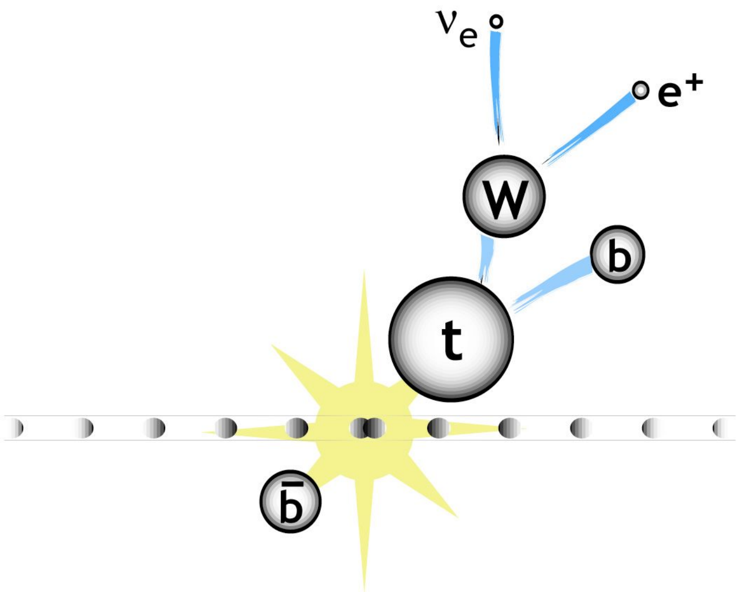
Challenging the Standard Model with top quarks

Wolfgang Wagner
Bergische Universität Wuppertal, Germany
and
ATLAS Collaboration

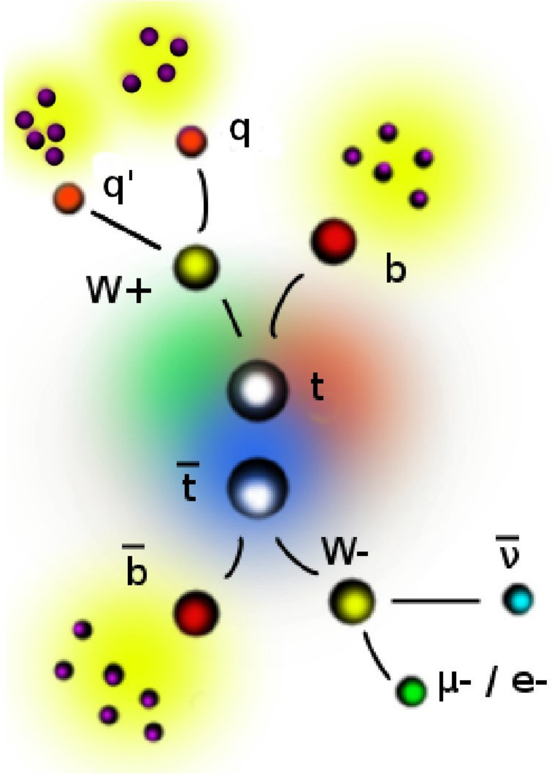
Seminar at Shandong University, Jinan
28 September 2019



Contents

BERGISCHE UNIVERSITÄT WUPPERTAL

1) The top-quark in the Standard Model (SM)
2) The Large Hadron Collider and the ATLAS detector
3) Direct searches for new particles
4) Indirect searches / searches for anomalous couplings
5) Precision measurements of top-quark properties



Quarks and leptons

Q_{em}			
$= +\frac{2}{3}\,e$	Up	Charm	Top
$= -\frac{1}{3}\,e$	Down	Strange	Bottom
$= 0$	ν_e	ν_μ	ν_τ
$= -\,e$	Elektron	Myon	Tauon

- Structureless, point-like.
- Fermions, carry spin $\frac{1}{2}$
- Quarks carry electric, weak and colour charge.
- „Matter fields“

Antiparticles

- Every quark species and every lepton species have a partner, their antiparticles.
- Particles and antiparticles have exaktly the same mass.
- They have opposite charges (mirror charges).

Particle		Antiparticle
Electron e^-	⇔	Antielectron = Positron e^+
Strange quark s	⇔	Antistrange quark $\bar{s}$
Tau neutrino ν_τ	⇔	Tau antineutrino $\bar{\nu}_\tau$

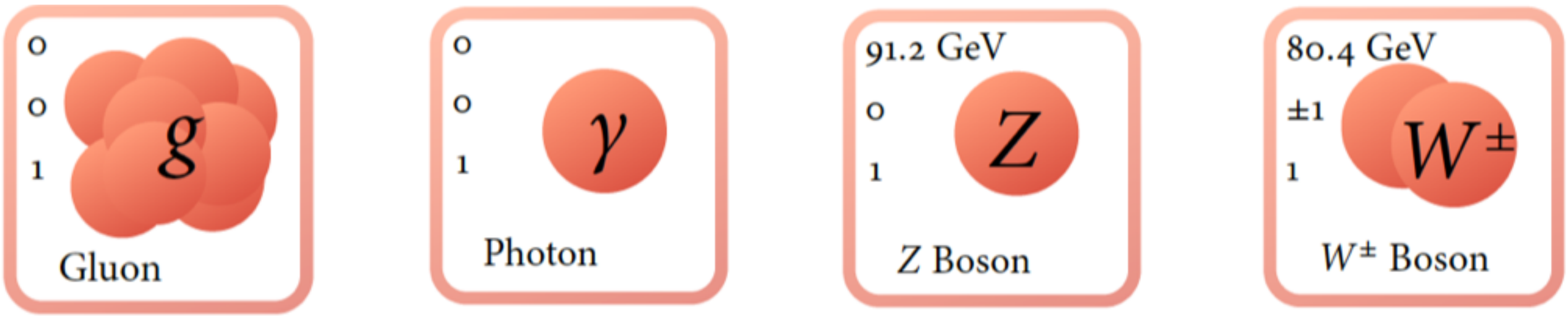
The Standard Model: a theory of interactions

Most remarkable feature of the SM:

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

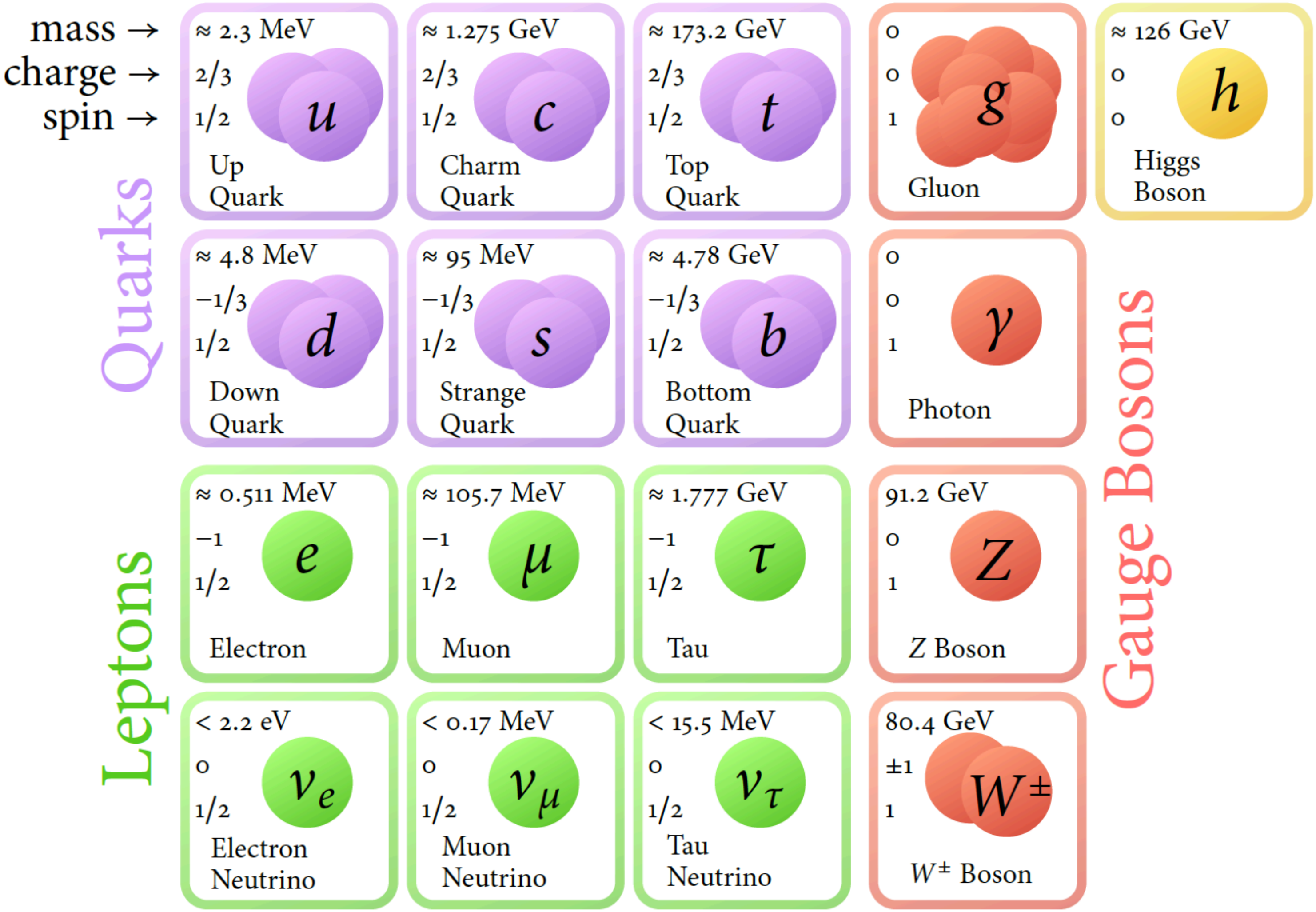
$$\psi \longrightarrow \exp(i\,\vec{\theta}(x_\mu)\cdot\vec{a})\;\psi \qquad \lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\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

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



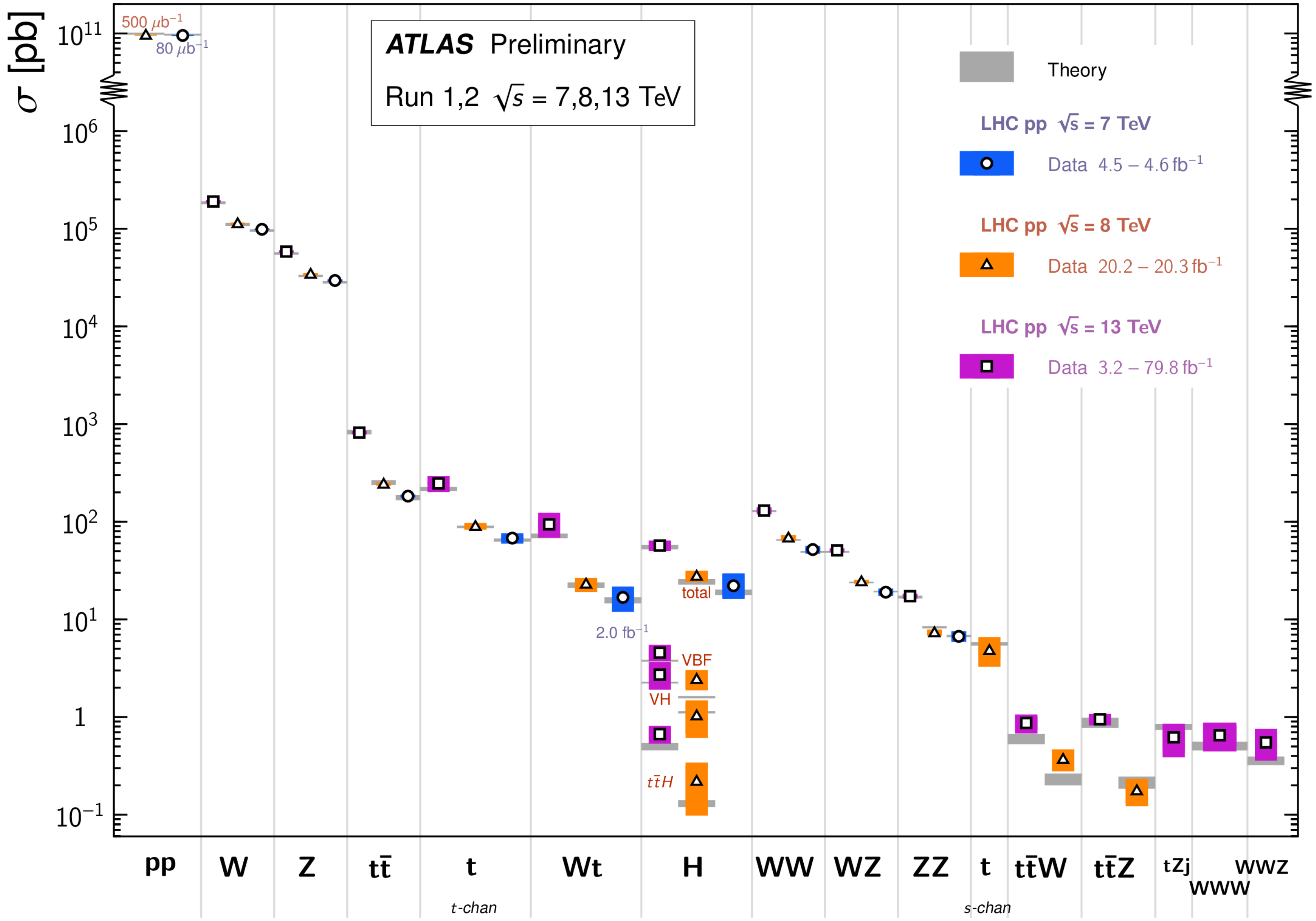
Gauge bosons mediate interactions

Particles of the Standard Model



Success of the Standard Model

Standard Model Total Production Cross Section Measurements *Status: July 2019*



The SM describes all known particle physics phenomena with high precision.

