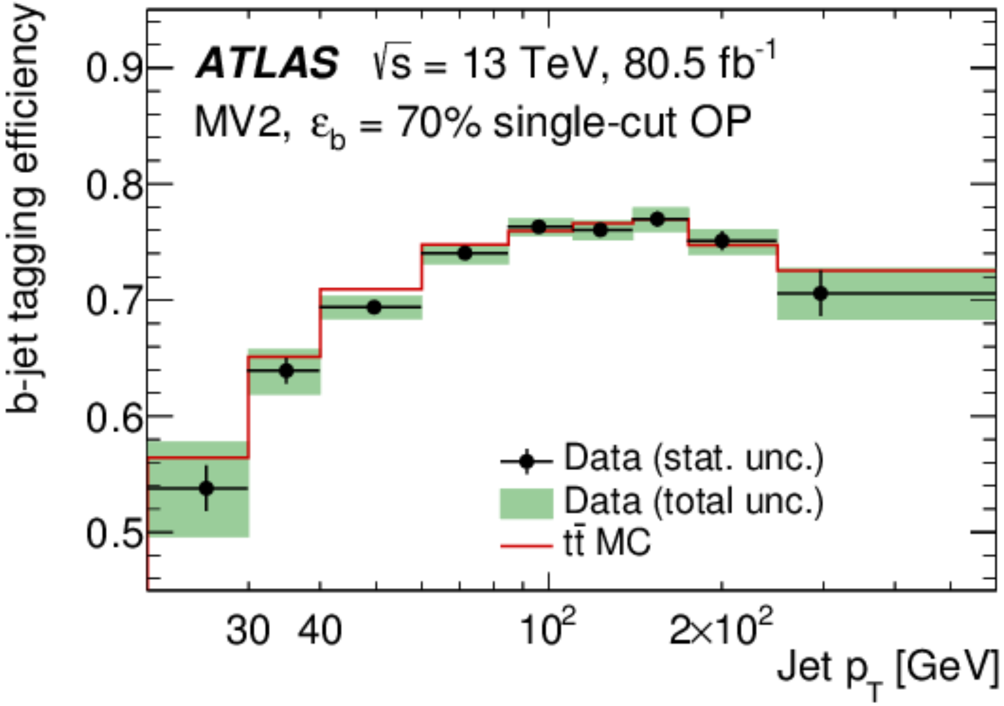
CDF experiment at Fermilab



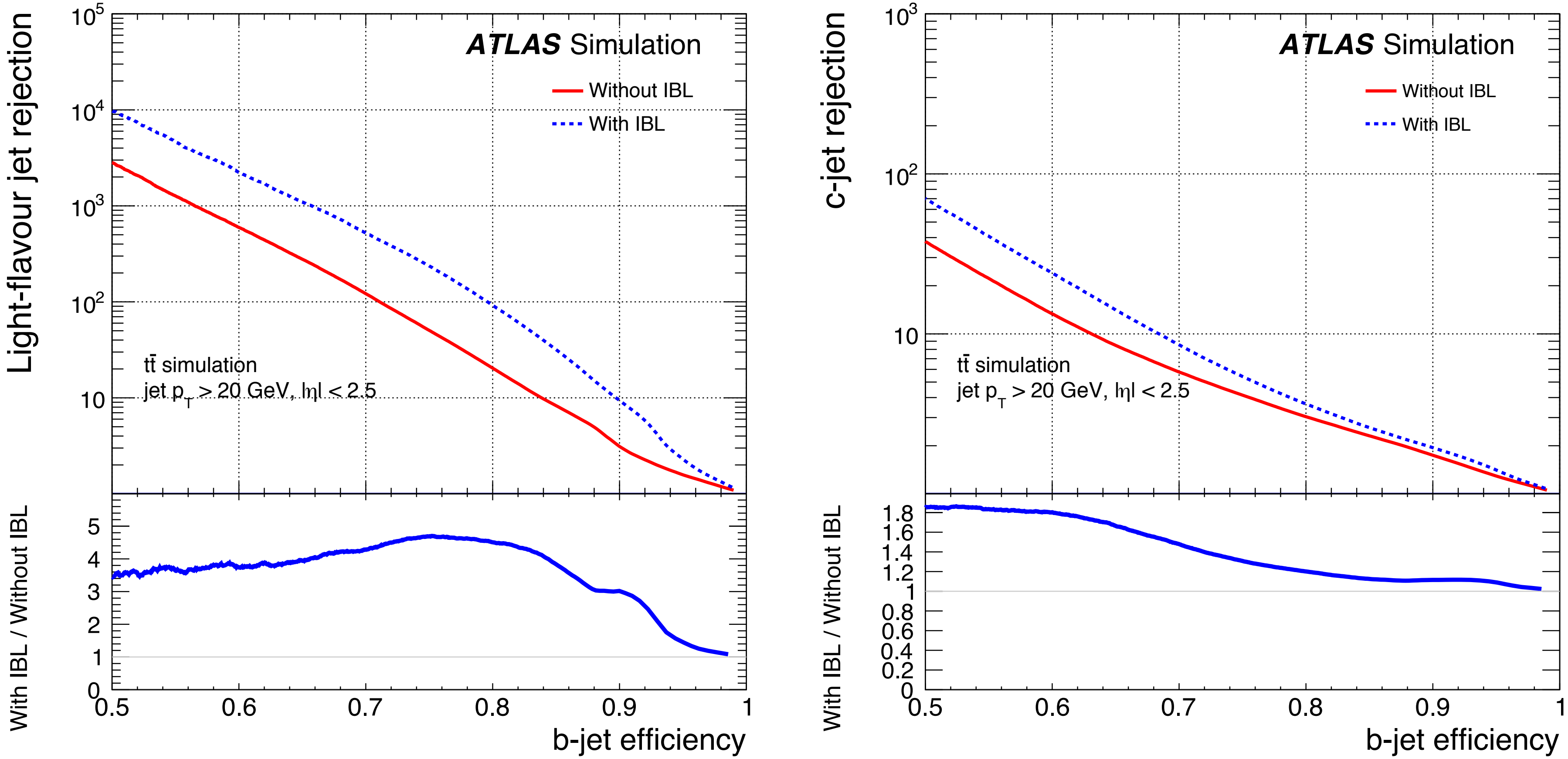
Flavour-tagging with multivariate techniques

- Use many discriminating features of *b*-jets, *c*-jets and light-jets to identify them.
- ATLAS Collaboration, ATLAS *b*-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 79 (2019) 970, arXiv:1907.05120.



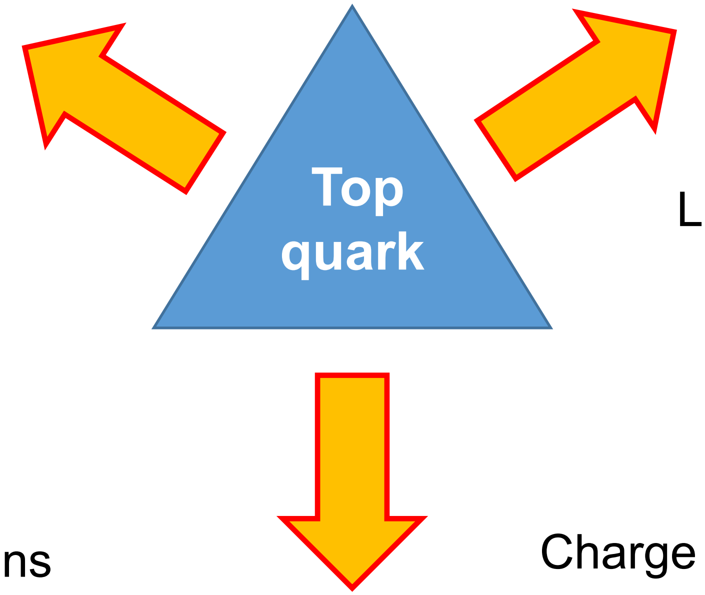


B-tagging improvements due to the IBL



Mis-identification of light-flavour jets and c-jets massively reduced for the same b-tagging efficiency.

Challenging the Standard Model with top quarks



Leptoquarks

Supersymmetry

Vector-like quarks

Direct searches

Heavy Higgs bosons

Rare decays

CP violation

Indirect searches

Flavour-changing neutral currents

Lepton-flavour violation

Spin correlations

Charge asymmetry

Precision measurements

Polarisation

Differential and total cross-sections

W helicity in top-quark decay

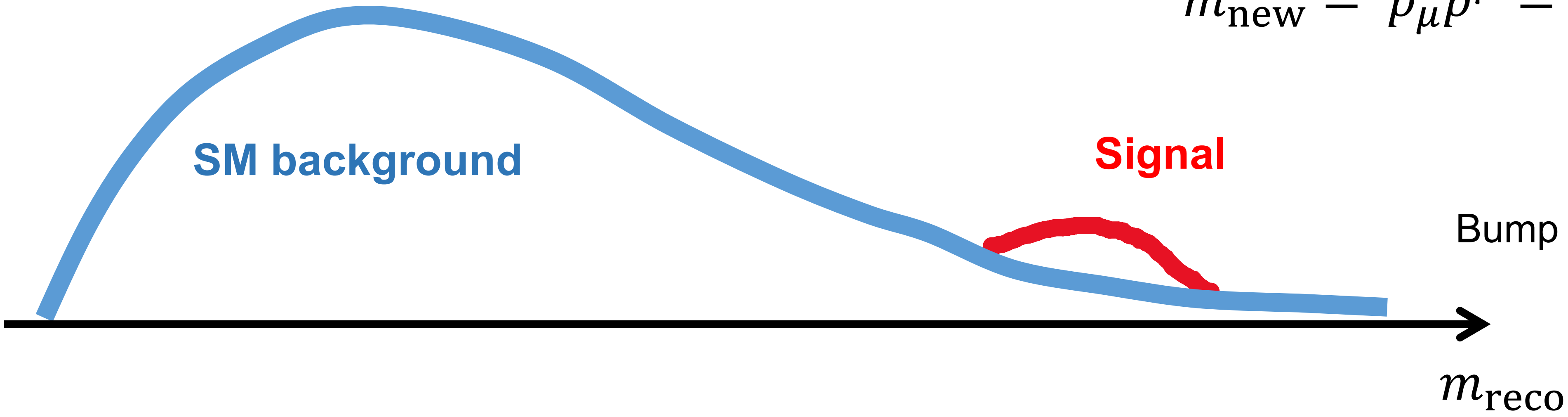
Top-quark mass

Chapter 3

Direct searches for new particles

(So-called on-shell production)

$$m_{\mathrm{new}}^2 = p_\mu p^\mu = E^2 - \vec{p} \cdot \vec{p}$$



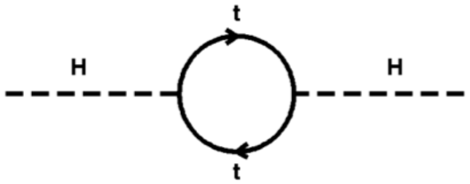
Bump search

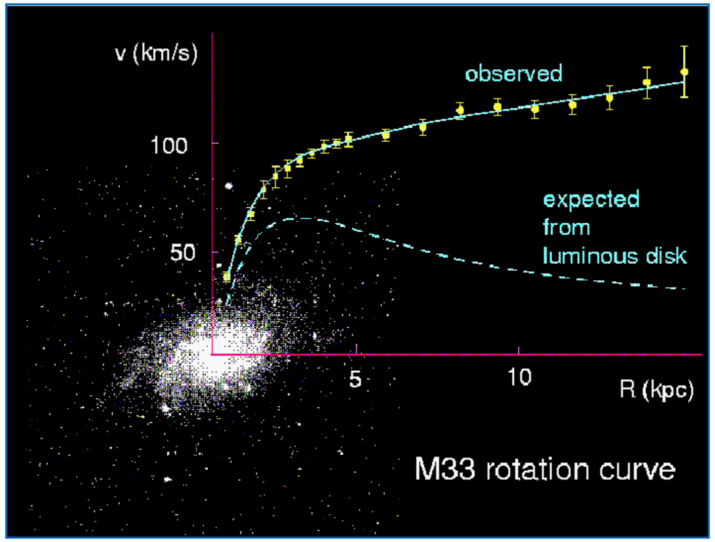
Warum “brauchen” wir neue Teilchen?

Offene Fragen der Elementarteilchenphysik

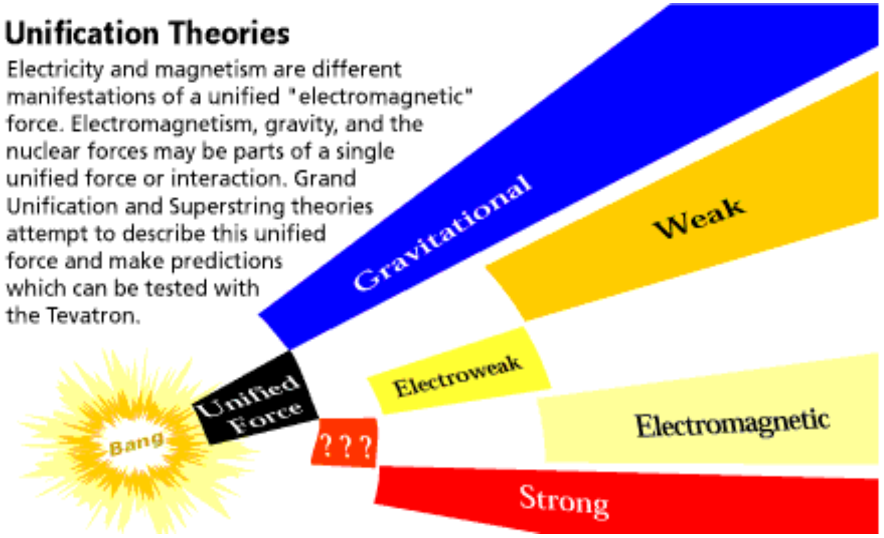
- Materie-Antimaterie-Asymmetrie im Universum
- Neutrinos haben Masse (Neutrinooszillationen)
- Natur der Dunklen Materie
- Kommensurabilität (Gleichheit von Proton- und Elektronladung)
- Große Vereinheitlichung der Kräfte
- Das Hierarchieproblem „Natürlichkeit“ der Higgs-Massen-Skala

$$\frac{m_H}{m_{\text{Planck}}} \simeq 10^{-16}\ \text{GeV}$$





M33 rotation curve

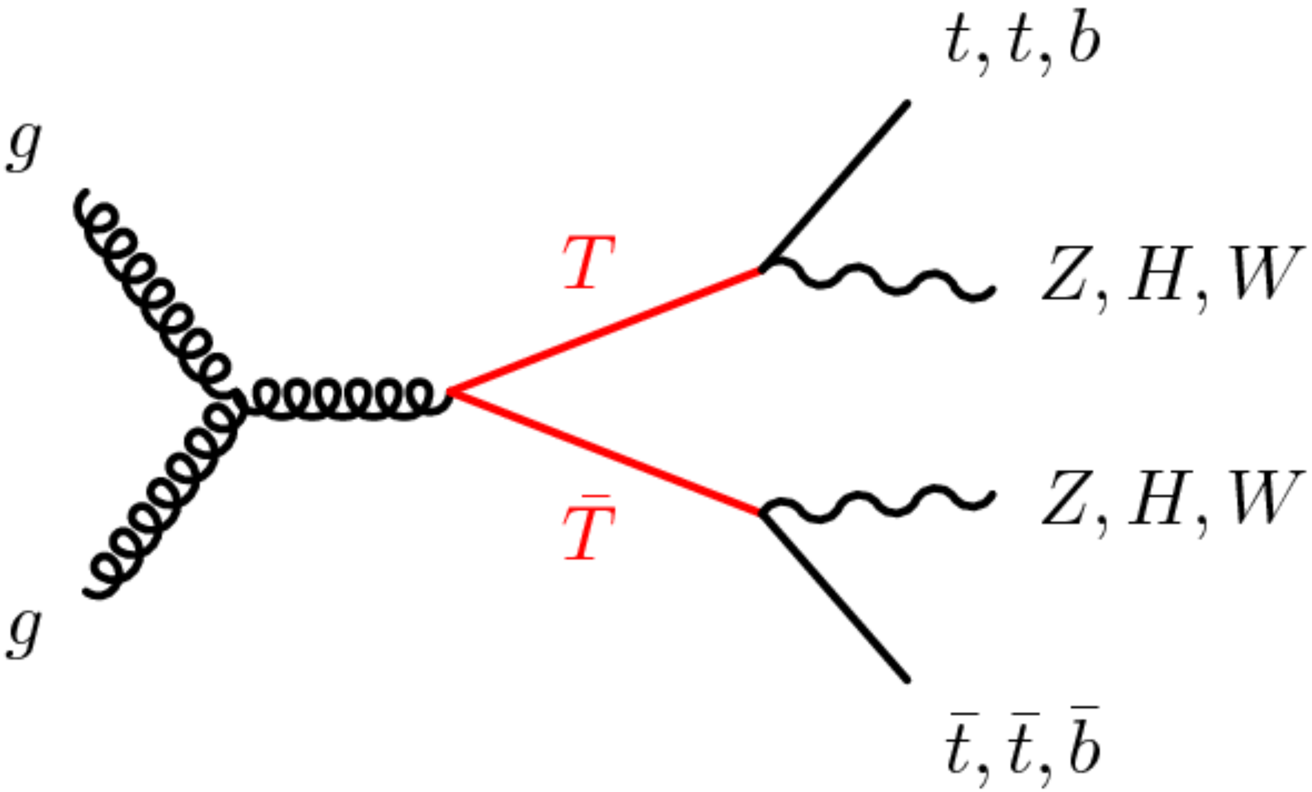


Unification Theories

Electricity and magnetism are different manifestations of a unified "electromagnetic" force. Electromagnetism, gravity, and the nuclear forces may be parts of a single unified force or interaction. Grand Unification and Superstring theories attempt to describe this unified force and make predictions which can be tested with the Tevatron.