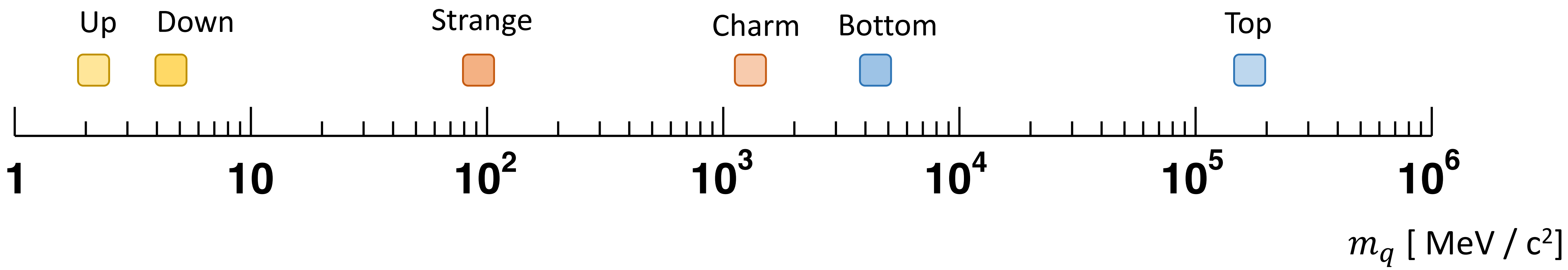
A great success of 20th century science!

(Neutrino oscillations are an exception to some extent)

The astounding mass hierarchy quarks

BERGISCHE UNIVERSITÄT WUPPERTAL

- Quark masses exhibit a very pronounced mass hierarchy.
- Reason is unknown.
- Warning: Quark masses are a complex concept, since quarks are no free particles.

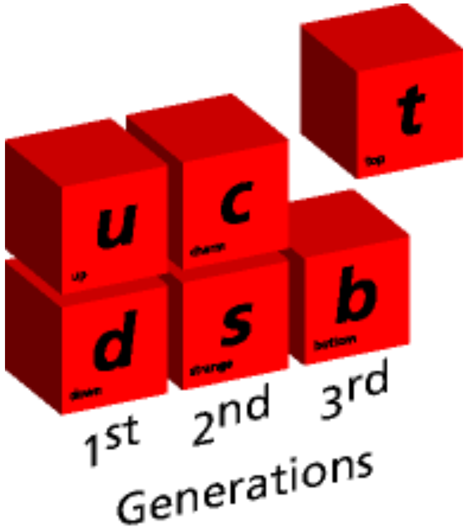


Reference:

http://pdg.lbl.gov/2017/tables/rpp2017-sum-quarks.pdf

The top quark

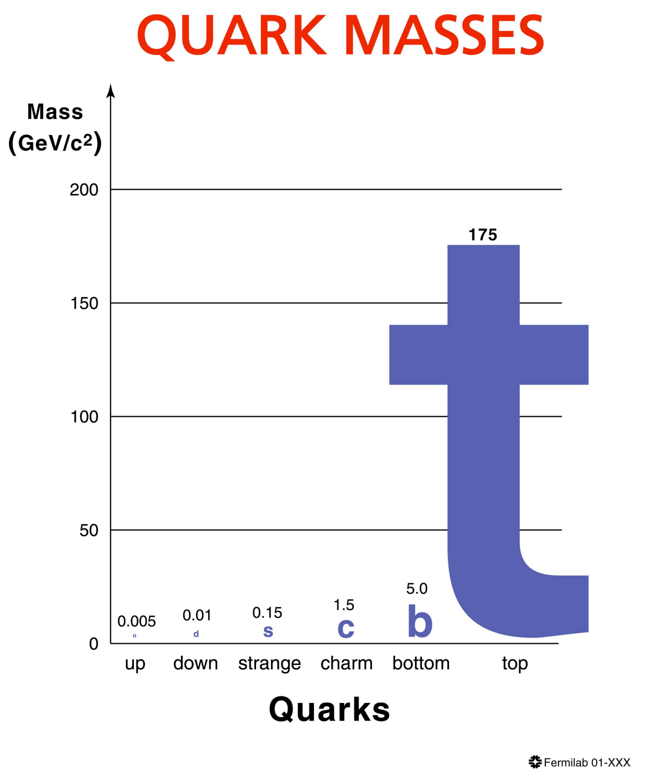
BERGISCHE UNIVERSITÄT WUPPERTAL



- Weak-isospin partner of the b-quark.
- Charge: +2/3 e
- Spin: ½
- The by far 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:

$$\tau_{\text{top}} \propto \left(\frac{M_W}{M_{\text{top}}}\right)^3$$

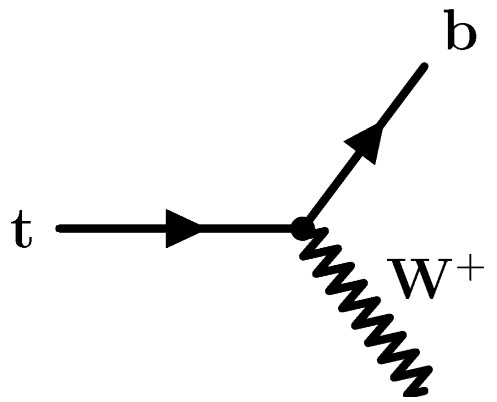
$$\tau_{\text{top}} \approx 4.7 \cdot 10^{-25}\ \text{s}$$

⇒ Top quark decays as a quasi free particle

⇒ Spin information and polarisation are accessible

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

Top-quark decay



- Via the weak interaction
- Involves left-handed chiral fermion fields

$$\psi_L = \frac{1}{2}(1 - \gamma_5)\,\psi$$

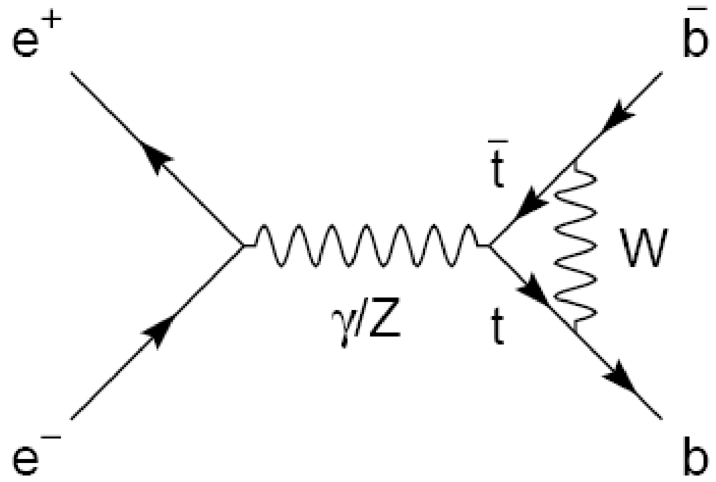
- Since $|V_{tb}| \approx 1, \mathcal{B}(t \to Wb) \approx 1$

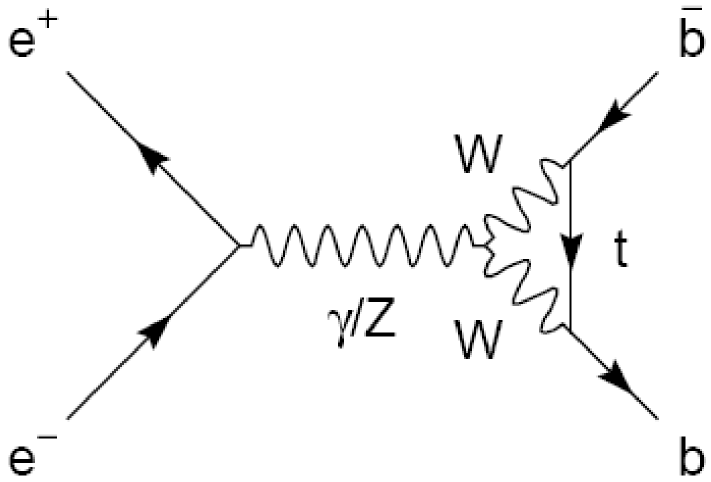
$$< |\mathcal{M}|^2 > = \frac{g_w{}^2}{16} \text{trace} [\, \gamma^\mu (1 - \gamma^5) (p_1{}^\mu \gamma_\mu + m_1 c)\, \gamma^\nu (1 - \gamma^5) (p_2{}^\mu \gamma_\mu + m_2 c) \,] (-g_{\mu\nu} + \frac{p_{3\mu} p_{3\nu}}{(m_w c)^2})$$

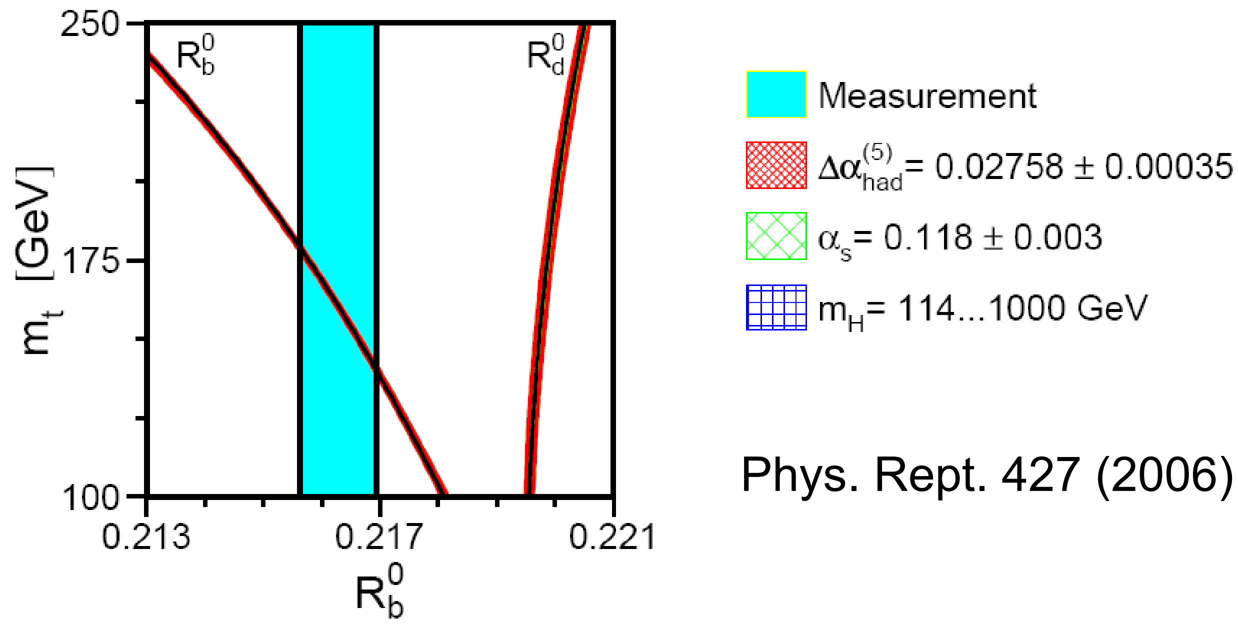
$$< |\mathcal{M}|^2 > = \frac{g_w^2\, c^2}{4\, m_w^2} (m_t{}^2 - m_w^2)(m_t{}^2 + 2m_w^2)$$

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

BERGISCHE UNIVERSITÄT WUPPERTAL





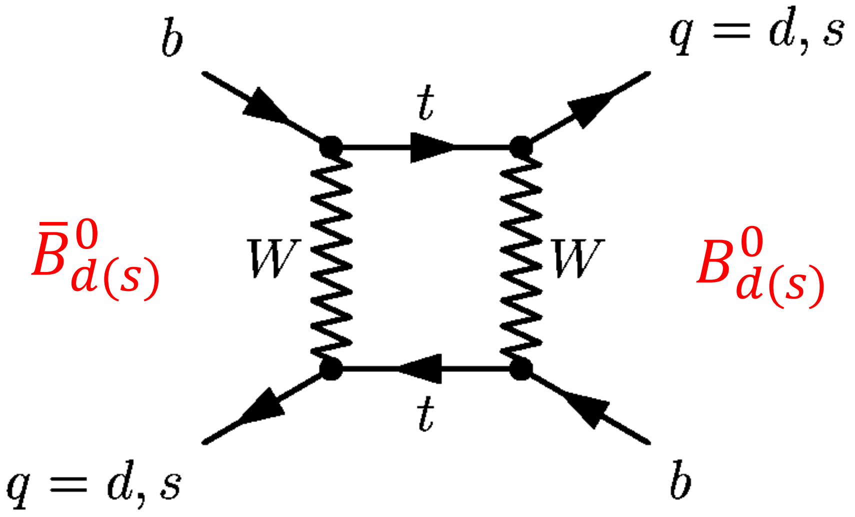


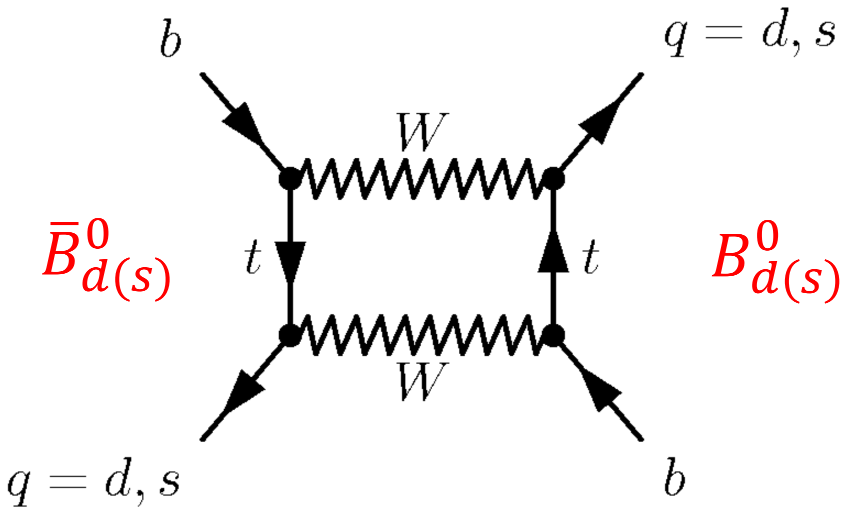
Phys. Rept. 427 (2006) 257

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

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

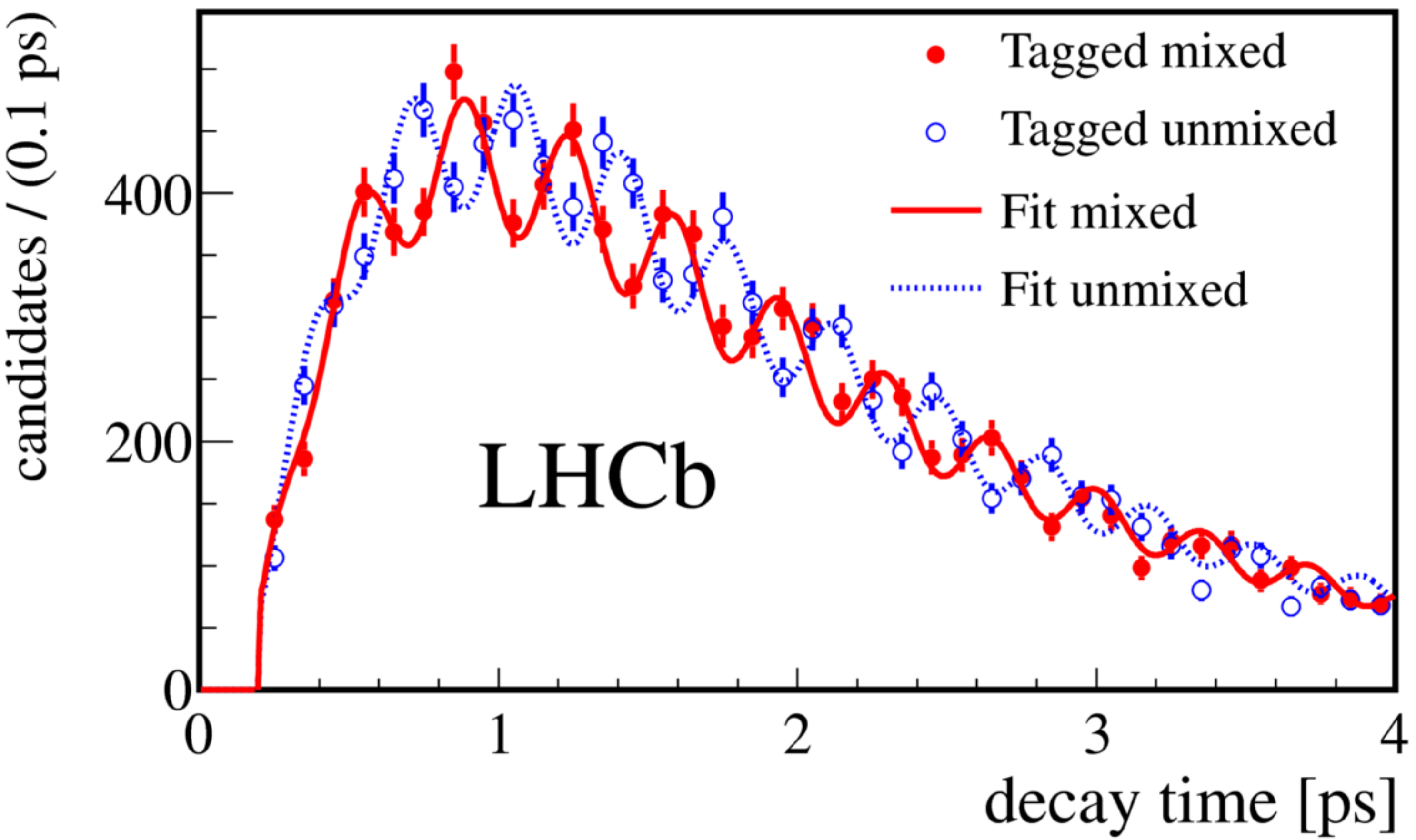
Top-quarks in loops: $B^0_{d(s)} - \bar{B}^0_{d(s)}$ mixing





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

B_s^0 mixing



Tagged mixed =
different flavour at production and decay

Tagged unmixed =
same flavour at production and decay

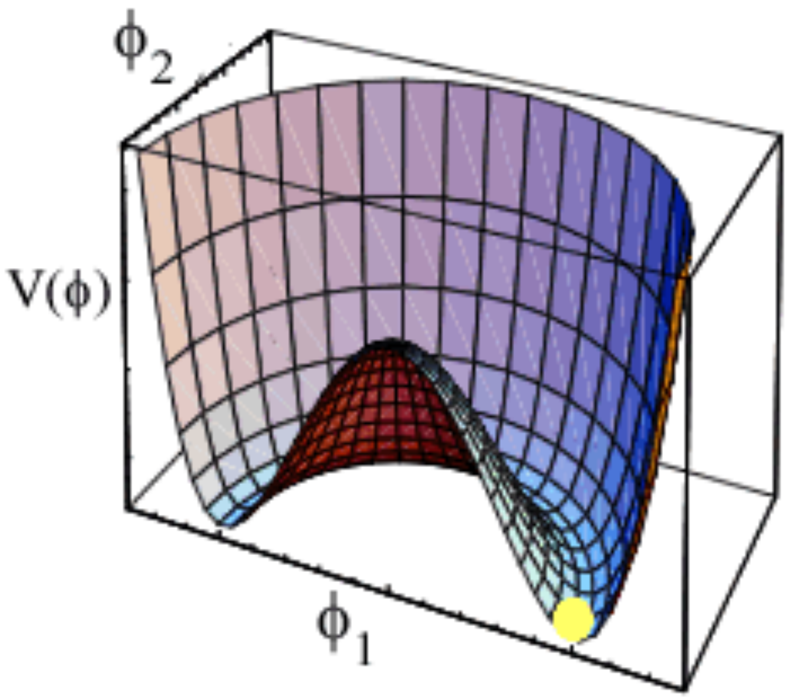
The mixing frequency is given by

Δm_s = 17.768 ± 0.023 (stat.) ± 0.006 (syst.) ps^{-1}

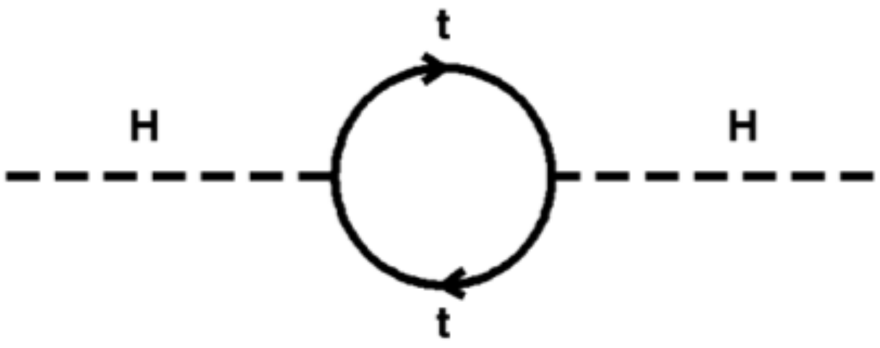
The top-quark and the Higgs

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.



Top-quark loops contribute to the Higgs propagator.