Searches for vector-like top quarks

Pair production of vector-like top quark partners (T)



Pair production cross section does not depend on any BSM couplings. It is pure QCD.

- T quarks have spin $\frac{1}{2}$
- Left-handed and right-handed states have the same electroweak coupling = no need to consider chiral states
- Avoids exclusion of a simple sequential 4th generation as obtained from Higgs production cross sections at the LHC.
- Contributions by T quarks dampen large quadratic corrections to the Higgs boson mass (propagator).
  → Solution to the naturalness problem
- Occur in Little Higgs or Composite Higgs models.

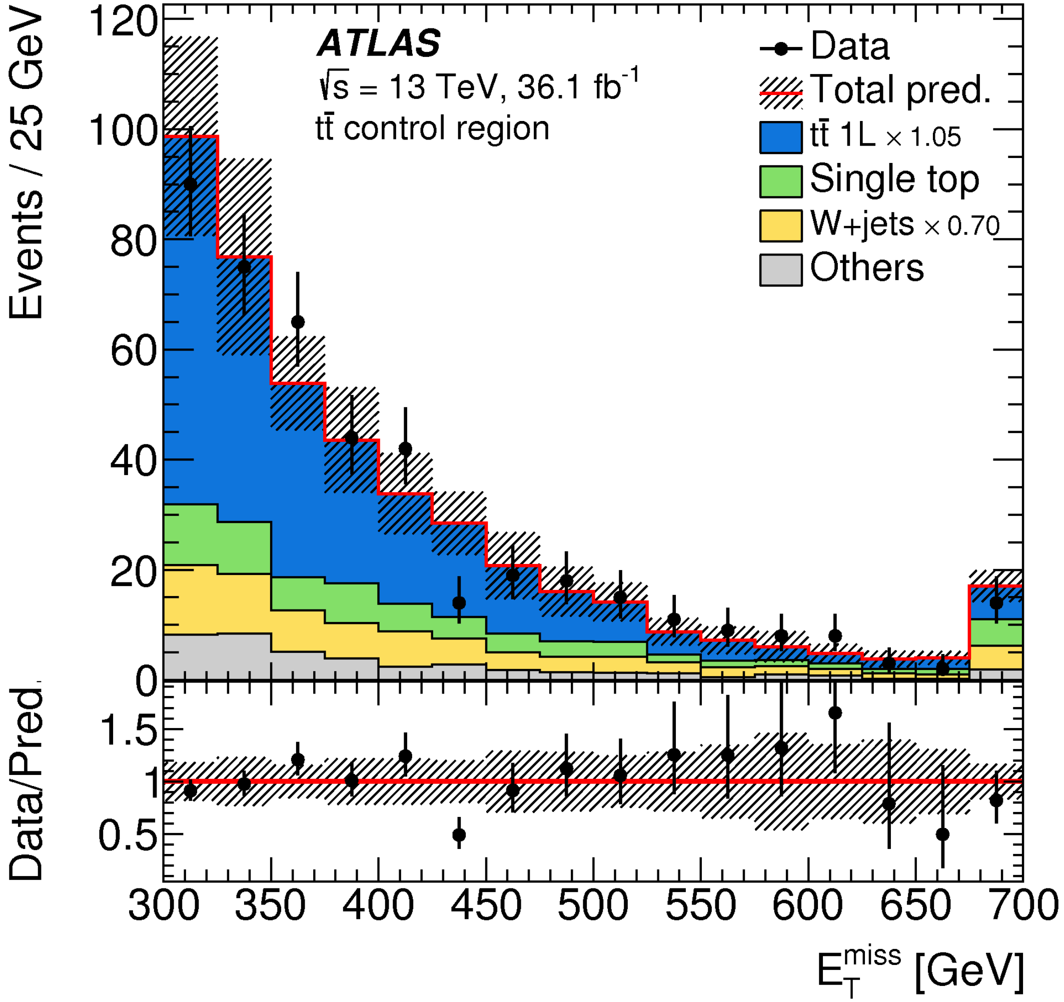
Search in the $T\bar{T} \rightarrow Zt + X$ with $Z \rightarrow \nu\bar{\nu}$ channel

arXiv:1705.10751 JHEP 08 (2017) 052

Basic event selection:

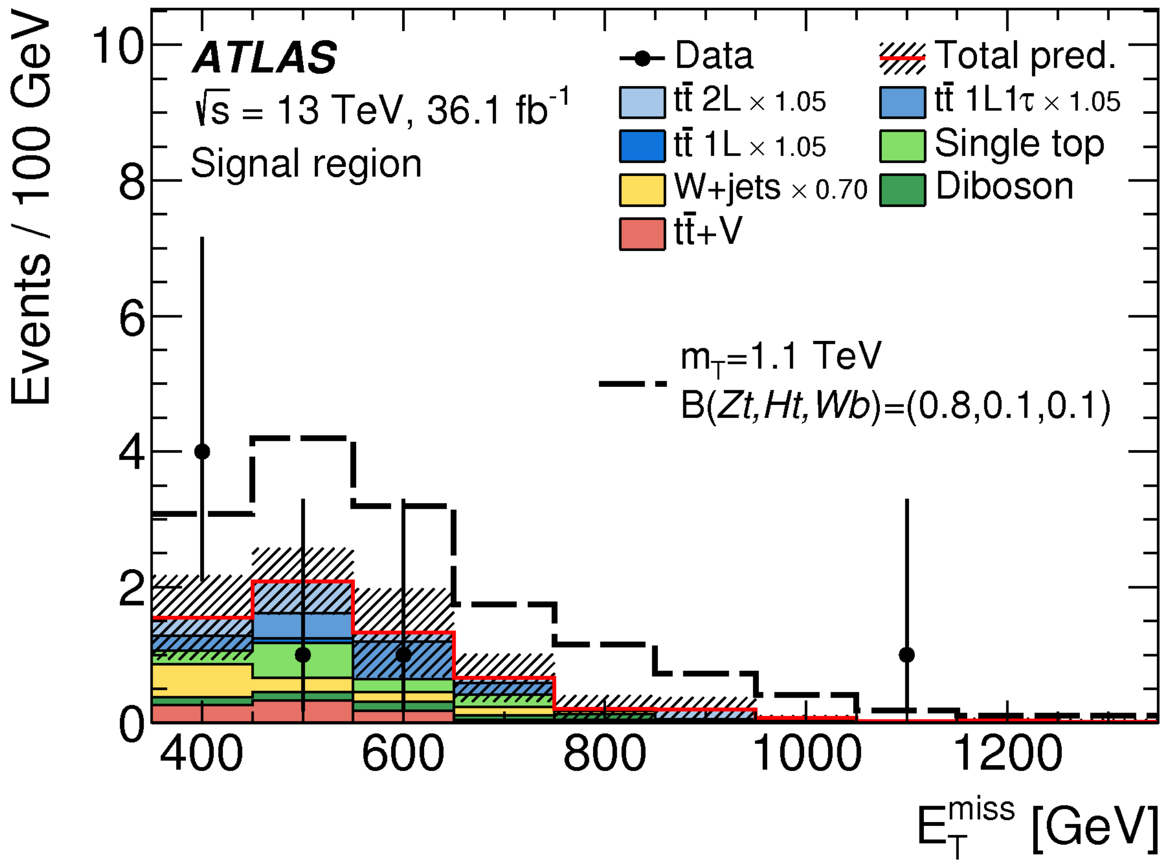
- $E_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV
- exactly 1 charged lepton (trigger)
- ≥ 4 jets with (small) $R = 0.4$
- Re-cluster jets to large-R jets with $R = 1.0$: ≥ 2 large-R jets

$t\bar{t}$ control region with 30 GeV $\leq m_T(W) \leq 90$ GeV



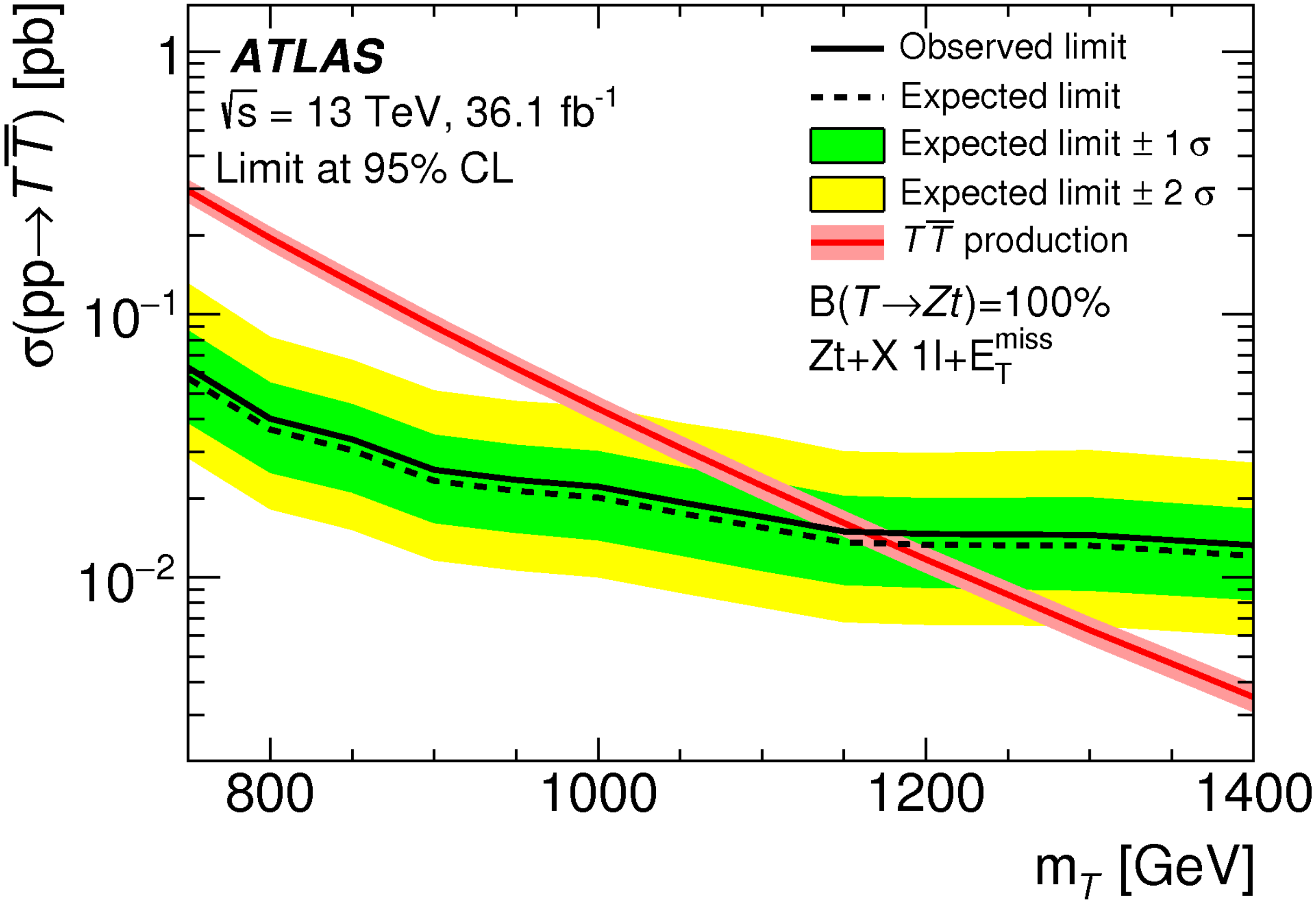
Signal region

with $m_T(W) \geq 170$ GeV



Region	SR
Observed events	7
Fitted bkg events	6.1 ± 1.9
Fitted $t\bar{t}$ events	2.5 ± 1.7
Fitted W + jets events	1.1 ± 0.7
Fitted singletop events	1.1 ± 0.7
Fitted $t\bar{t} + V$ events	0.91 ± 0.20
Fitted diboson events	0.6 ± 0.6
MC exp. bkg events	6.5

Exclusion limits on $T\bar{T} \rightarrow Zt + X$

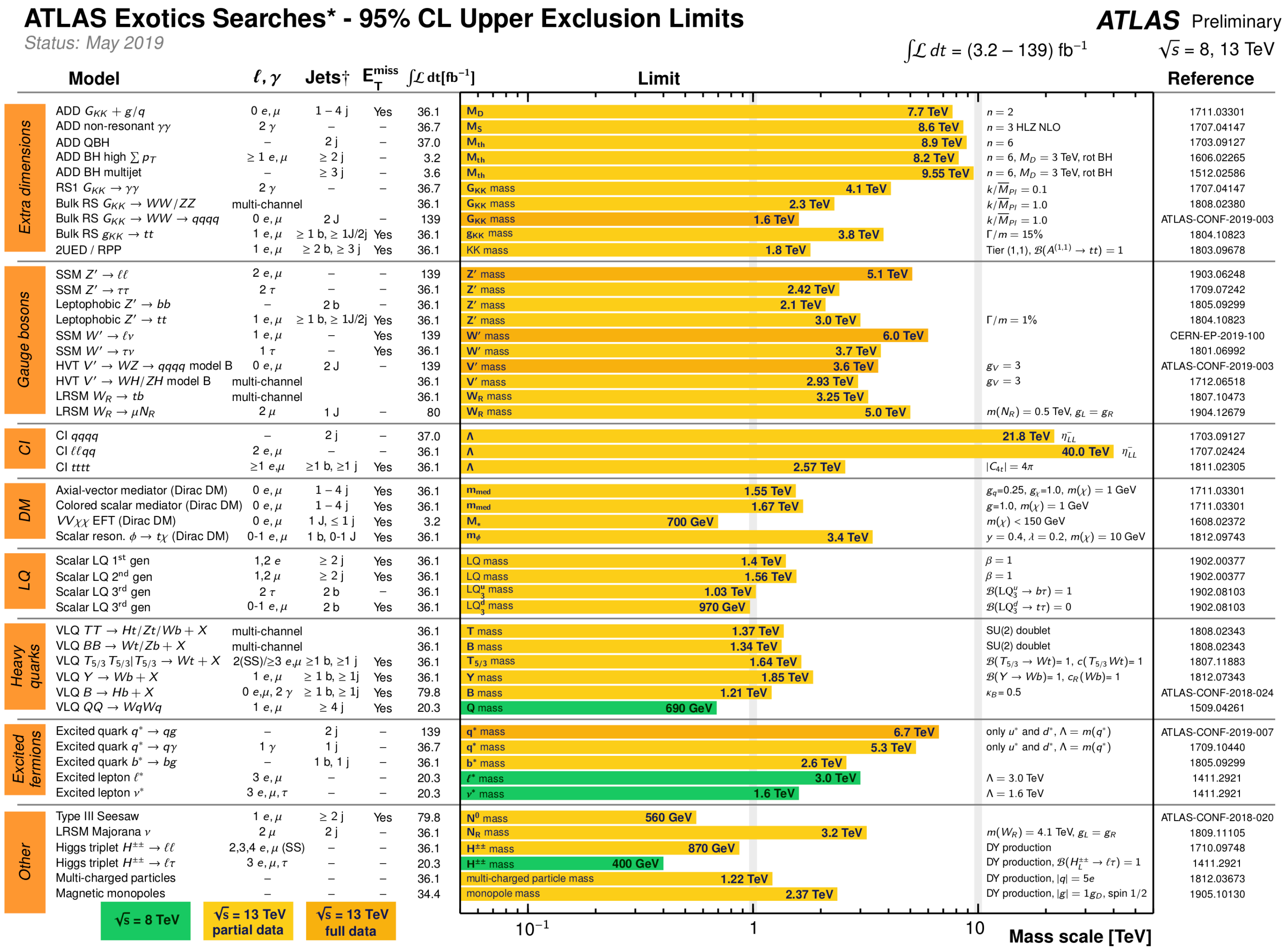


- T quarks with $m_T < 1.16$ TeV are excluded if $\mathcal{B}(T \rightarrow Zt) = 100\%$ is assumed.
- Account for other decay modes ($T \rightarrow Ht$ and $T \rightarrow Wb$):
  - Singlet model: $m_T < 0.87$ TeV
  - Doublet model: $m_T < 1.05$ TeV

Indirect vs. direct Searches for New Physics

- No evidence (yet) for *on-shell* production of new particles.
- Lower limits are growing.
- Will (soon) face steep drop in parton luminosity.