The running of the Higgs self-coupling

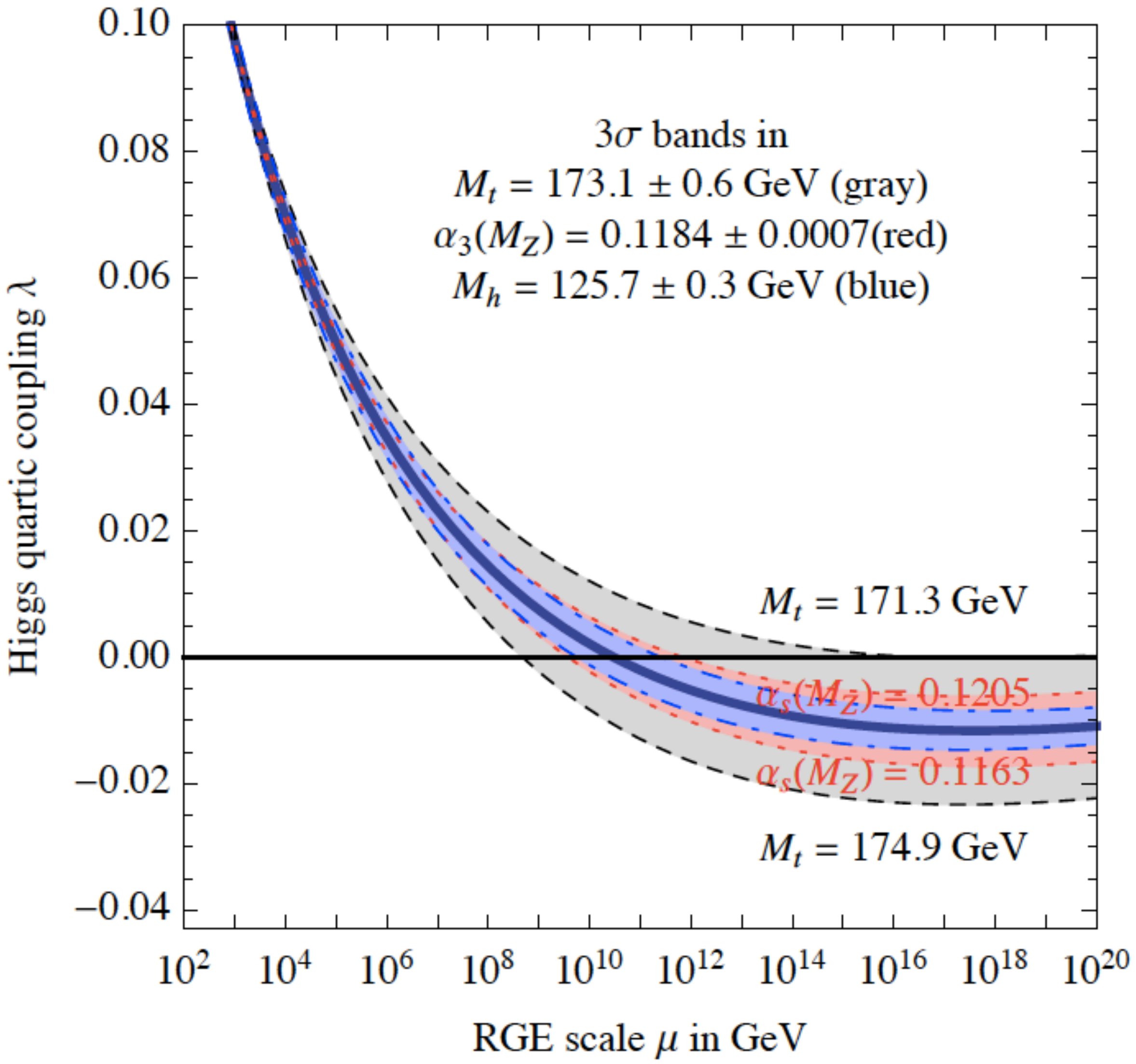
BERGISCHE UNIVERSITÄT WUPPERTAL

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

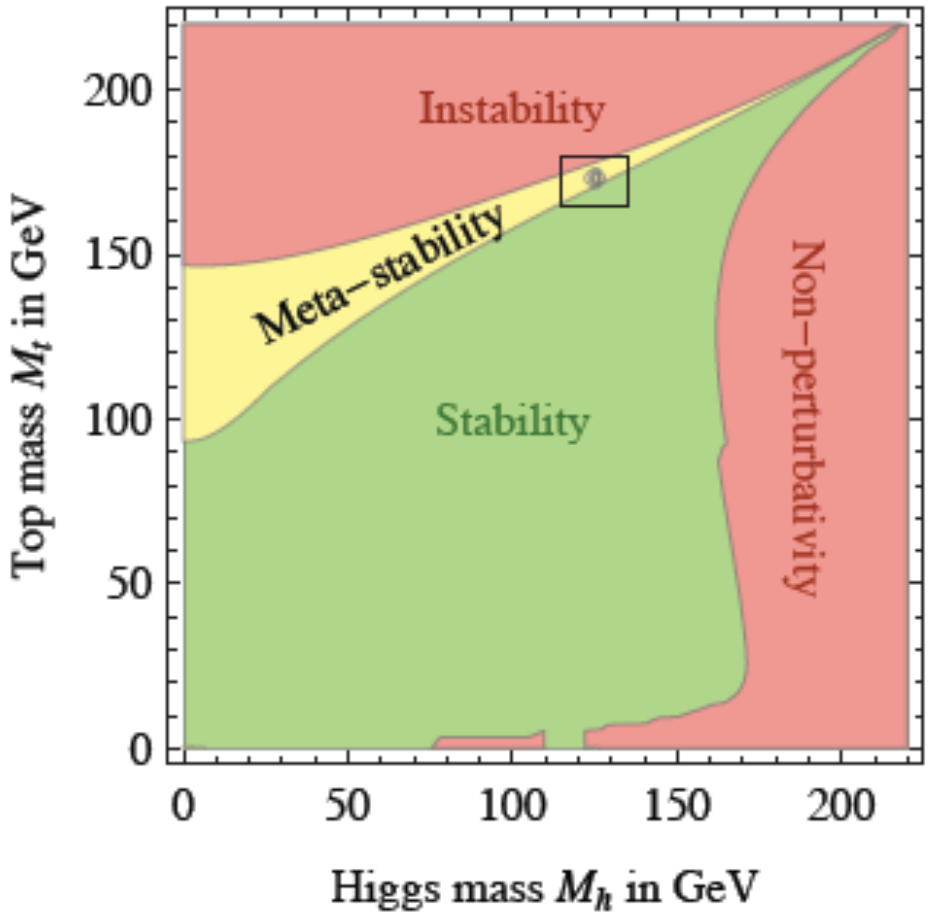
$$\lambda = \lambda(q^2)$$

- The Higgs self-coupling λ is not a constant.
- Loop corrections $\longrightarrow$ dependence on momentum scale μ
- Main contributions from top-quark
- Condition for absolute stability of the potential: $\lambda(q^2) > 0$

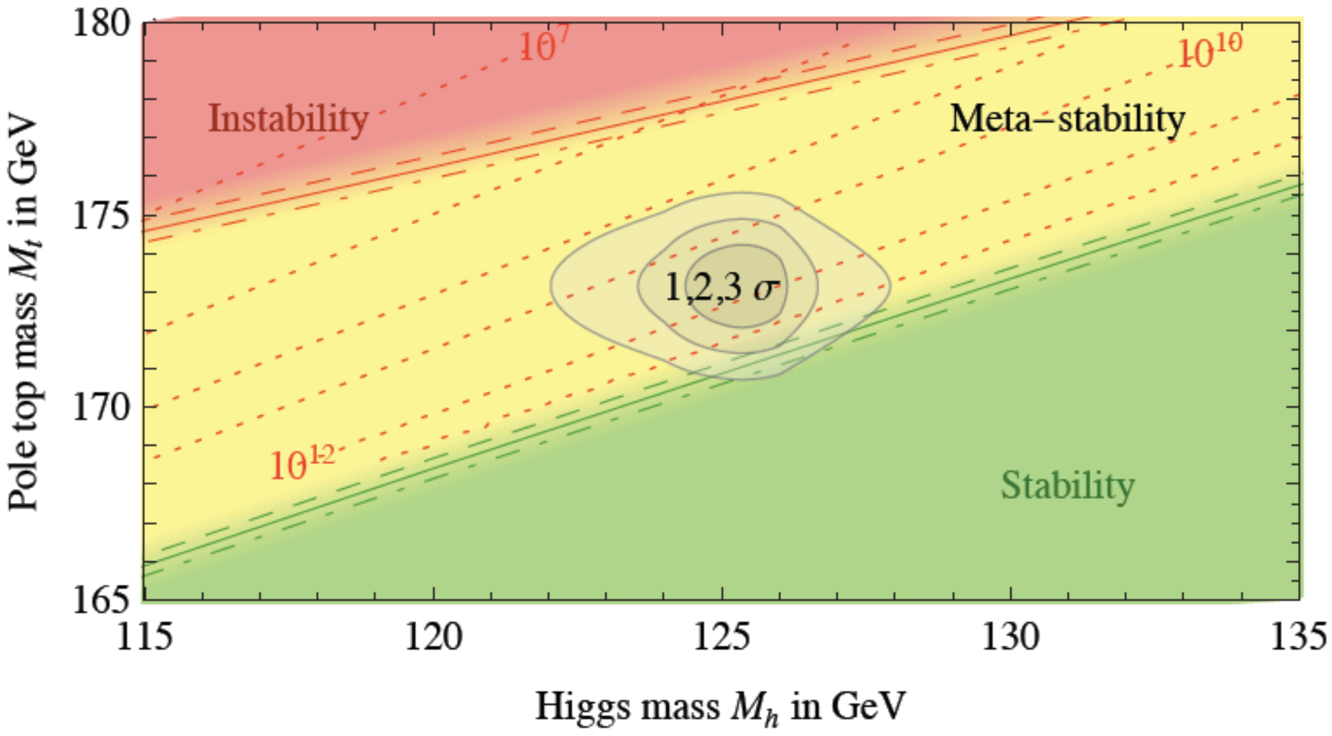
$$M_H \geqslant 129.2 + 1.8 \times \left(\frac{m_t^{\text{pole}} - 173.2\ \text{GeV}}{0.9\ \text{GeV}}\right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0\ \text{GeV}$$



Vacuum stability



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



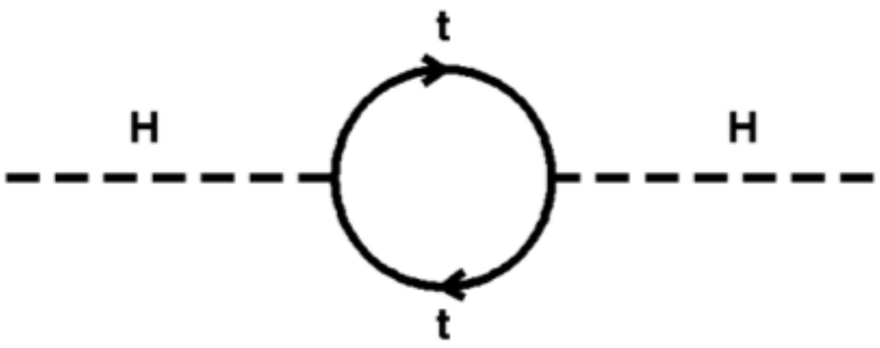
Top-quark mass is important parameter (value and uncertainty).

Corrections to the Higgs mass

At leading order, the Higgs mass is given by the vacuum expectation value (minimum) of the potential of the Higgs field:

$$m_{\mathrm{H}} \simeq v \simeq 10^2 \text{ GeV}$$

At higher orders, loop corrections shift the Higgs boson mass:



$$m_H^2 \rightarrow m_H^2 + \delta m_H^2$$

$$\delta m_H^2 = g^2 \int^{\Lambda} \frac{d^4k}{k^2} \simeq g^2 \Lambda^2$$

Integral *diverges*, is regulated by a cut-off Λ.

- All fermions to which the Higgs field couples contribute to the loop corrections.
- There can be cancellations between different contributions.

The hierarchy problem and naturalness

BERGISCHE UNIVERSITÄT WUPPERTAL

- The Planck mass defines a maximum scale of validity for the Standard Model.
- At energies close to the Planck scale, gravity has similar strength as the other interactions.

$$M_{\text{Planck}} \equiv (8\pi G_{\text{Newton}})^{-1/2} = 2.4 \cdot 10^{18}\ \text{GeV}$$

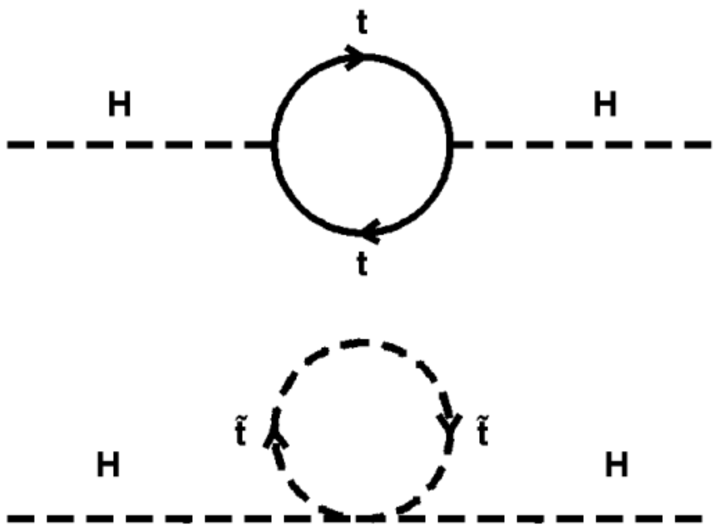
- New physics laws have to kick in at M_{Planck}.
- In this sense $\Lambda \simeq M_{\text{Planck}}$ would be a *natural* choice.
- But

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

The hierarchy problem!