Access higher mass scales by deviations in coupling measurements and search for rare processes.



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (3.2 – 139) fb^{-1}

$\sqrt{s}$ = 8, 13 TeV

	Model	ℓ,γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK}+g/q$	0 e,μ	1 – 4 j	Yes	36.1	🟨 M_D	7.7 TeV	$n=2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S	8.6 TeV	$n=3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th}	8.9 TeV	$n=6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	🟨 M_{th}	8.2 TeV	$n=6$, $M_D=3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th}	9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\to\gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl}=0.1$	1707.04147
	Bulk RS $G_{KK}\to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl}=1.0$	1808.02380
	Bulk RS $G_{KK}\to WW\to qqqq$	0 e,μ	2 J	–	139	🟧 G_{KK} mass	1.6 TeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK}\to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass	3.8 TeV	$\Gamma/m=15\%$	1804.10823
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$	1803.09678
Gauge bosons	SSM $Z'\to\ell\ell$	2 e,μ	–	–	139	🟧 Z' mass	5.1 TeV		1903.06248
	SSM $Z'\to\tau\tau$	2 τ	–	–	36.1	🟨 Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z'\to bb$	–	2 b	–	36.1	🟨 Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z'\to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z' mass	3.0 TeV	$\Gamma/m=1\%$	1804.10823
	SSM $W'\to\ell\nu$	1 e,μ	–	Yes	139	🟧 W' mass	6.0 TeV		CERN-EP-2019-100
	SSM $W'\to\tau\nu$	1 τ	–	Yes	36.1	🟨 W' mass	3.7 TeV		1801.06992
	HVT $V'\to WZ\to qqqq$ model B	0 e,μ	2 J	–	139	🟧 V' mass	3.6 TeV	$g_V=3$	ATLAS-CONF-2019-003
	HVT $V'\to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass	2.93 TeV	$g_V=3$	1712.06518
	LRSM $W_R\to tb$	multi-channel			36.1	🟨 W_R mass	3.25 TeV		1807.10473
	LRSM $W_R\to\mu N_R$	2 μ	1 J	–	80	🟨 W_R mass	5.0 TeV	$m(N_R)=0.5$ TeV, $g_L=g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ	21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	2 e,μ	–	–	36.1	🟨 Λ	40.0 TeV	η_{LL}^{-}	1707.02424
	CI $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 Λ	2.57 TeV	$\lvert C_{4t}\rvert=4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e,μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi)=1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e,μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.67 TeV	g=1.0, $m(\chi)=1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_*	700 GeV	$m(\chi)<150$ GeV	1608.02372
	Scalar reson. $\phi\to t\chi$ (Dirac DM)	0-1 e,μ	1 b, 0-1 J	Yes	36.1	🟨 m_ϕ	3.4 TeV	$y=0.4$, $\lambda=0.2$, $m(\chi)=10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	🟨 LQ mass	1.4 TeV	$\beta=1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	🟨 LQ mass	1.56 TeV	$\beta=1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	🟨 LQ_3^u mass	1.03 TeV	$\mathcal{B}(LQ_3^u\to b\tau)=1$	1902.08103
	Scalar LQ 3rd gen	0-1 e,μ	2 b	Yes	36.1	🟨 LQ_3^d mass	970 GeV	$\mathcal{B}(LQ_3^d\to t\tau)=0$	1902.08103
Heavy quarks	VLQ $TT\to Ht/Zt/Wb+X$	multi-channel			36.1	🟨 T mass	1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB\to Wt/Zb+X$	multi-channel			36.1	🟨 B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\vert T_{5/3}\to Wt+X$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 $T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y\to Wb+X$	1 e,μ	≥ 1 b, ≥ 1j	Yes	36.1	🟨 Y mass	1.85 TeV	$\mathcal{B}(Y\to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B\to Hb+X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ\to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	🟩 Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^*\to qg$	–	2 j	–	139	🟧 q^* mass	6.7 TeV	only u^* and d^*, $\Lambda=m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^*\to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass	5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1709.10440
	Excited quark $b^*\to bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	🟩 ℓ^* mass	3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	🟩 ν^* mass	1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e,μ	≥ 2 j	Yes	79.8	🟨 N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	🟨 N_R mass	3.2 TeV	$m(W_R)=4.1$ TeV, $g_L=g_R$	1809.11105
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	2,3,4 e,μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm}\to\ell\tau$	3 e,μ,τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm}\to\ell\tau)=1$	1411.2921
	Multi-charged particles	–	–	–	36.1	🟨 multi-charged particle mass	1.22 TeV	DY production, $\lvert q\rvert=5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	🟨 monopole mass	2.37 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV partial data

🟧 $\sqrt{s}$ = 13 TeV full data

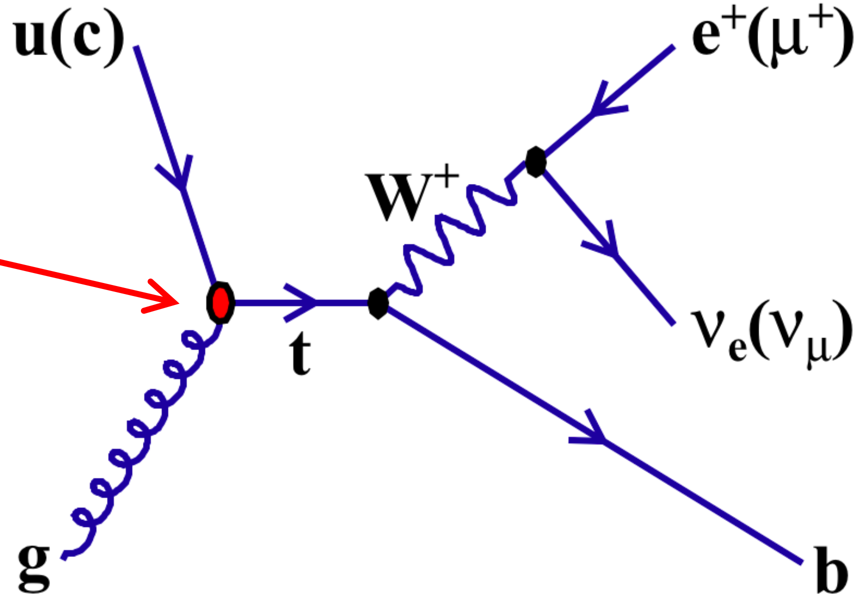
*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Chapter 4

Indirect searches / searches for anomalous couplings

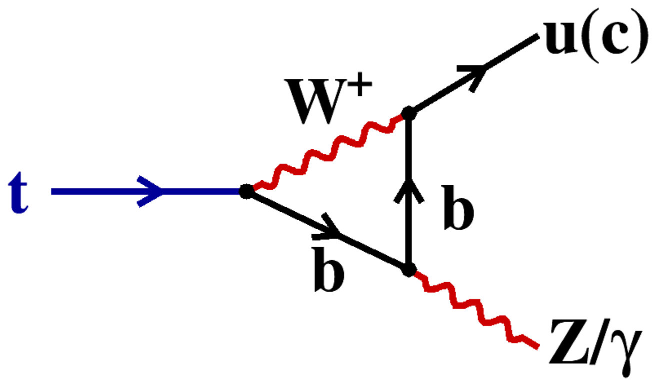
Parameterise new physics (full theory) by effective couplings at vertices.



→ Recall Fermi theory of nuclear beta decay

Decays via flavour-changing neutral currents (FCNC)

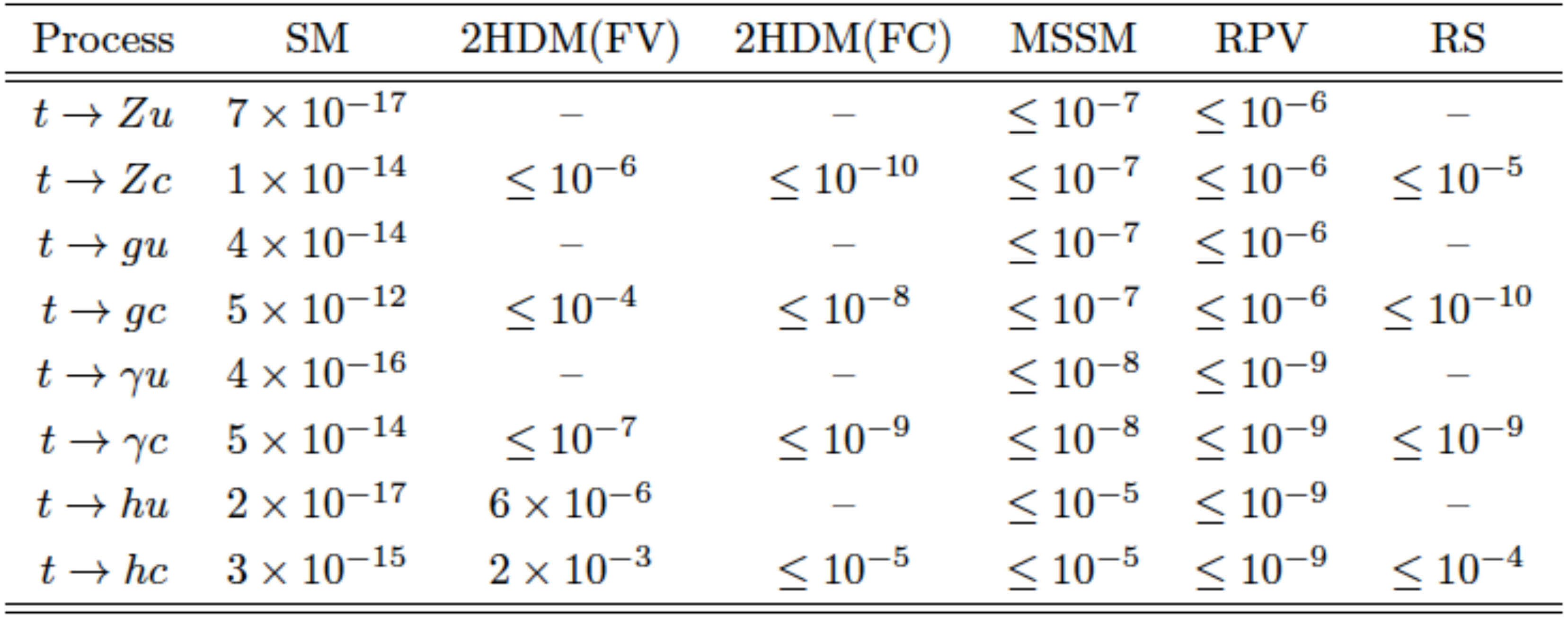
- Do not exist at tree (Born) level in the SM
- Very strongly suppressed at next-to-leading order (loop level): GIM mechanism = CKM unitarity
- Suppression is lifted by non-degenerate quark masses.
- Branching ratios are extremely small.



	$Br(t \to q\gamma)$	$Br(t \to qZ)$	$Br(t \to qg)$
$q = u$	3.7×10^{-16}	8×10^{-17}	3.7×10^{-14}
$q = c$	4.6×10^{-14}	1×10^{-14}	4.6×10^{-12}

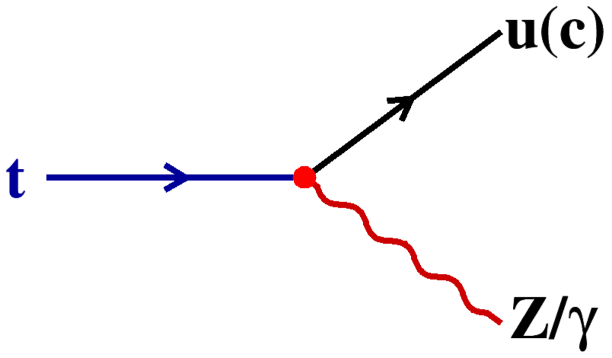
FCNC in theories beyond the SM

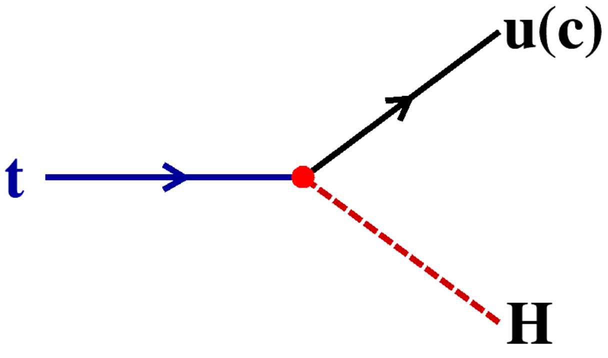
Branching ratios of top-quark decays in SM and BSM theories:

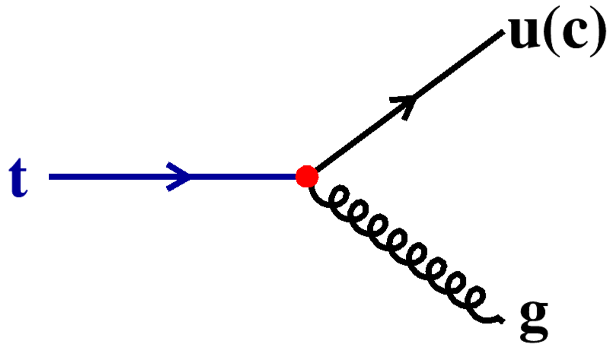


Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Snowmass Workshop 2013, arXiv: 1311.2028



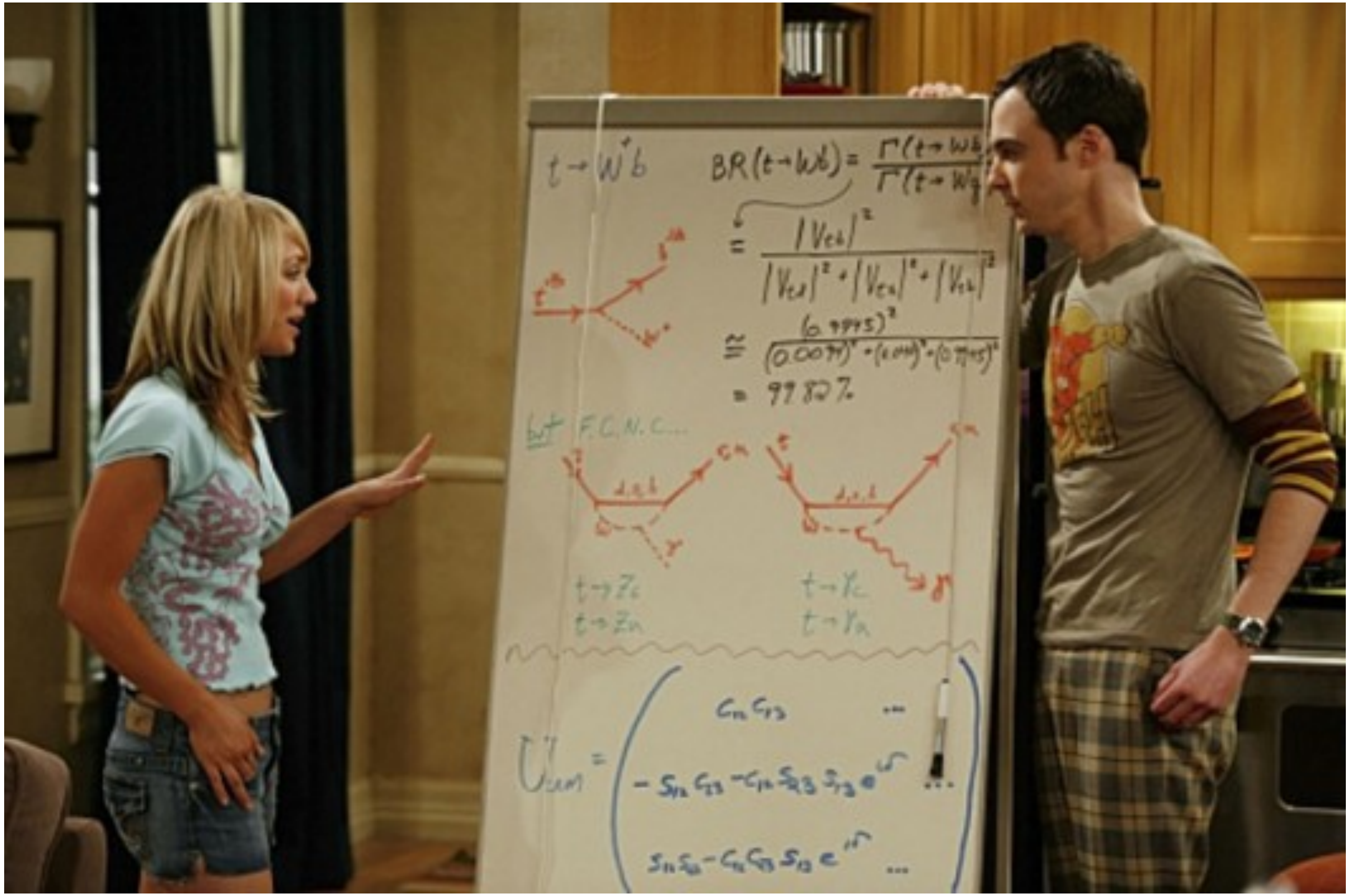




Strong enhancement!

Any FCNC signal is evidence for BSM physics!

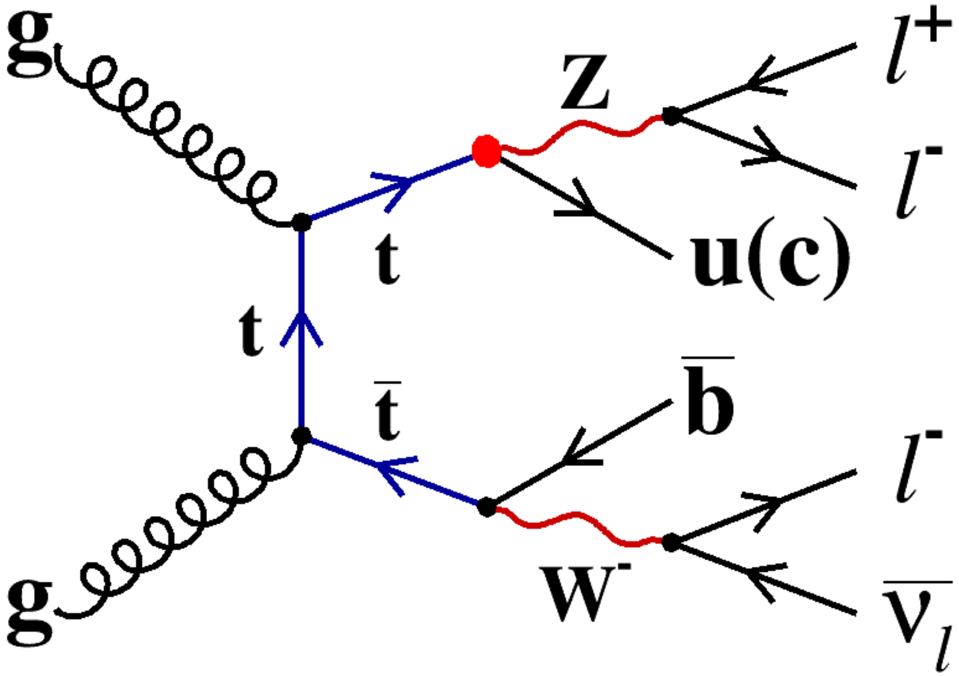
Even Hollywood knows: FCNC are exiting!



The Big Bang Theory

Search for $t \rightarrow qZ$ in $t\bar{t}$ production

ATLAS Collaboration, Search for flavour-changing neutral current top-quark decays $t \rightarrow qZ$ in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Journal of High Energy Physics (JHEP) 07 (2018) 176. arXiv: 1803.09923.



Signature and event selection

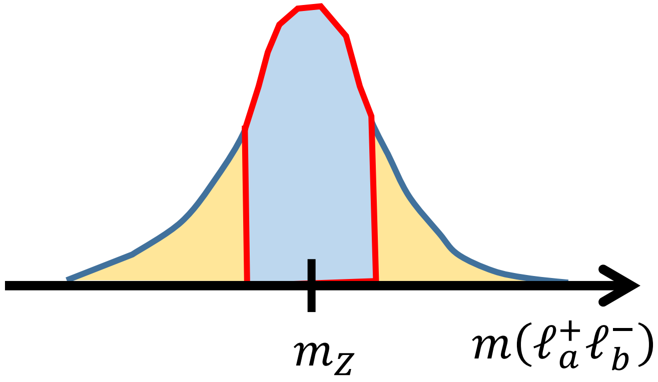
- 3 high-p_T, isolated charged leptons ($e^\pm$ or $\mu^\pm$) with $p_T > 15$ GeV
  - One if them with $p_T > 27$ GeV (trigger)
- ≥ 2 jets with $p_T > 25$ GeV
  - Exactly one of them *b*-tagged
- $E_T^{\text{miss}} > 20$ GeV

Main backgrounds:

- $t\bar{t}Z, tZ, WZ$ and ZZ production
- Non-prompt leptons from $Z +$ jets and $t\bar{t}$ production

Event reconstruction

- Reconstruction of the Z boson candidate ($Z^0 = \ell_a^+ \ell_b^-$)
  - Require opposite-sign (charge) same-flavour lepton pair (e^+e^- or $\mu^+\mu^-$)
  - $|m(\ell_a^+ \ell_b^-) - m_Z| < 15$ GeV
  - If two combinations, choose the pair closest to m_Z



- Reconstruction of top-quark candidates:
  - Minimize

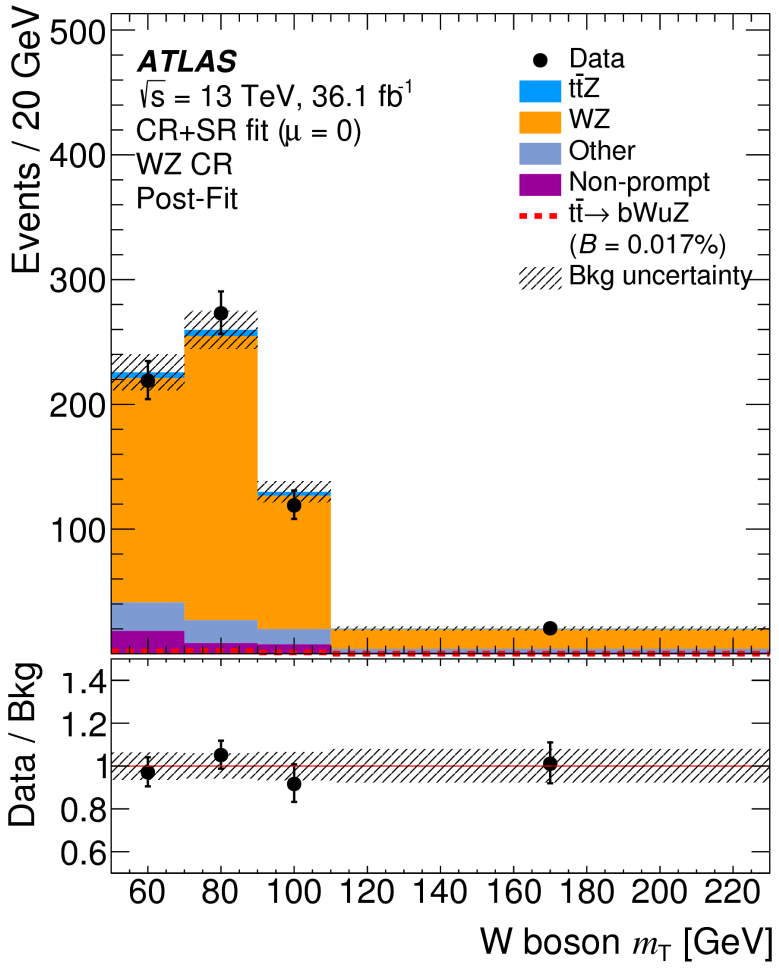
$$\chi^2 = \frac{\left(m^{\mathrm{reco}}_{j_a \ell_a \ell_b} - m_{t_{\mathrm{FCNC}}}\right)^2}{\sigma^2_{t_{\mathrm{FCNC}}}} + \frac{\left(m^{\mathrm{reco}}_{j_b \ell_c \nu} - m_{t_{\mathrm{SM}}}\right)^2}{\sigma^2_{t_{\mathrm{SM}}}} + \frac{\left(m^{\mathrm{reco}}_{\ell_c \nu} - m_W\right)^2}{\sigma^2_W}$$

  - Determine $p_z(\nu)$
  - Jet assignment
- Selection cuts: $\left|m^{\mathrm{reco}}_{j_a \ell_a \ell_b} - 172.5\ \mathrm{GeV}\right| < 40$ GeV, $\left|m^{\mathrm{reco}}_{j_b \ell_c \nu} - 172.5\ \mathrm{GeV}\right| < 40$ GeV, $\left|m^{\mathrm{reco}}_{\ell_c \nu} - 80.4\ \mathrm{GeV}\right| < 30$ GeV

Background estimate via control regions

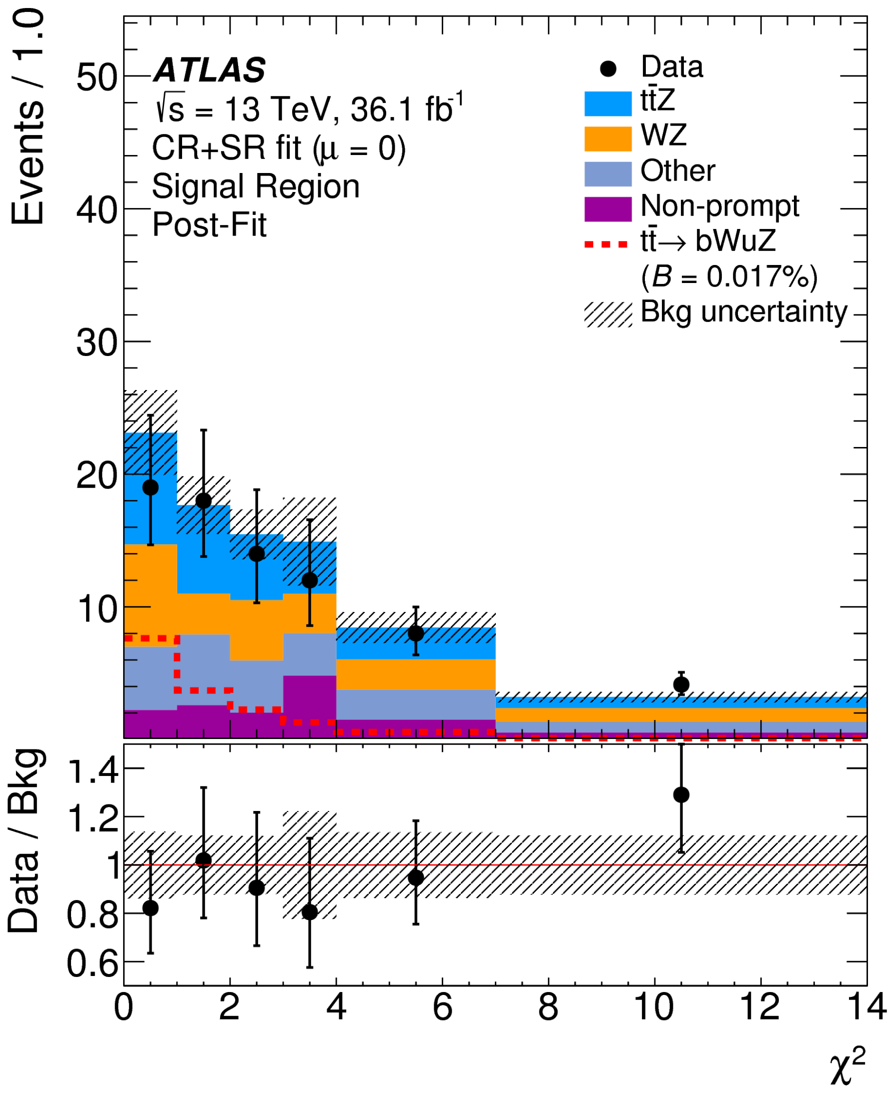
5 control regions are defined to determine the background rates

Sample	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0	Non-prompt lepton CR1
$t\bar{t}Z$	61 ± 9	16.3 ± 3.1	0 ± 0	6.1 ± 1.2	22.1 ± 3.2
WZ	9 ± 9	560 ± 240	0 ± 0	150 ± 70	20 ± 9
ZZ	0.07 ± 0.03	48 ± 11	92 ± 20	58 ± 16	9.0 ± 2.3
Non-prompt leptons	3 ± 6	28 ± 16	0 ± 0	150 ± 50	140 ± 70
Other backgrounds	13.4 ± 2.7	22 ± 5	1.0 ± 0.6	17 ± 6	32 ± 6
Total background	87 ± 15	670 ± 240	93 ± 20	380 ± 90	230 ± 70
Data	81	734	87	433	260
Data / Bkg	0.94 ± 0.19	1.1 ± 0.4	0.94 ± 0.23	1.13 ± 0.28	1.1 ± 0.4

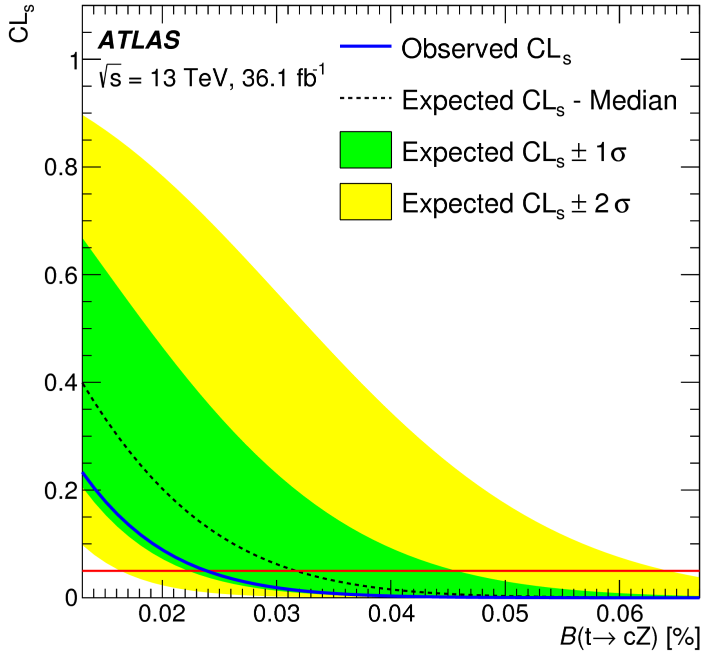


For each region the distribution of a particular discriminant is included in the final maximum likelihood fit.