- Could be solved by introducing new physics at a lower scale, „close“ to the Higgs mass.

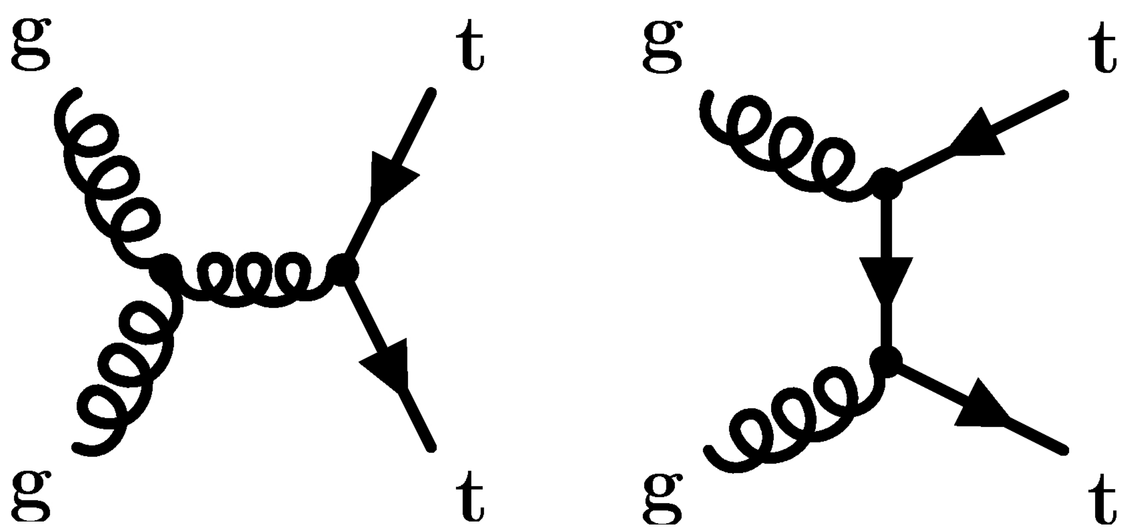
Regulation of the loop corrections



Addition of new particles lead to loop corrections which cancel the divergences.

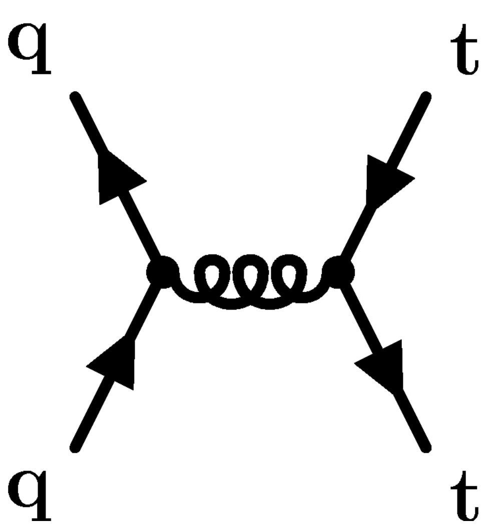
Top-quark-antiquark pair production

Gluon-gluon fusion



~10%

Quark-antiquark annihilation



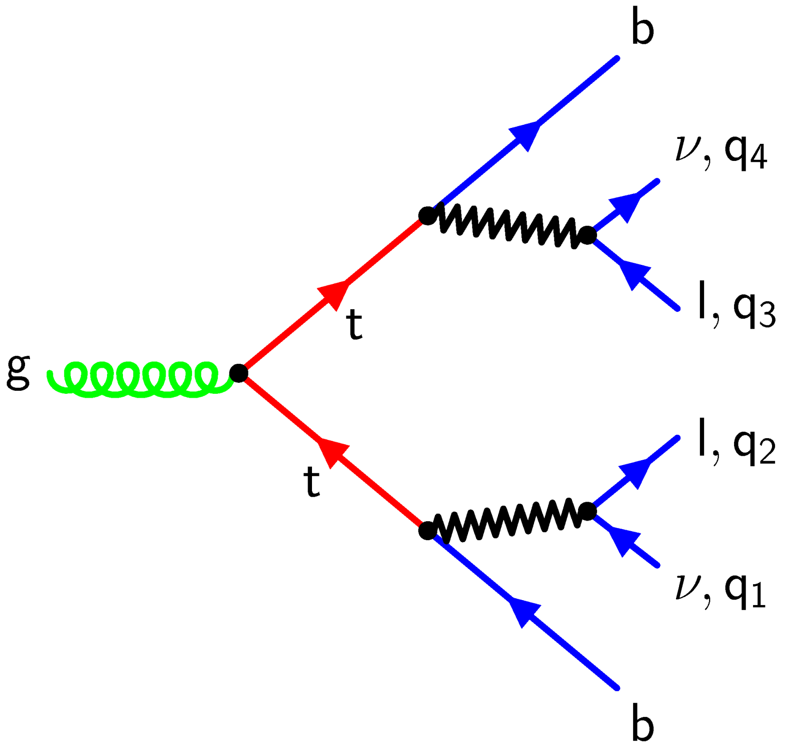
~90%

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

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

Relative uncertainty = 5.5%

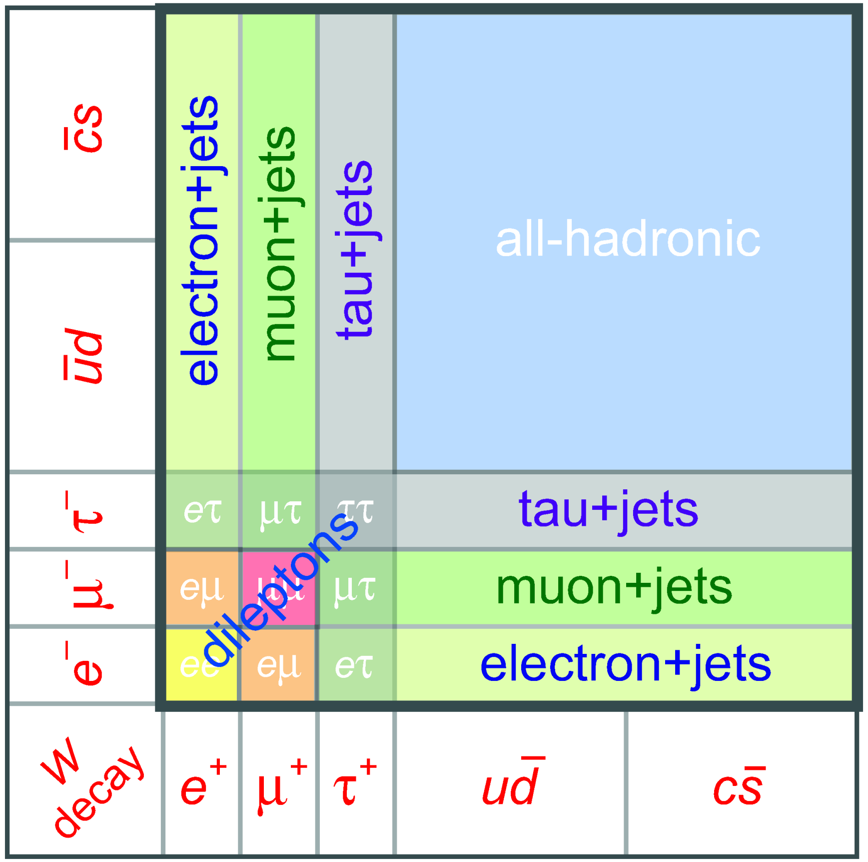
Classification of top-quark events



Based on the decay modes of the W bosons from top-quark decay.

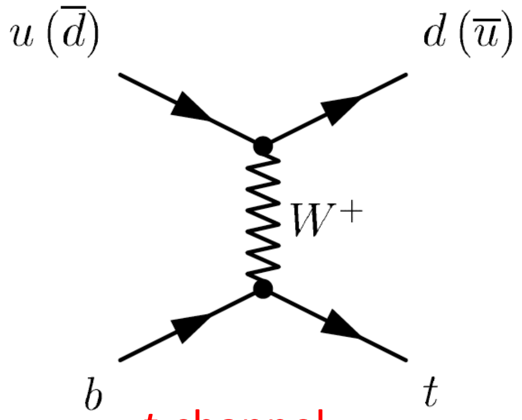
1) Di-lepton (e, μ)
2) Lepton + jets
3) Tau channels
4) All-hadronic

Top Pair Decay Channels

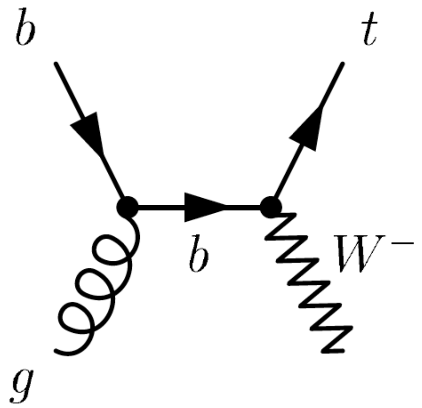


W decay	$e\nu/\mu\nu$	$\tau\nu$	$q\bar{q}'$
$e\nu/\mu\nu$	5%	5%	30%
$\tau\nu$	–	1%	15%
$q\bar{q}'$	–	–	44%

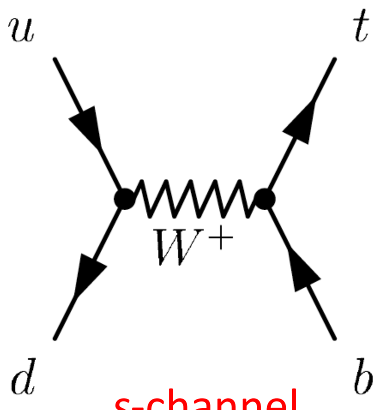
Single top-quark production



t-channel
(*tq* production)



tW production

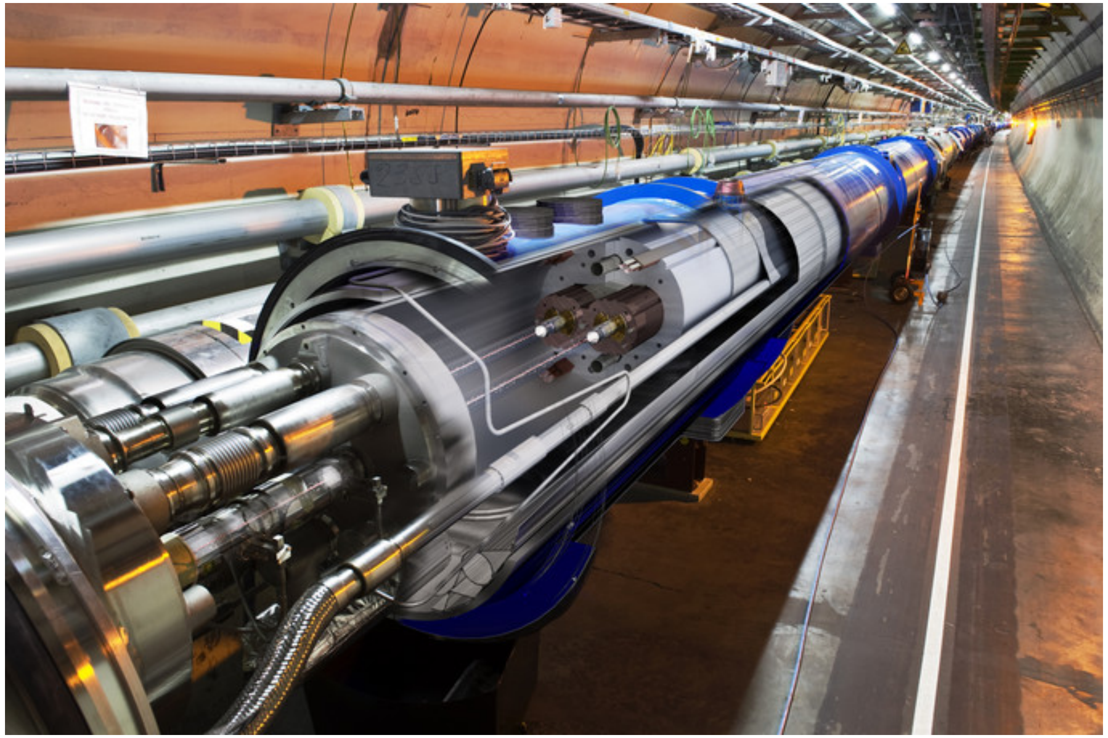


s-channel
($t\bar{b}$ production)