Fit result and upper limits

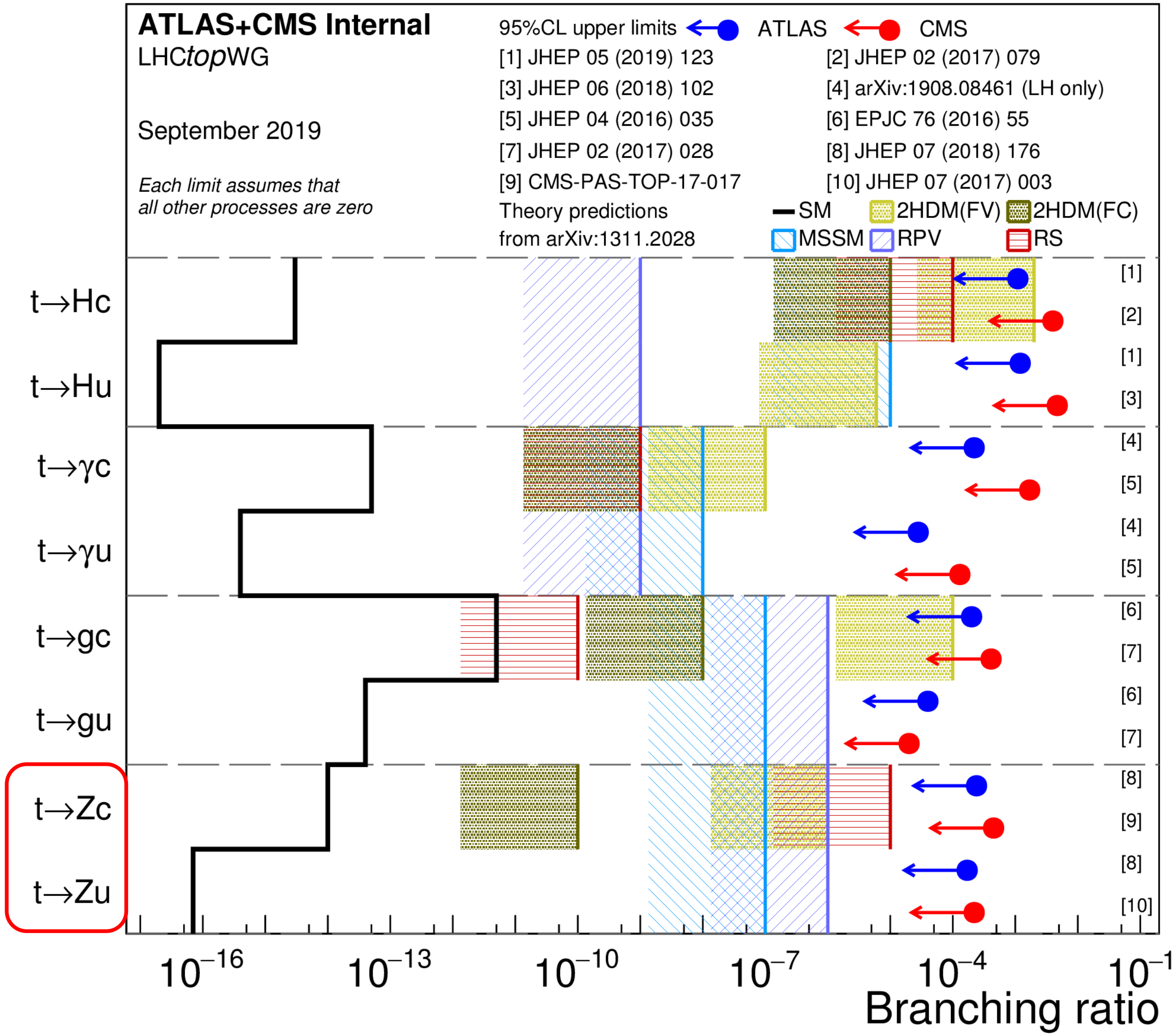


- Use CLs method to set upper limits.
- Test statistic: $q_\mu = -2\ \ln\dfrac{L\left(\mu,\hat{\hat{\theta}}\right)}{L\left(\hat{\mu},\hat{\theta}\right)}$



$\mathcal{B}(t\ \rightarrow uZ) < 1.7\ \cdot\ 10^{-4}$ and $\mathcal{B}(t\ \rightarrow cZ) < 2.4\ \cdot\ 10^{-4}$

Status of FCNC limits

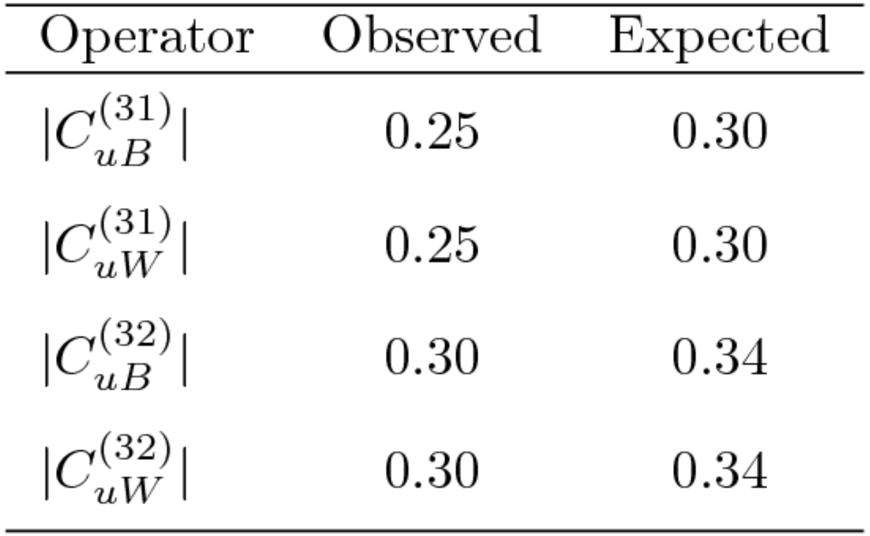


This analysis

Interpretation in an Effective Field Theory

Use generic framework to parameterise Beyond the Standard Model contributions:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i C_i \, \mathcal{O}_i + \text{h.c.}$$



Operator	Observed	Expected
$\lvert C_{uB}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uW}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uB}^{(32)} \rvert$	0.30	0.34
$\lvert C_{uW}^{(32)} \rvert$	0.30	0.34

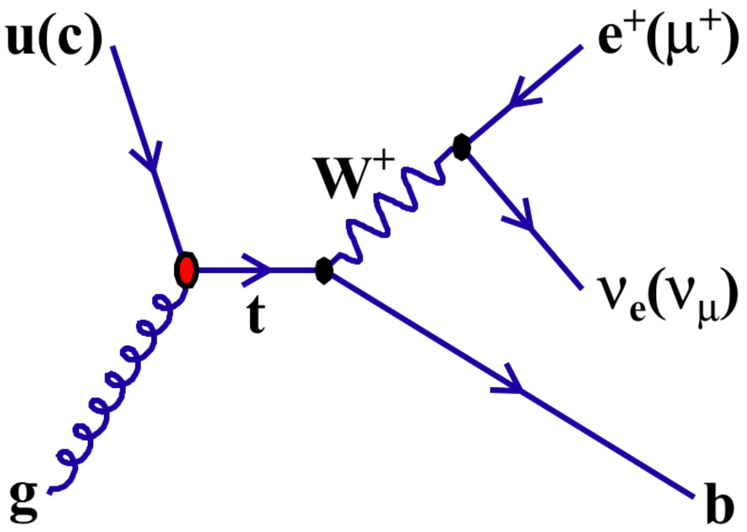
Use MadGraph5_aMC@NLO and FeynRules2.0 with the TopFCNC model.

Relevant operators for tqZ coupling:

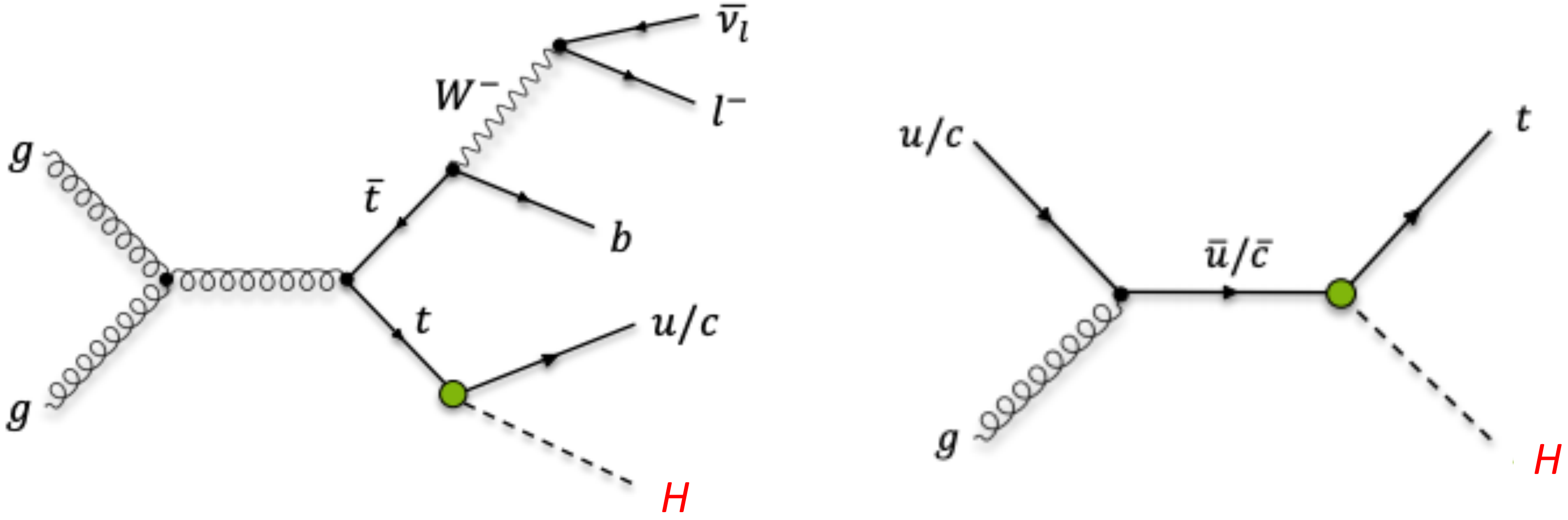
$\mathcal{O}_{uB}^{(3i)} = g_Y \, (\bar{q}_i \, \sigma^{\mu\nu} \, t) \, \tilde{\varphi} \, B_{\mu\nu}$ and

$\mathcal{O}_{uW}^{(3i)} = g_W \, (\bar{q}_i \, \sigma^{\mu\nu} \, \tau^I \, t) \, \tilde{\varphi} \, W_{\mu\nu}^I$

FCNC analysis in preparation



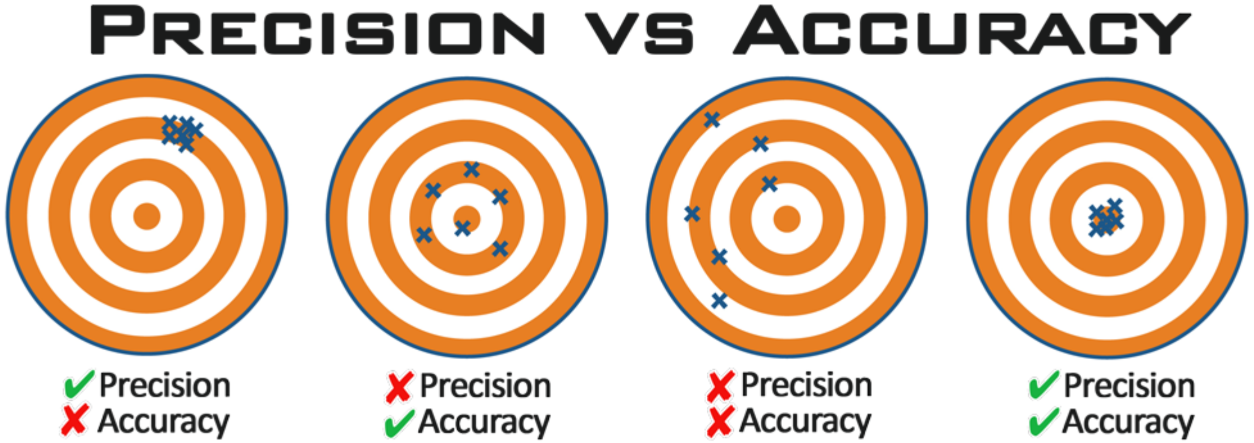
Search for single top-quark production via top-quark-gluon FCNC



Search for top-quark-Higgs FCNC couplings in top-quark decay and single top-quark production

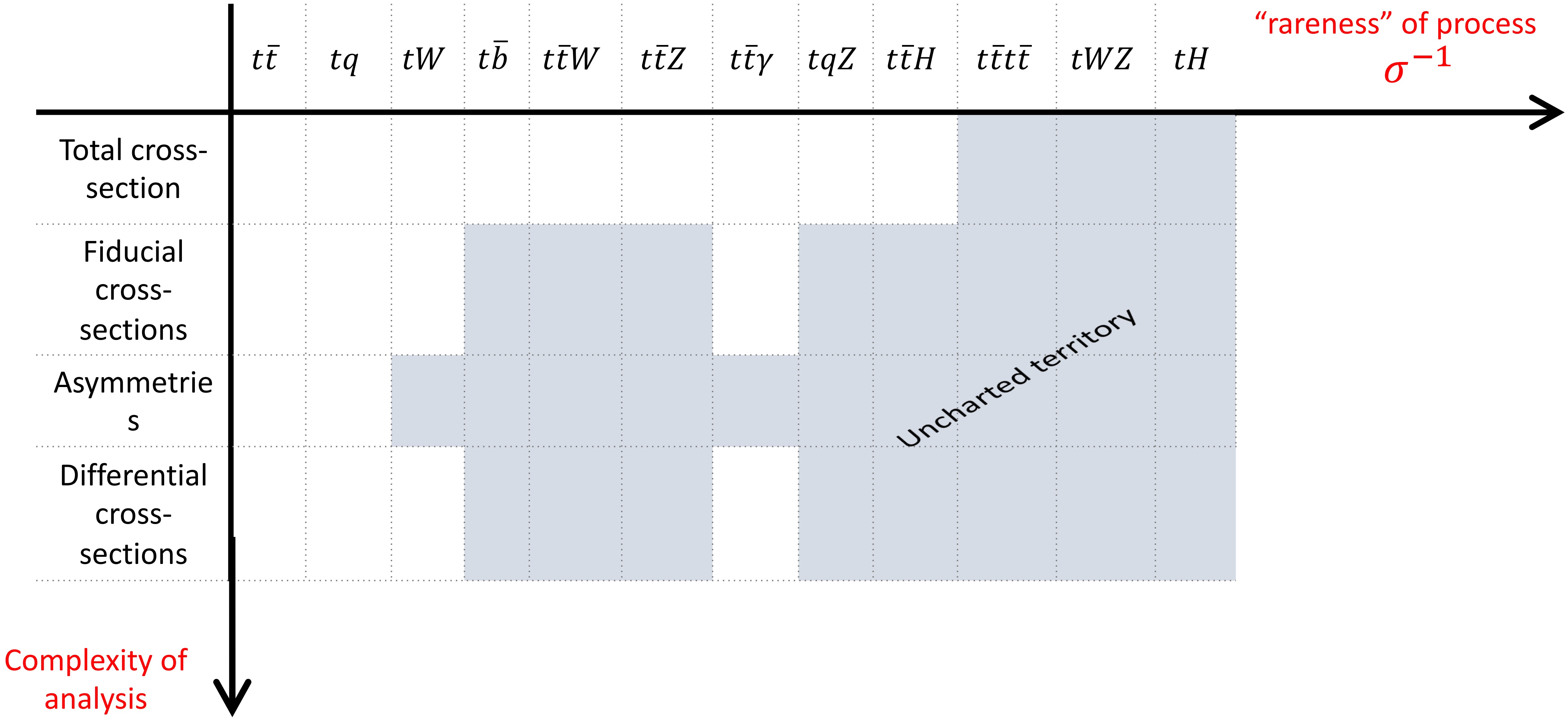
Chapter 5

Precision measurements of top-quark properties



Reduce statistical and systematic uncertainties!

Pushing the frontiers of complexity

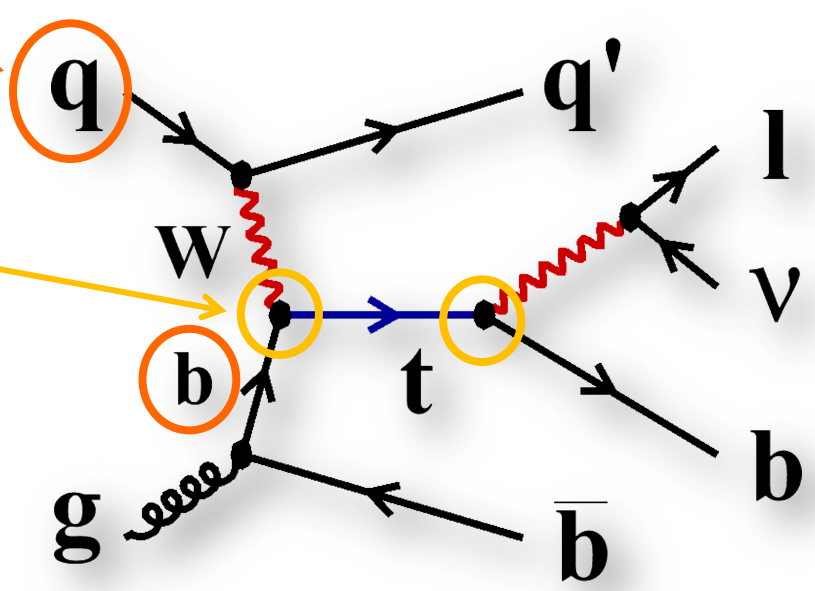


	$t\bar{t}$	tq	tW	$t\bar{b}$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}\gamma$	tqZ	$t\bar{t}H$	$t\bar{t}t\bar{t}$	tWZ	tH
Total cross-section										▨	▨	▨
Fiducial cross-sections				▨	▨	▨		▨	▨	▨	▨	▨
Asymmetries			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Differential cross-sections				▨	▨	▨		▨	▨	▨	▨	▨

“rareness” of process σ^{-1}

Complexity of analysis

An example: *t*-channel single top-quark production



parton distribution functions:
u-quark, *d*-quark, *b*-quark

weak coupling
- V_{tb}
- Lorentz structure

ATLAS Collaboration, Fiducial, total and differential cross-section measurements of *t*-channel single top-quark production in pp collisions at 8 TeV using data collected by the ATLAS detector, Eur. Phys. J. C 77 (2017) 531. arXiv: 1702.02859.

Observables

- total cross-sections

$$\sigma(tq) \quad \sigma(\bar{t}q)$$

- cross-section ratio

$$R_t = \frac{\sigma(tq)}{\sigma(\bar{t}q)}$$

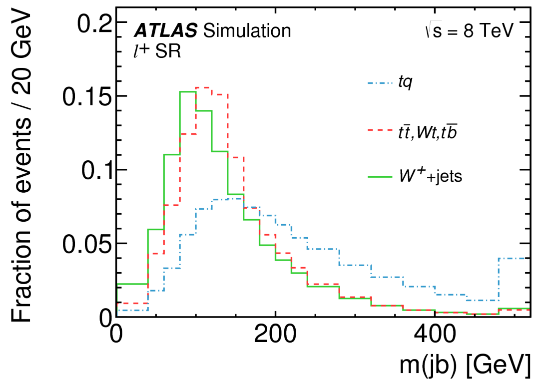
- differential cross-sections

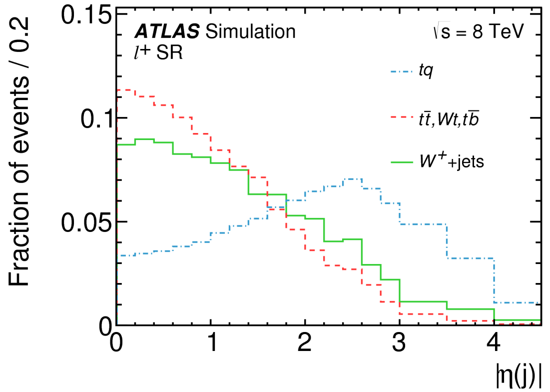
$$\frac{d\sigma(tq)}{dp_{\mathrm{T}}(t)} \quad \frac{d\sigma(tq)}{d|y(t)|}$$

Separating signal and background events with neural networks

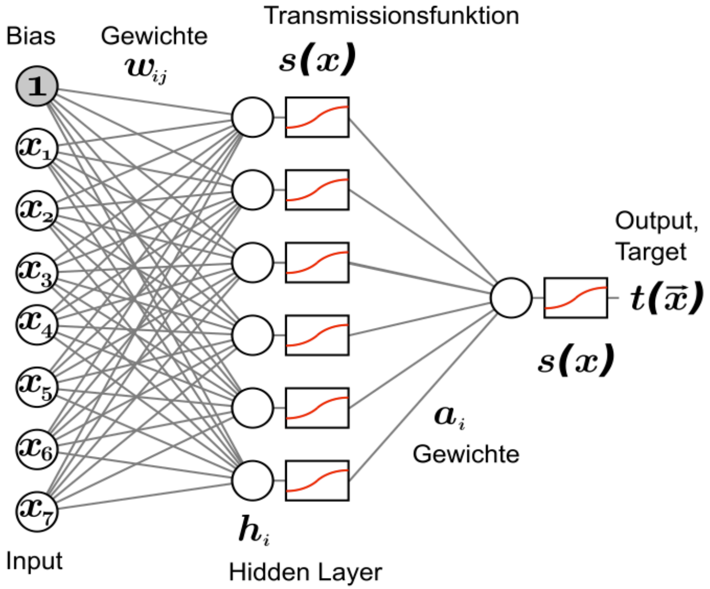
Signal purity after „regular“ event selection: 21% for tq and 14% for $\bar{t}q$

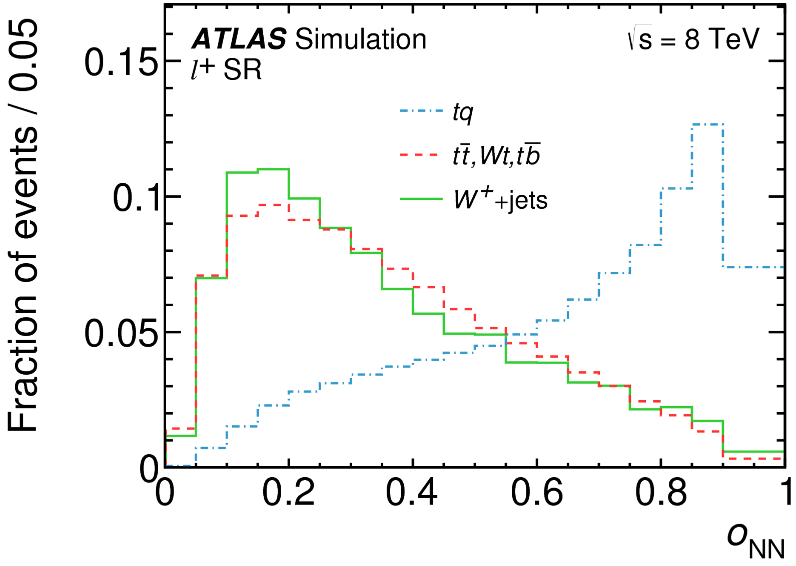
⇒ improve purity with multivariate methods





⋮

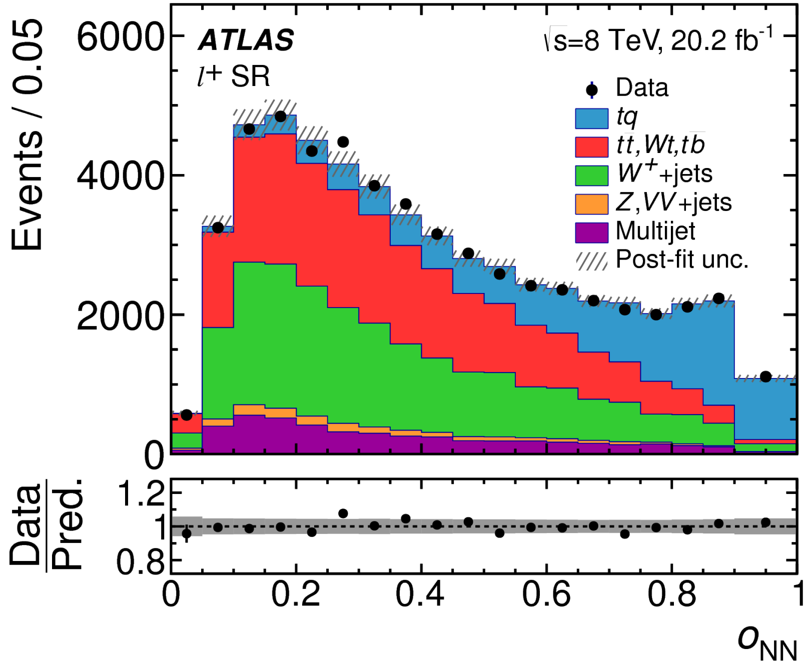




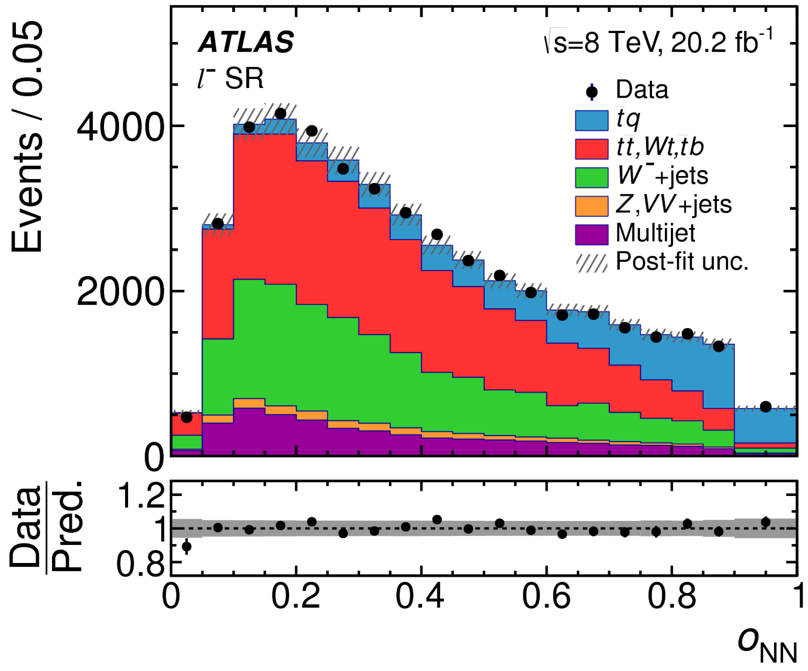
Determine yield of signal events

Perform a maximum likelihood fit to the discriminant distributions.

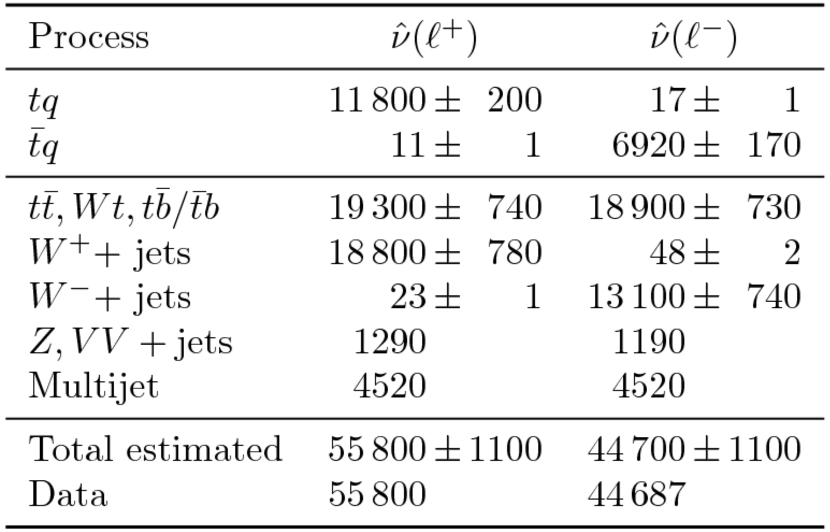
+ channel (top-quarks)



- channel (top-antiquarks)



Estimated event yields



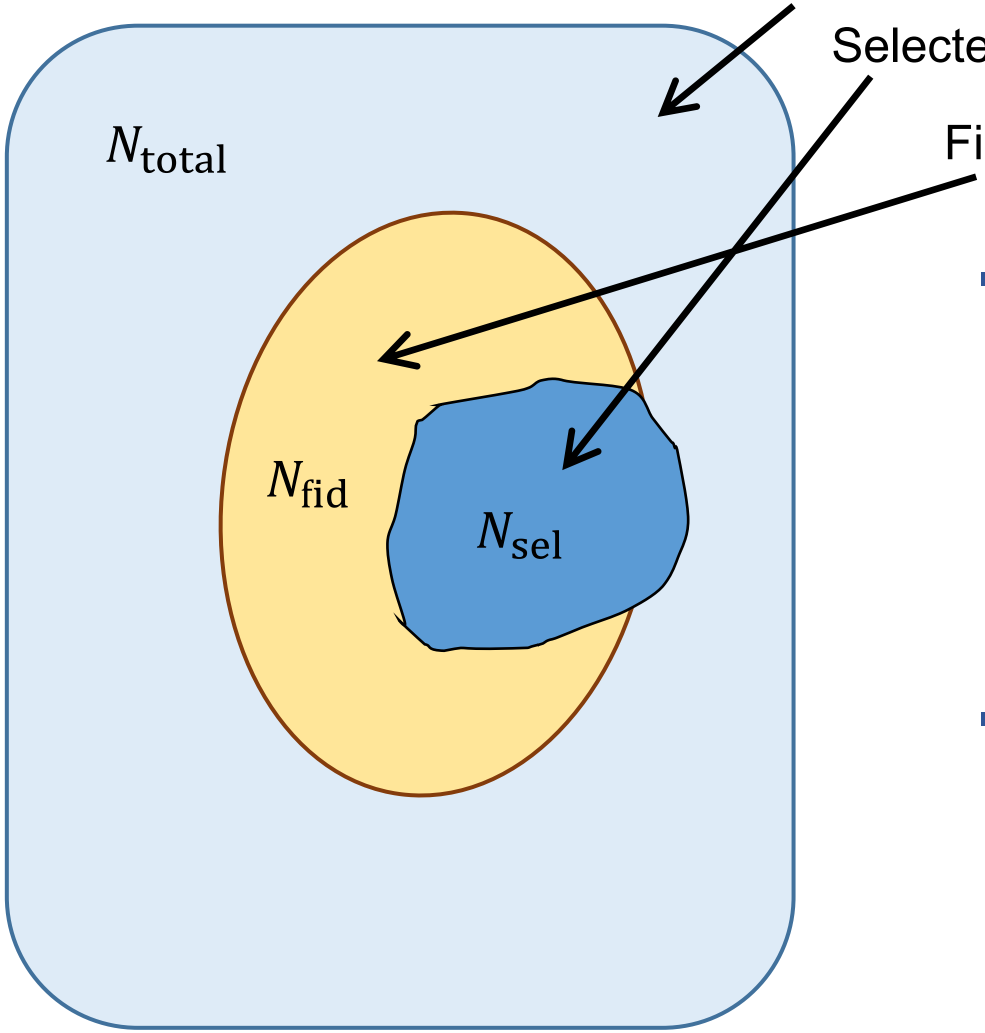
Process	$\hat{\nu}(\ell^+)$	$\hat{\nu}(\ell^-)$
tq	$11\,800 \pm 200$	17 ± 1
$\bar{t}q$	11 ± 1	6920 ± 170
$t\bar{t}, Wt, t\bar{b}/\bar{t}b$	$19\,300 \pm 740$	$18\,900 \pm 730$
$W^+ +$ jets	$18\,800 \pm 780$	48 ± 2
$W^- +$ jets	23 ± 1	$13\,100 \pm 740$
$Z, VV +$ jets	1290	1190
Multijet	4520	4520
Total estimated	$55\,800 \pm 1100$	$44\,700 \pm 1100$
Data	55 800	44 687

Regular way to turn event yields into cross-sections:

$$\hat{\sigma}_{\text{total}} = \frac{\hat{\nu}}{\varepsilon_{\text{total}}\,\mathcal{L}_{\text{int}}}$$

Total event detection efficiency

Fiducial cross-sections



Full phase space (parton level)

Selected phase space (reconstruction level)

Fiducial phase space (particle level)

- Implement selection at the level of stable particles in samples of obtained with Monte Carlo event generators (NLO matrix-element generators matched to parton shower generators)

  → determine fiducial acceptance: $A_{\text{fid}} = \frac{N_{\text{fid}}}{N_{\text{total}}}$

- Determine cross-section with respect to the fiducial phase space:

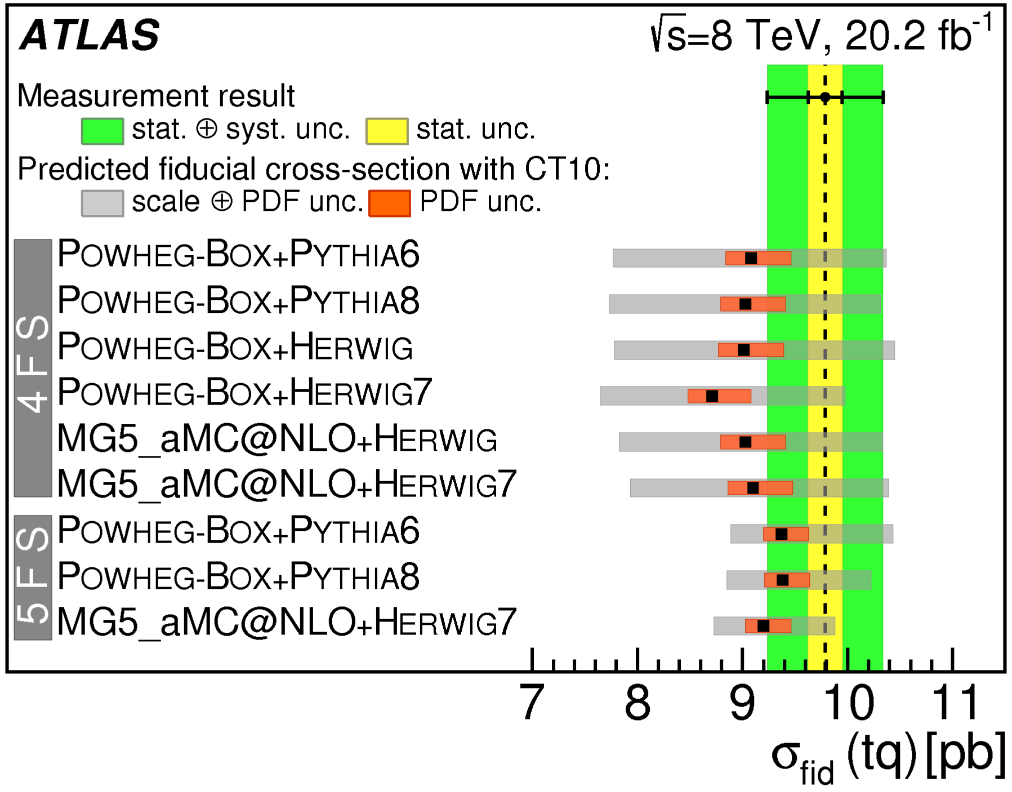
$$\sigma_{\text{fid}} = \frac{N_{\text{fid}}}{N_{\text{sel}}} \cdot \frac{\hat{\nu}}{L_{\text{int}}}$$

→ Extrapolation and associated uncertainties are reduced!