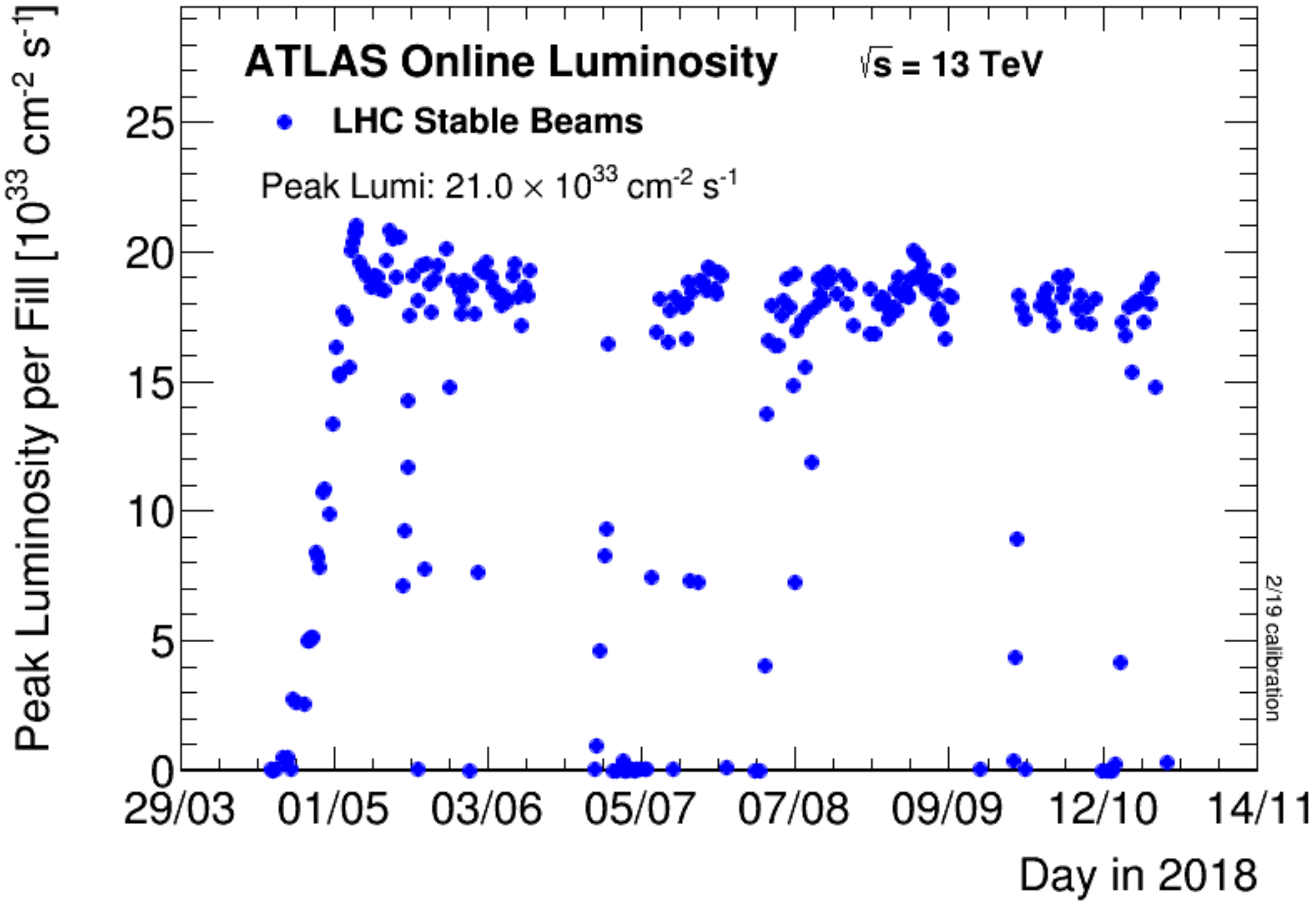
BERGISCHE UNIVERSITÄT WUPPERTAL

Chapter 2

The Large Hadron Collider and the ATLAS detector



Peak luminosity in 2018



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

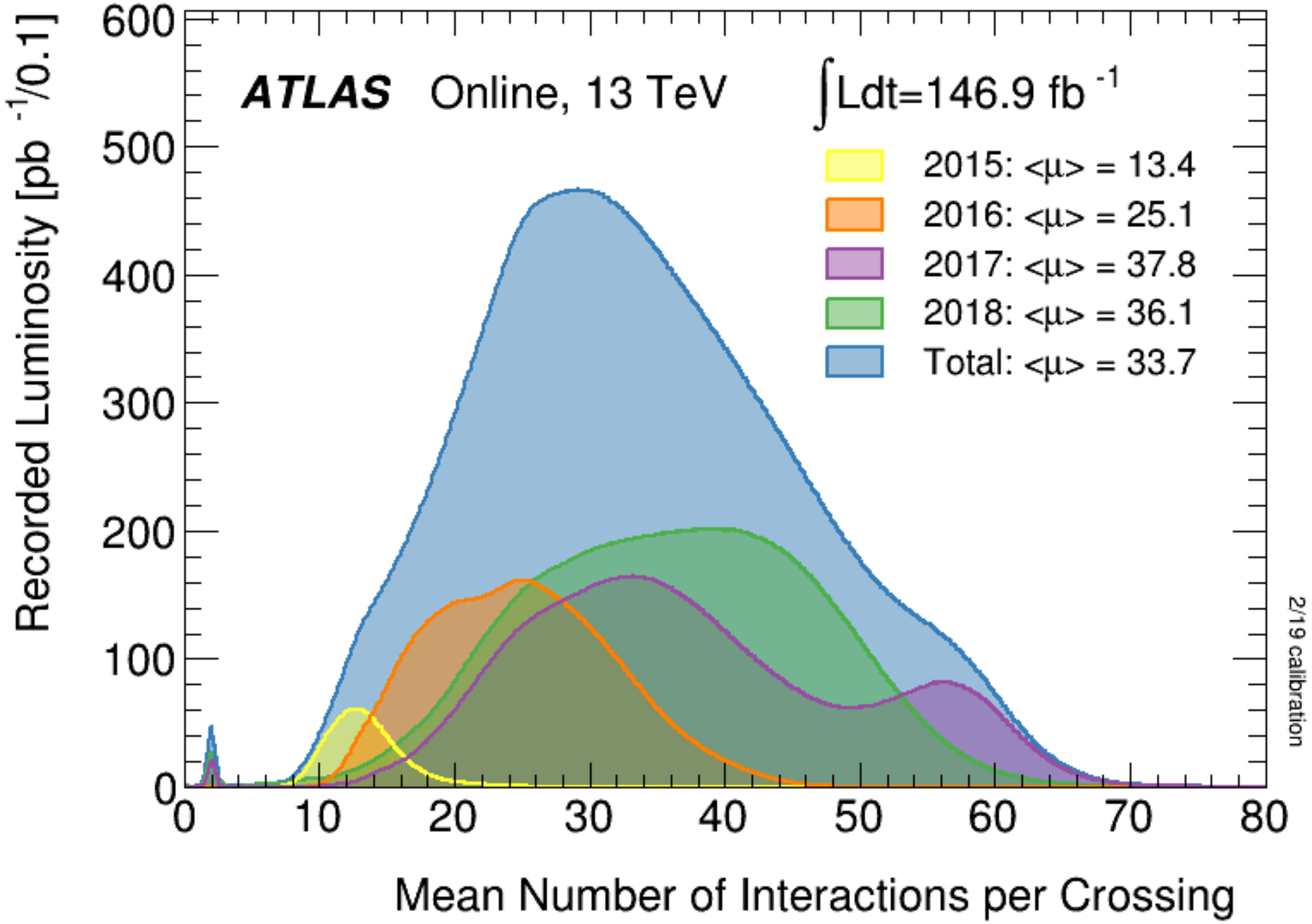
L: Luminosity

σ: Cross section

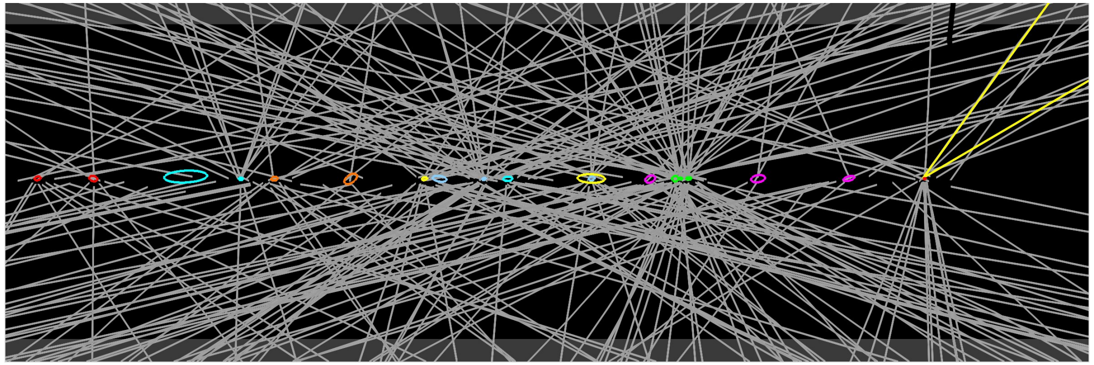
Units: $cm^{-2}\ s^{-1}$

Same units as a particle current density.