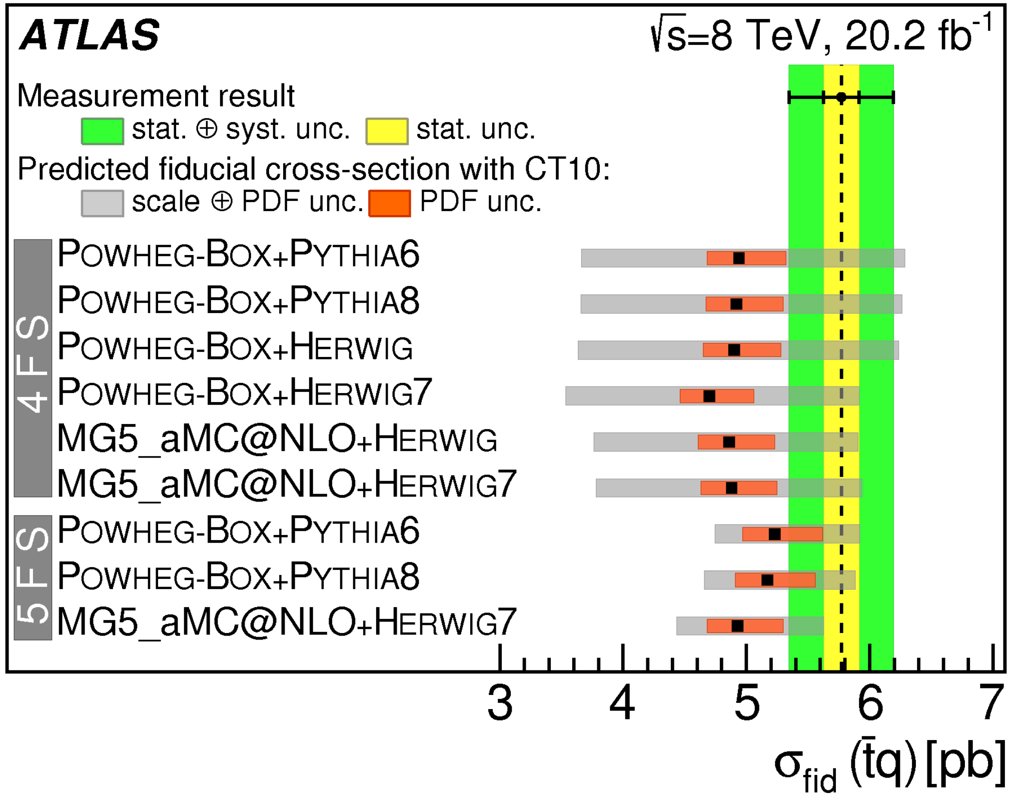
Fiducial tq and $\bar{t}q$ cross-section results

Comparison to predictions by NLO ME generators + different parton-shower programs.

Top-quark



Top-antiquark

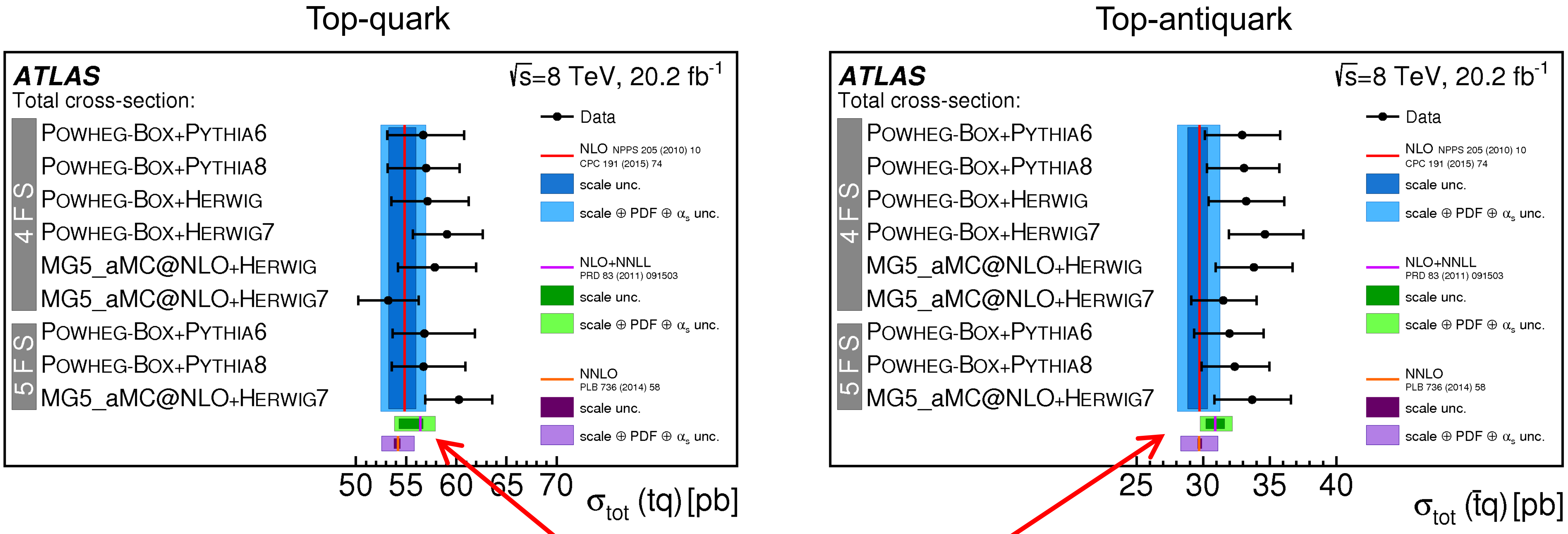


Total uncertainty: 5.8 % (top-quark)

Total uncertainty: 7.8 % (top-antiquark)

Total cross-sections

Extrapolation to the full phase space: $\sigma_{\text{tot}} = \frac{1}{A_{\text{fid}}} \cdot \sigma_{\text{fid}}$ Done for different generator setups.



Comparison to fixed-order calculations

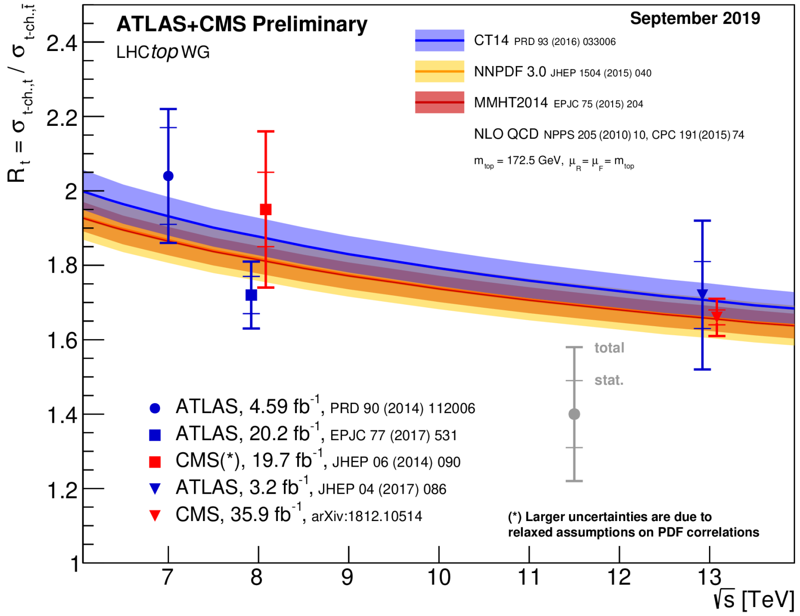
Total uncertainty: $^{+7.6}_{-6.7}$ % (top-quark)

Total uncertainty: $^{+9.1}_{-8.4}$ % (top-antiquark)

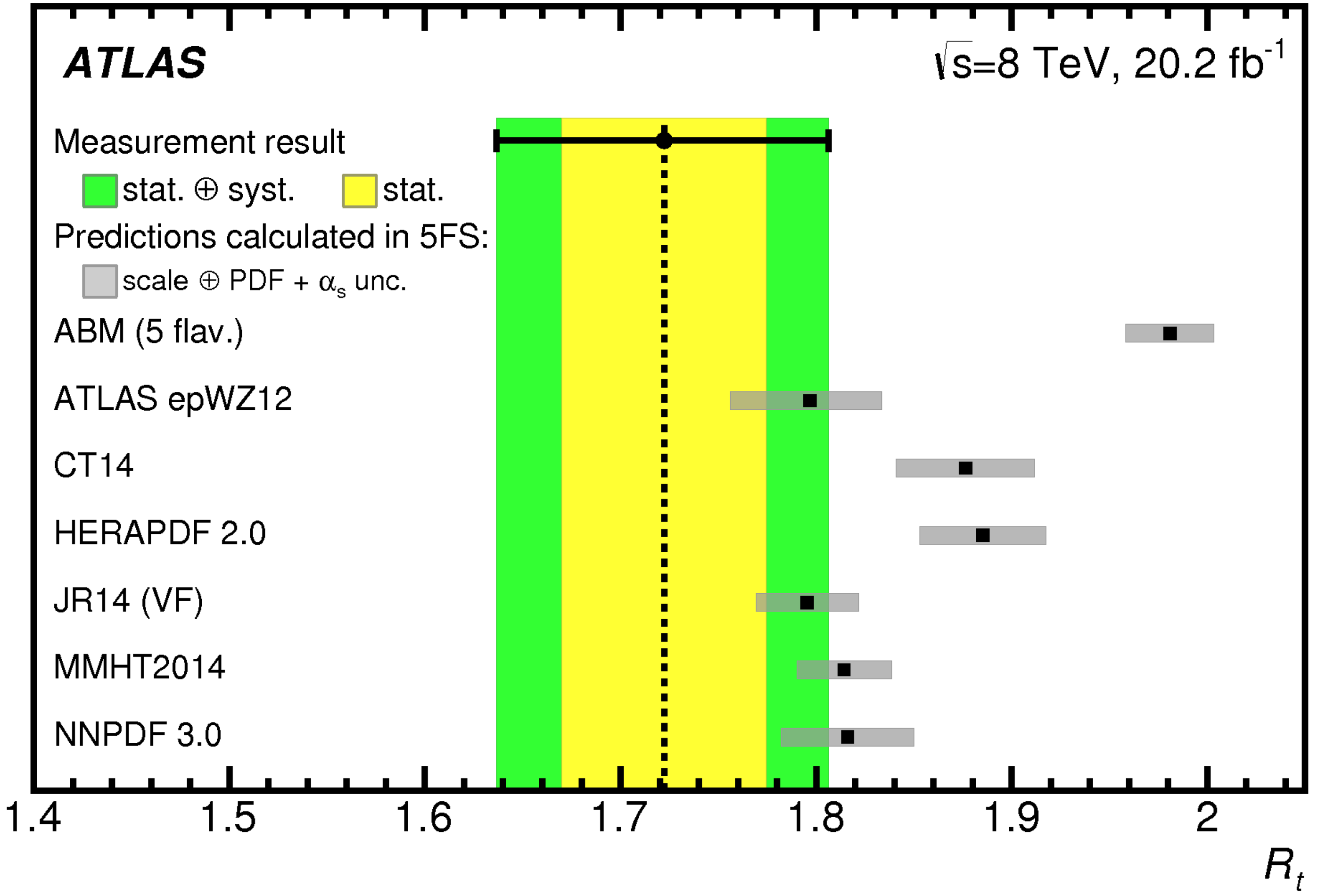
Cross-section ratio R$_t$ of tq to $\bar{t}q$ production

$$R_t = \frac{\sigma_{\text{tot}}(tq)}{\sigma_{\text{tot}}(\bar{t}q)}$$

- Total uncertainty: **± 5.0 %**
- Statistically limited
- Comparison to predictions with different PDF sets.



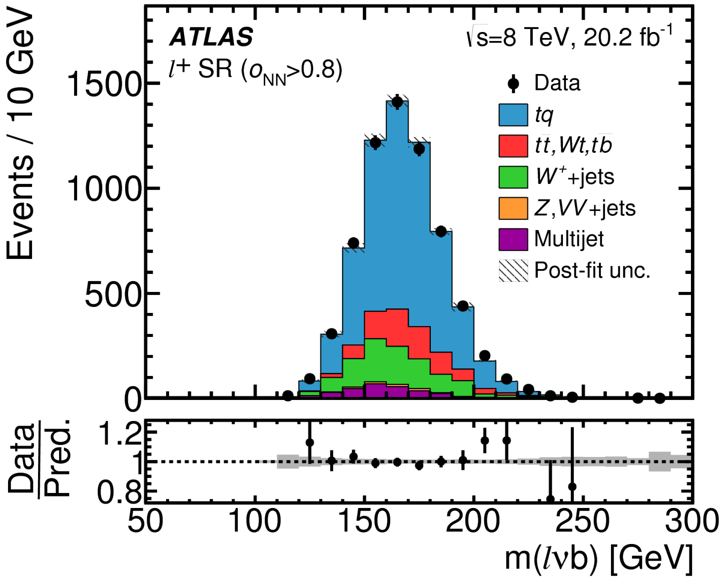
$$R_t = \frac{\sigma_{\text{tot}}(tq)}{\sigma_{\text{tot}}(\bar{t}q)} = 1.72 \pm 0.05\,(\text{stat.}) \pm 0.07\,(\text{exp.}) = 1.72 \pm 0.09$$

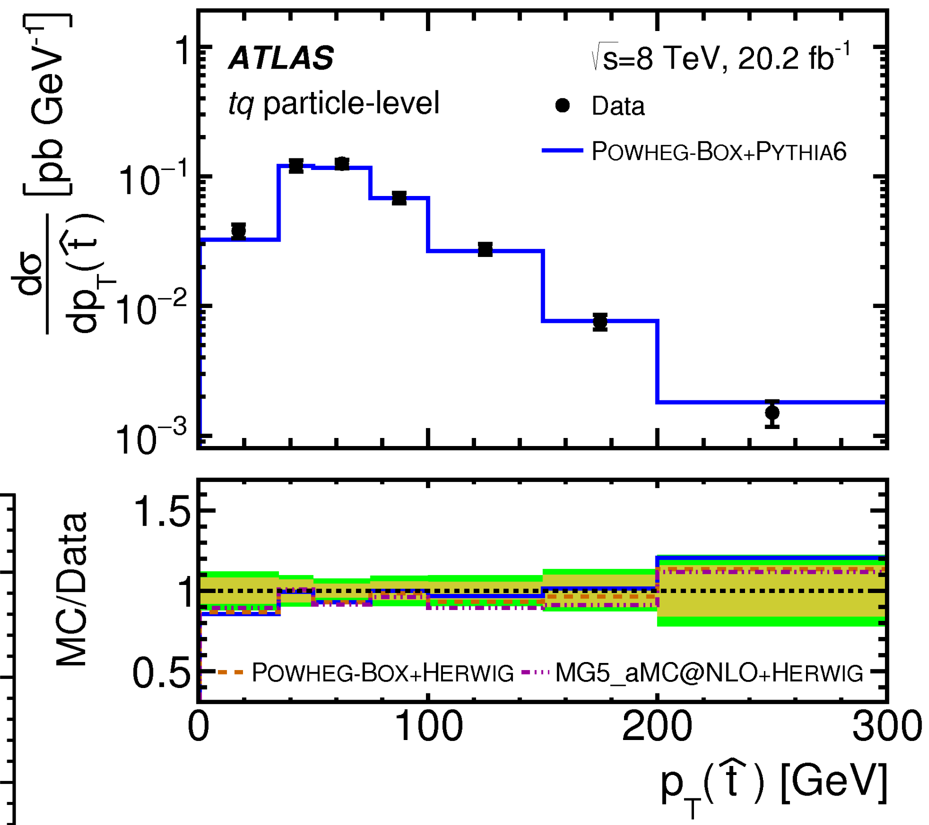


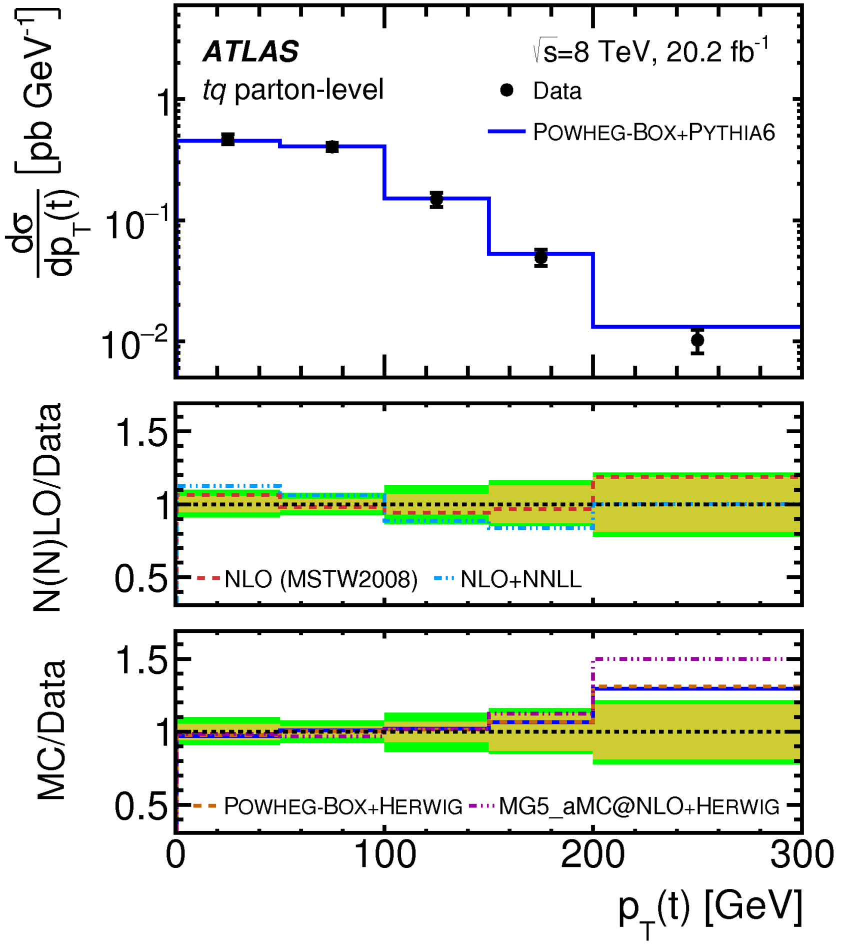
arXiv: 1702.02859 [hep-ex]