Number of pp interactions per bunch crossing

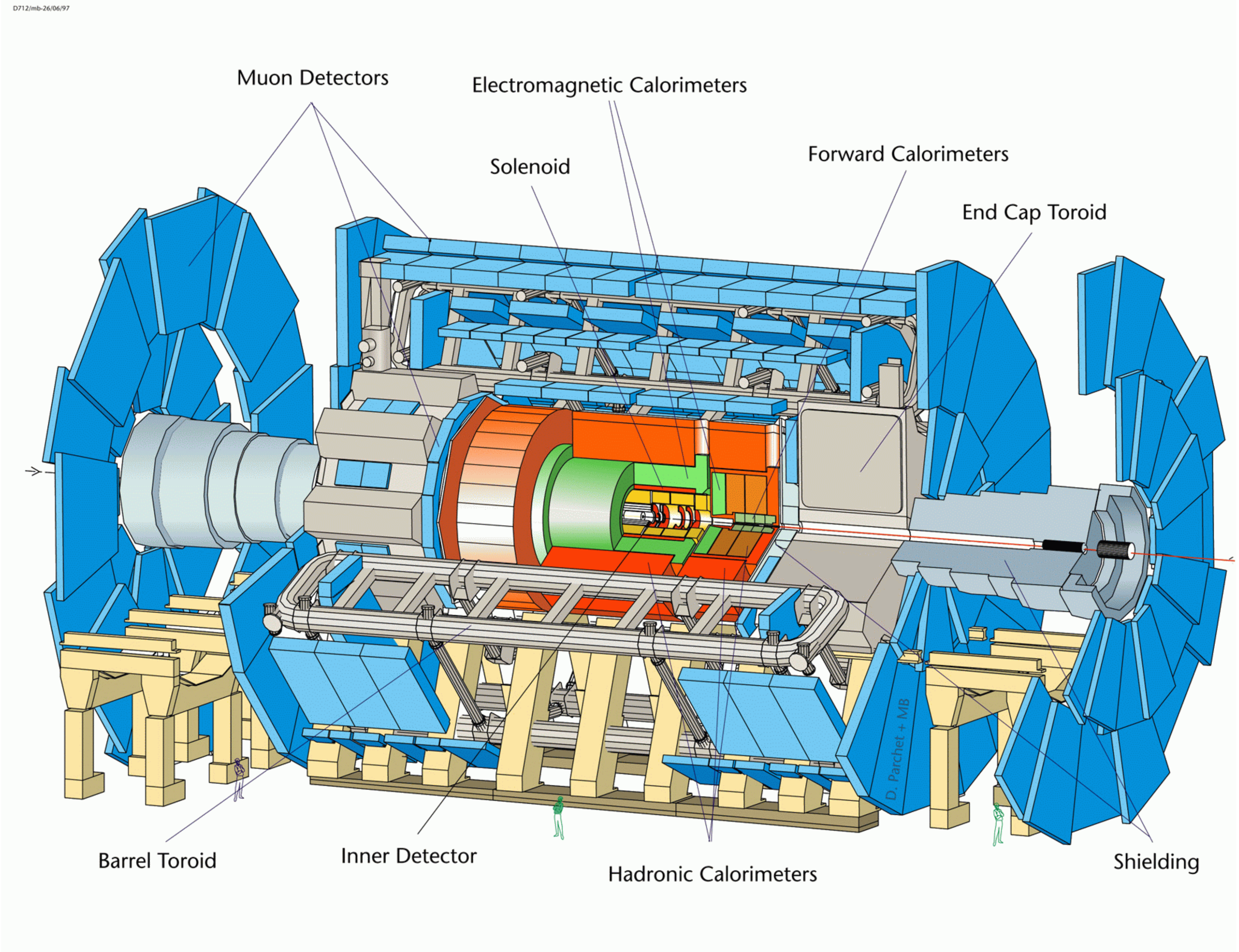


Integrated luminosity „good for physics“ = 139 fb^{-1}



The ATLAS detector

BERGISCHE
UNIVERSITÄT
WUPPERTAL

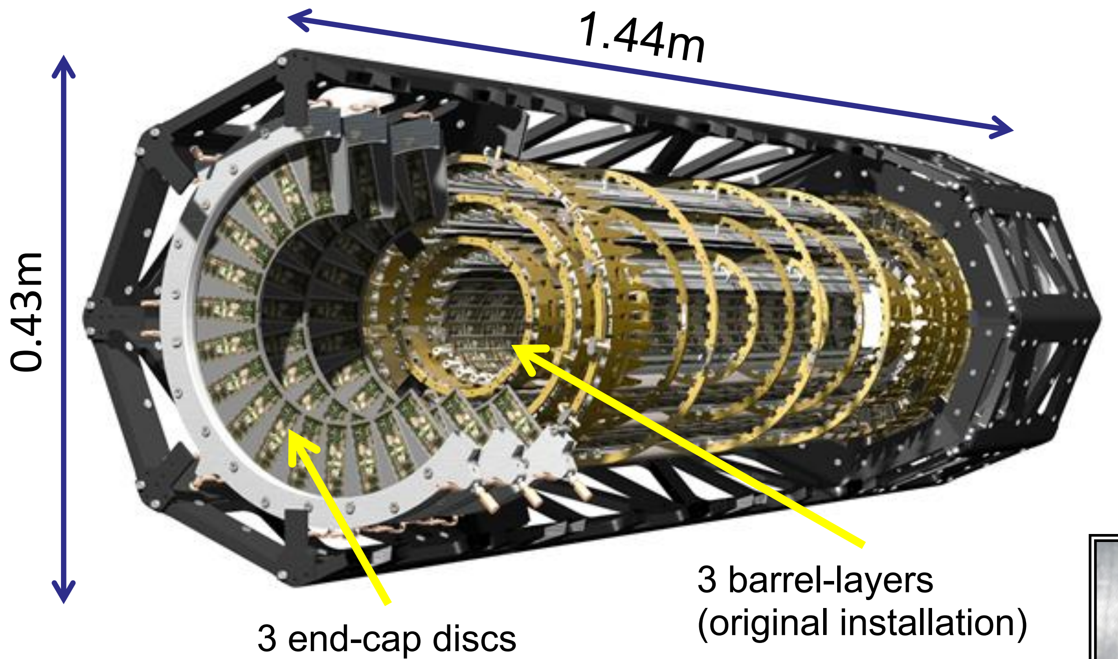


46 m long and 24 m high

Main components (= sub-detectors)

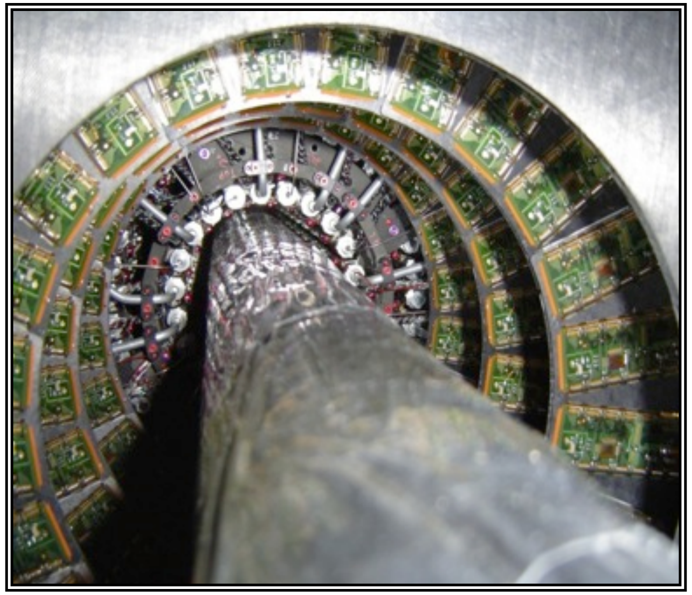
- Inner detector
  ⟶ tracks of charged particles
- Calorimeters
  ⟶ photons
  ⟶ electrons
  ⟶ hadronic jets (quarks and gluons)
- Muon system
  ⟶ muons
- Magnet systems
  ⟶ bending of charged particles

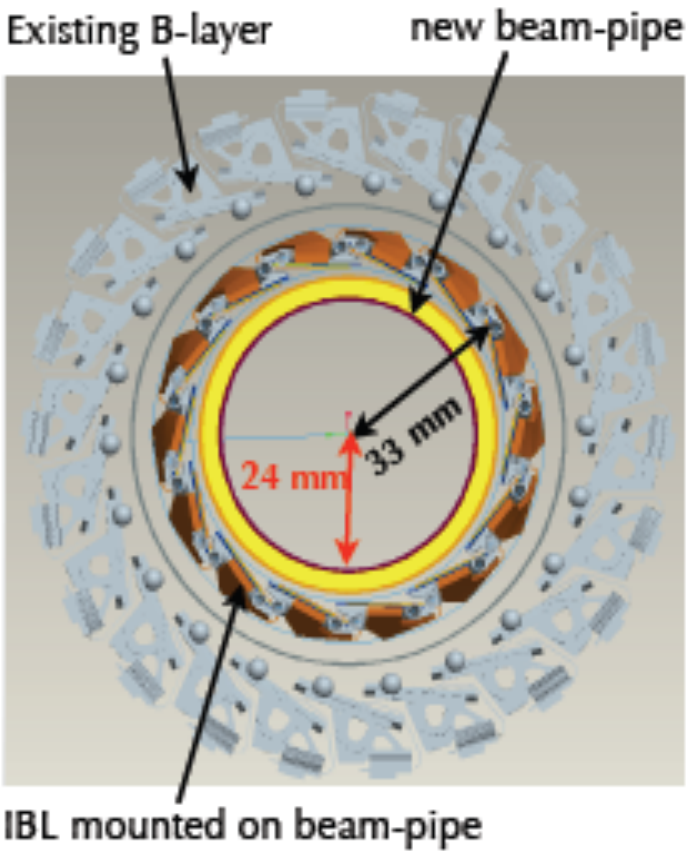
The ATLAS Pixel detector



- 3 to 4 precise track hits up to $|\eta|< 2.5$:
  - $R\Phi$ resolution: 10 μm
  - η (or z) resolution: 115 μm
- 4 shells in central region
- 3 discs in forward region
- 92 million pixel cells

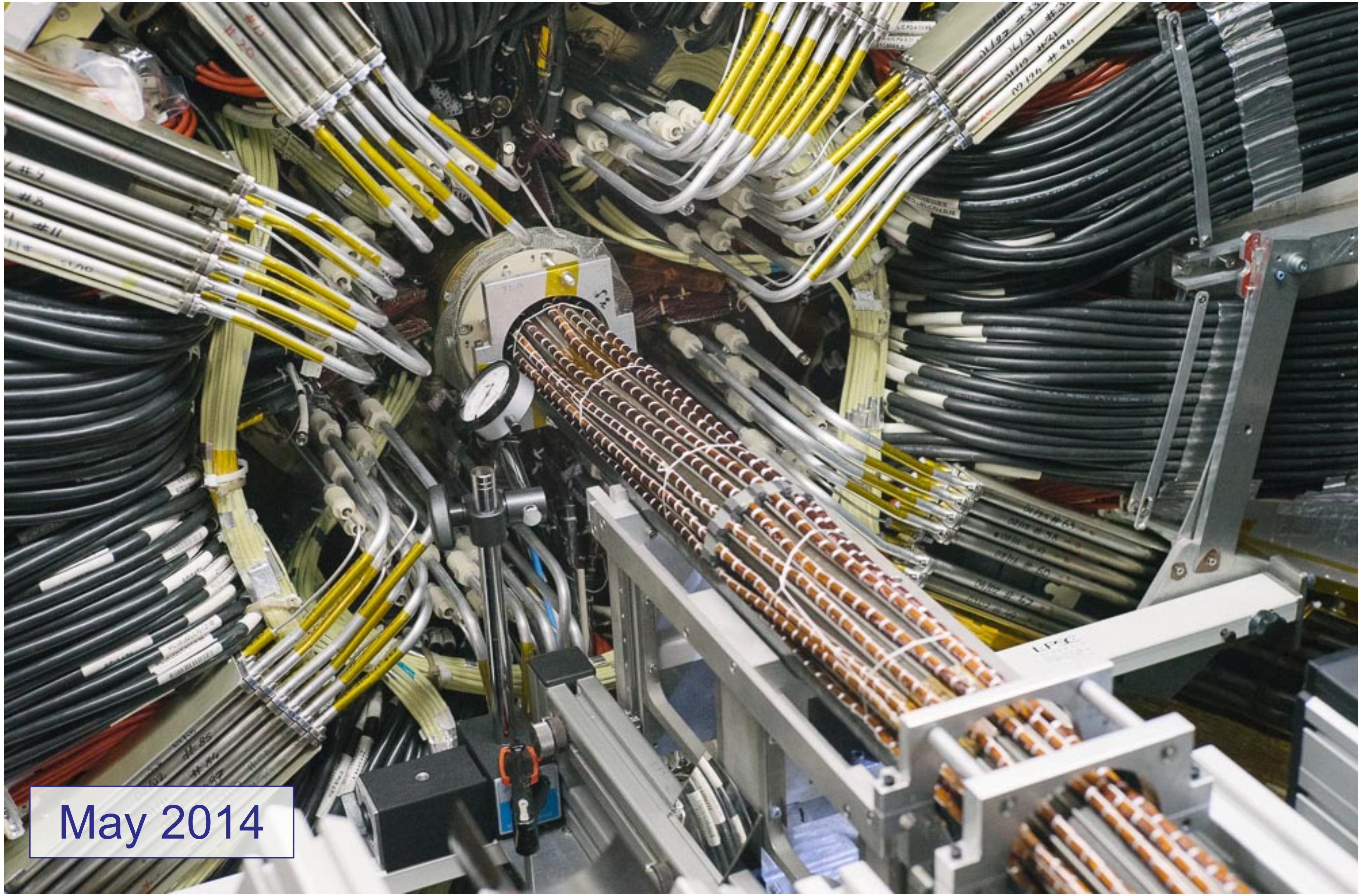
- 4th layer installed in 2014.
- Radiation hard up to 2.4×10^{16} p/cm^2