Differential tq and $\bar{t}q$ cross-sections

- Enrich *tq* events by cut on NN discriminant
- Particle level:
  use pseudo-top quark ($\hat{t}$),
  defined with stable particles
- Parton level:
  compare unfolded data also
  to fixed-order calculations





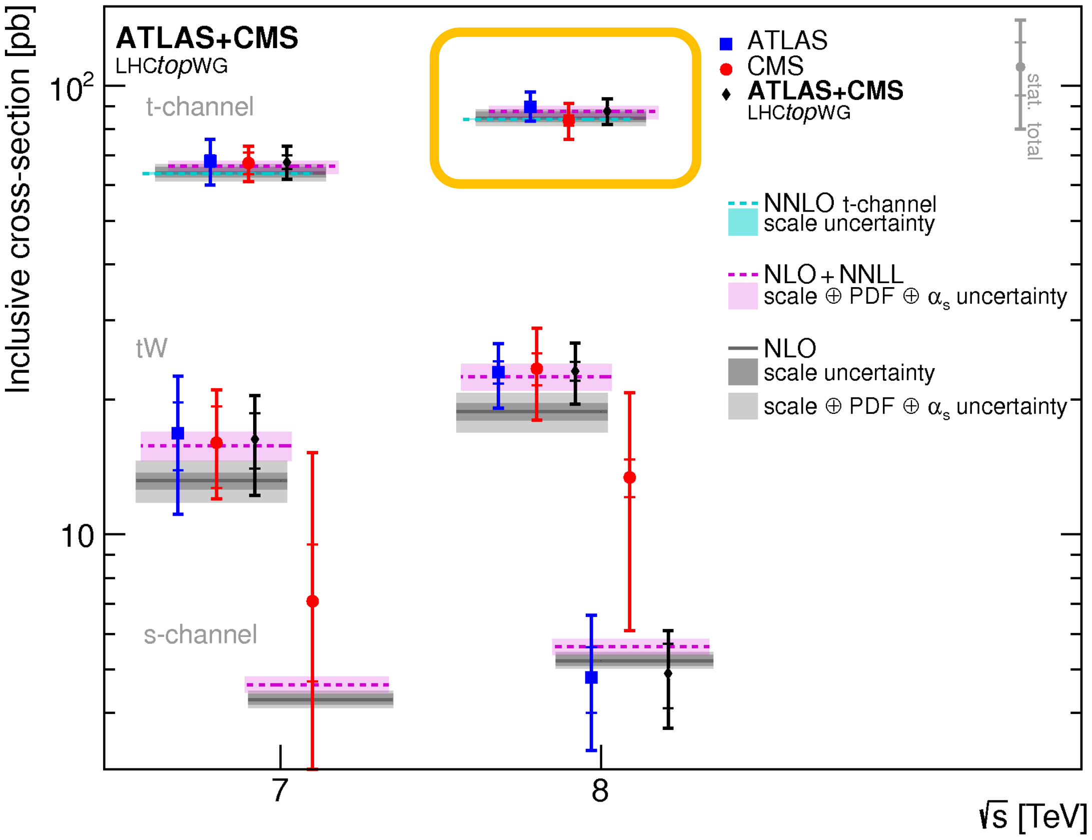


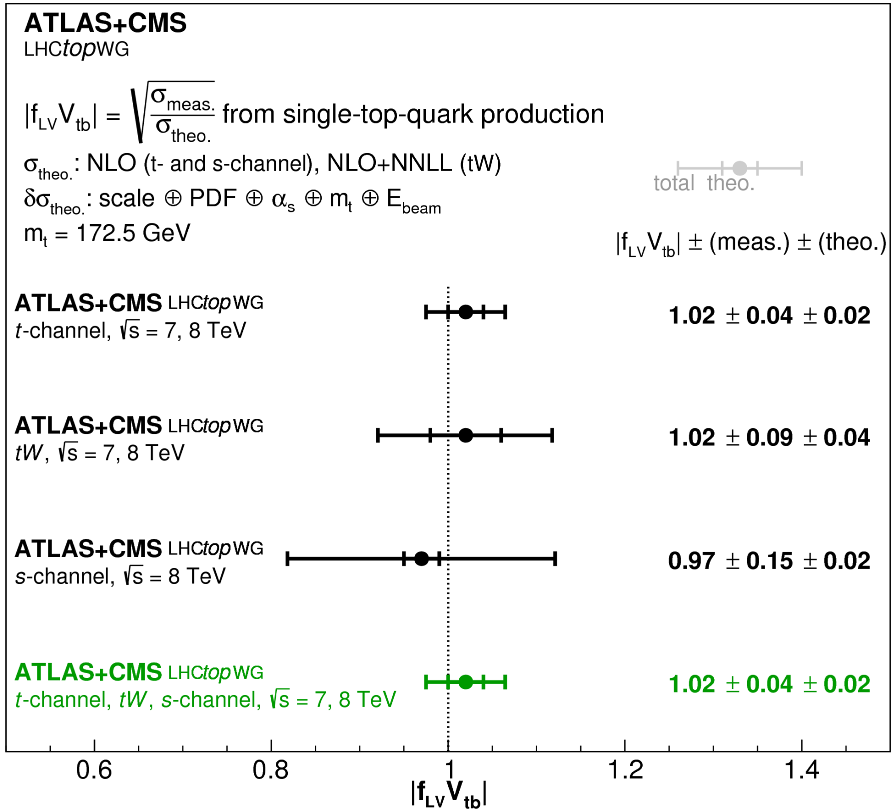
Observe good agreement with predictions by NLO generators.

Combination with CMS and determination of $|f_{LV} \cdot V_{tb}|$

JHEP 05 (2019) 088

Using $|f_{\mathrm{LV}} \cdot V_{tb}| = \sqrt{\dfrac{\sigma_{\mathrm{meas}}}{\sigma_{\mathrm{pred}}}}$

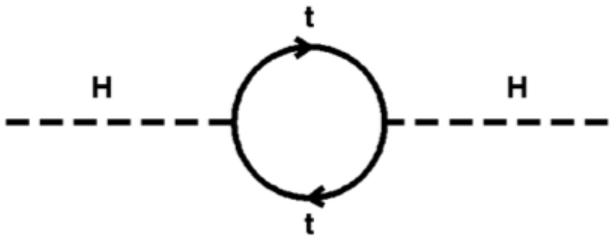


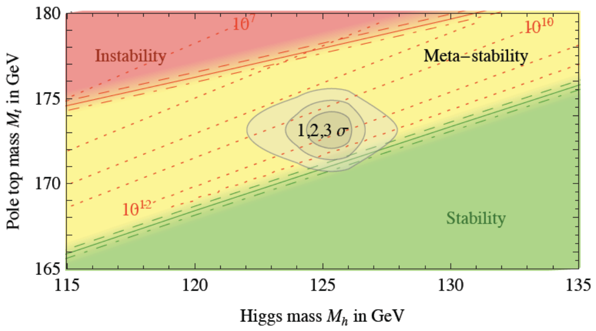


- Define the additional left-handed form factor f_{LV} to parameterise deviations from the SM.
- Assume V-A vertex structure to be unchanged.

Zusammenfassung

Die Rolle des Top-Quarks im Standardmodell

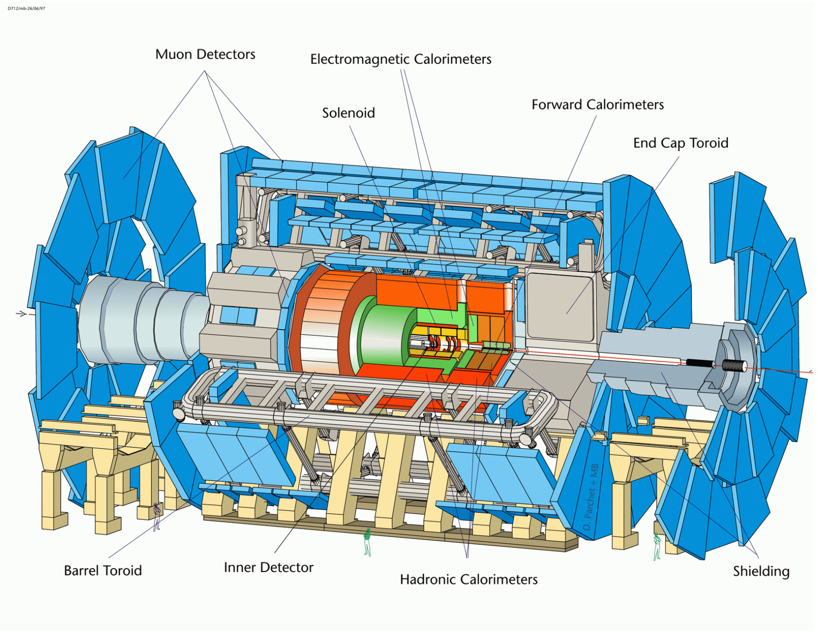


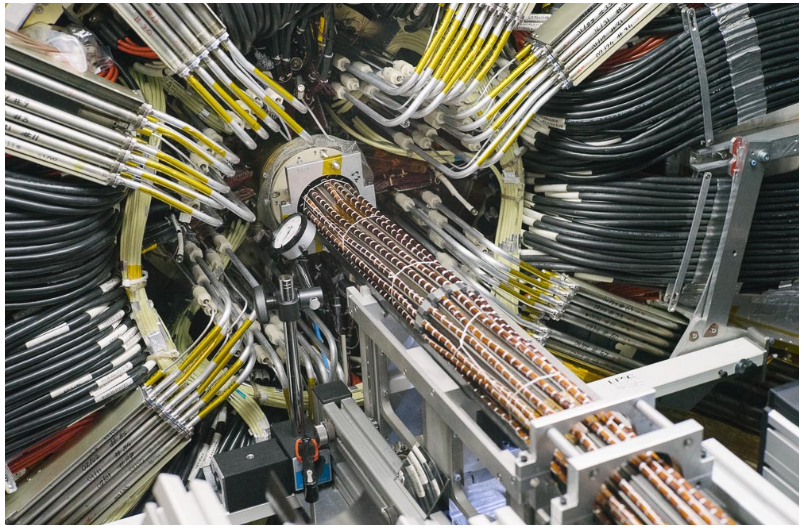


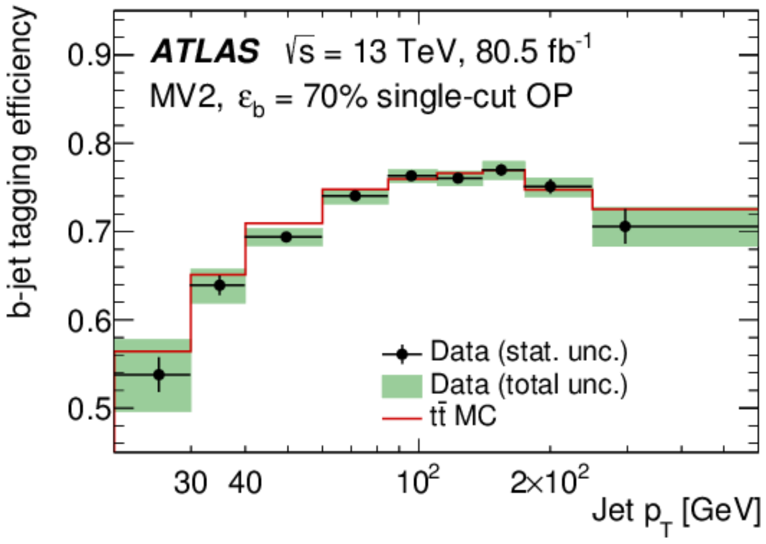
Der ATLAS-Detektor

Einbau des IBL

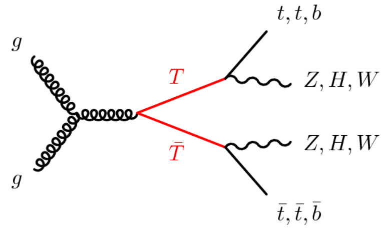
Identifikation von *b*-Quark-Jets

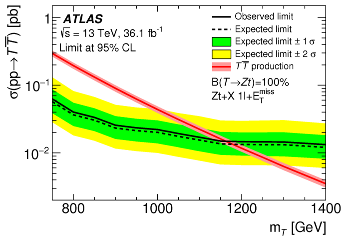


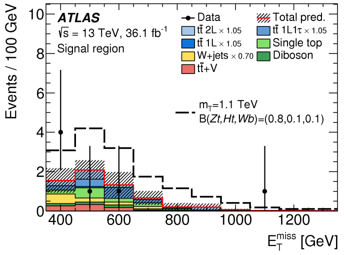




Summary: Challenging the Standard Model with top quarks

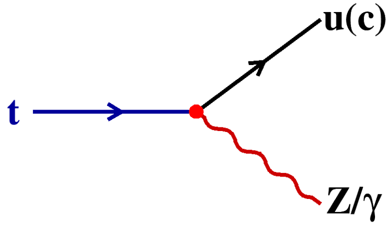






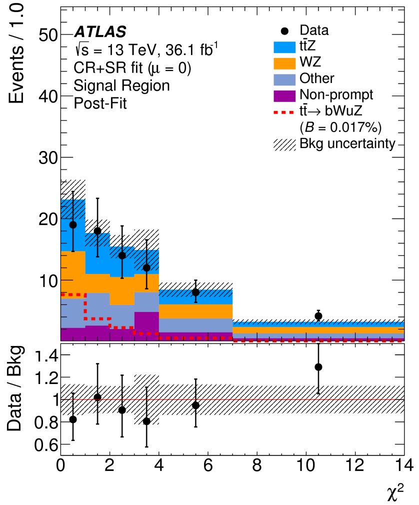
Direct searches

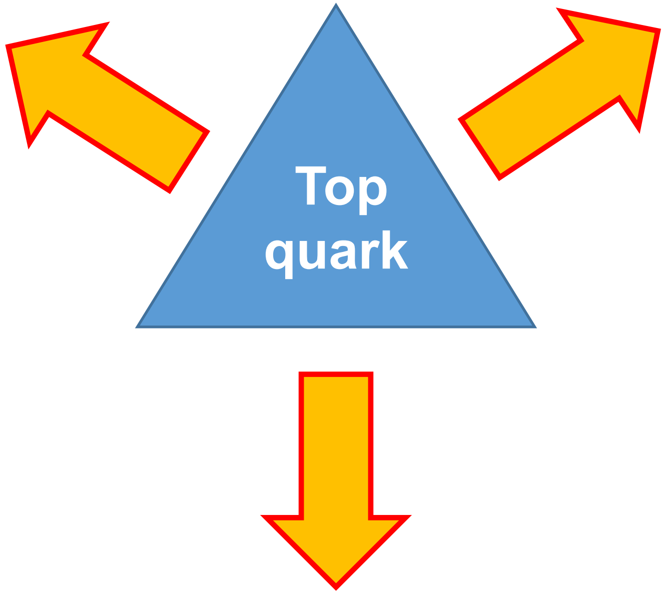
Vector-like quarks



Indirect searches

Flavour-changing neutral currents





Top quark

Precision measurements

Total, fiducial and differential cross-sections of t-channel single top-quark production