Installation of the new pixel layer: the IBL

BERGISCHE UNIVERSITÄT WUPPERTAL



May 2014

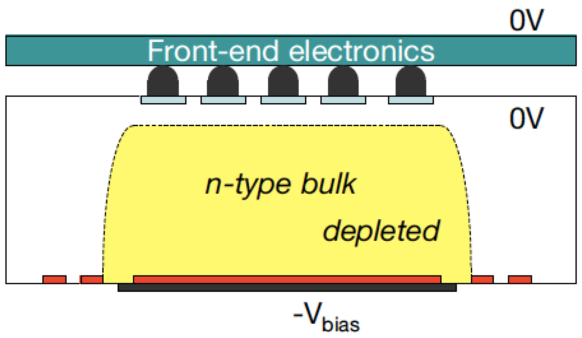
IBL =
Insertable B-Layer

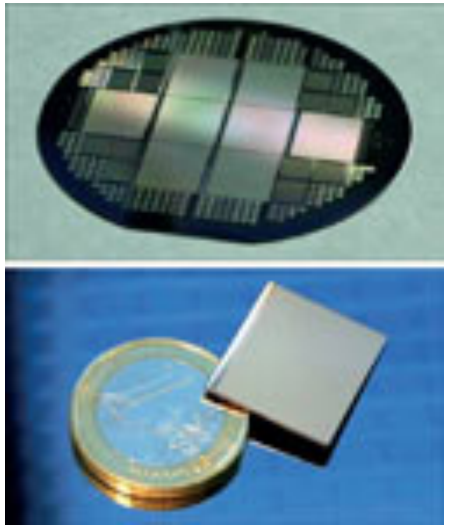
Designed and produced with vital contributions of the Wuppertal HEP group:

1) Support structures (carbon foam and carbon fibre compound)
2) Detector readout
3) Detector monitoring and control

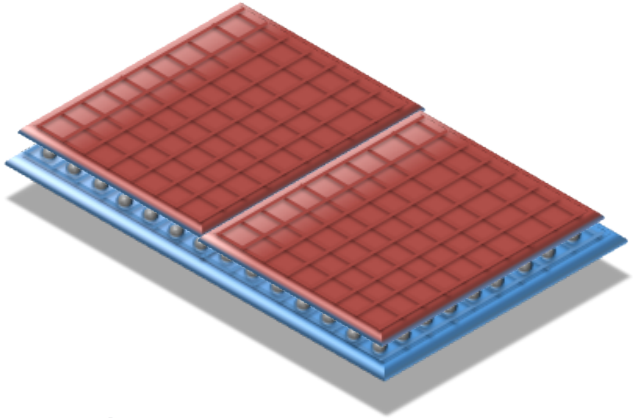
Components of the Pixel detector

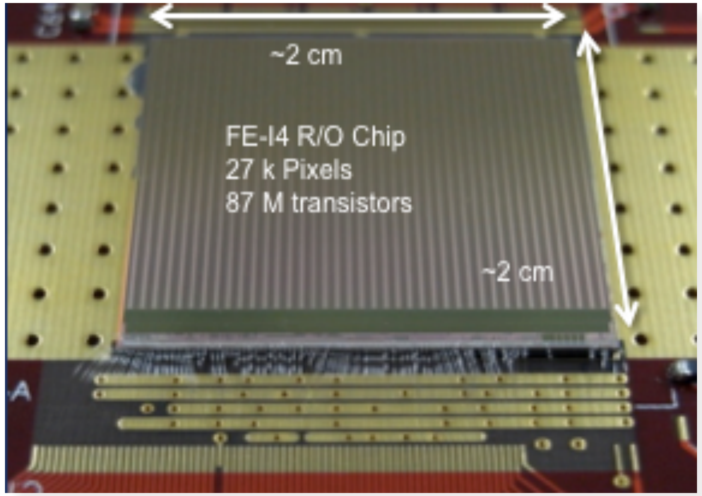
1) Sensors



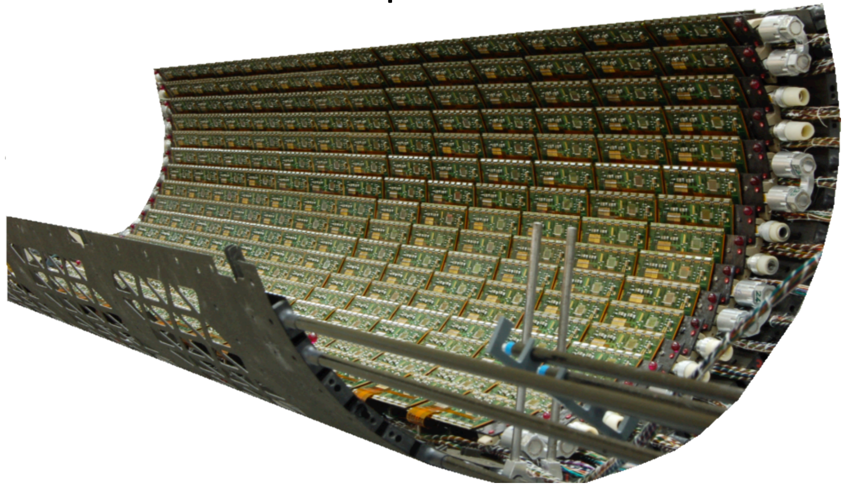


2) Front-end electronics

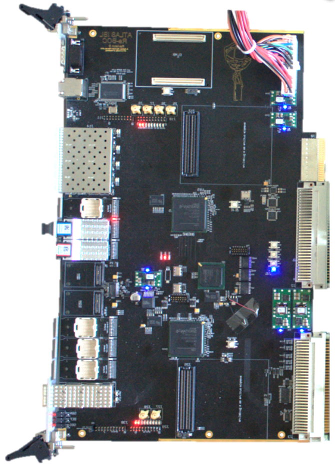




3) Mechanical support structures made of carbon fibre compounds



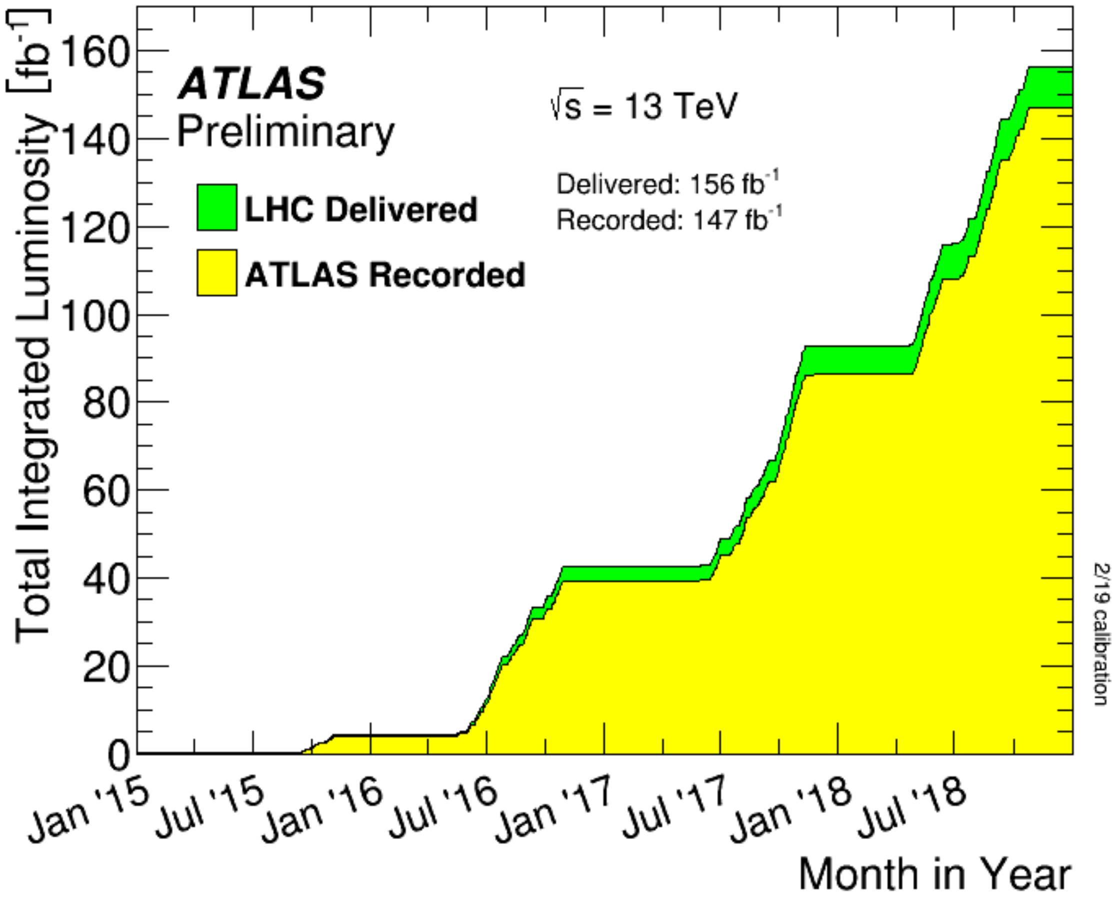
4) Readout and data acquisition system

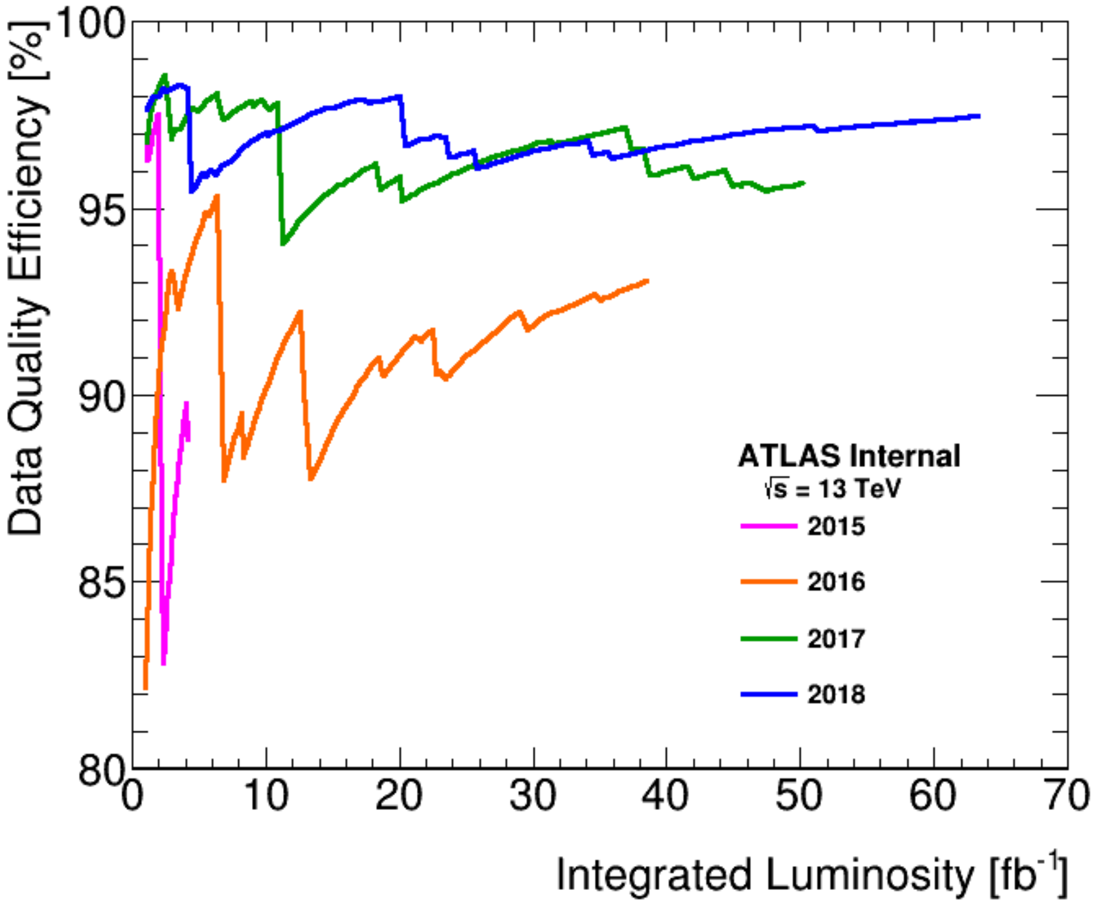


5) Monitoring and control system

Integrated luminosity and data-taking efficiency

BERGISCHE UNIVERSITÄT WUPPERTAL



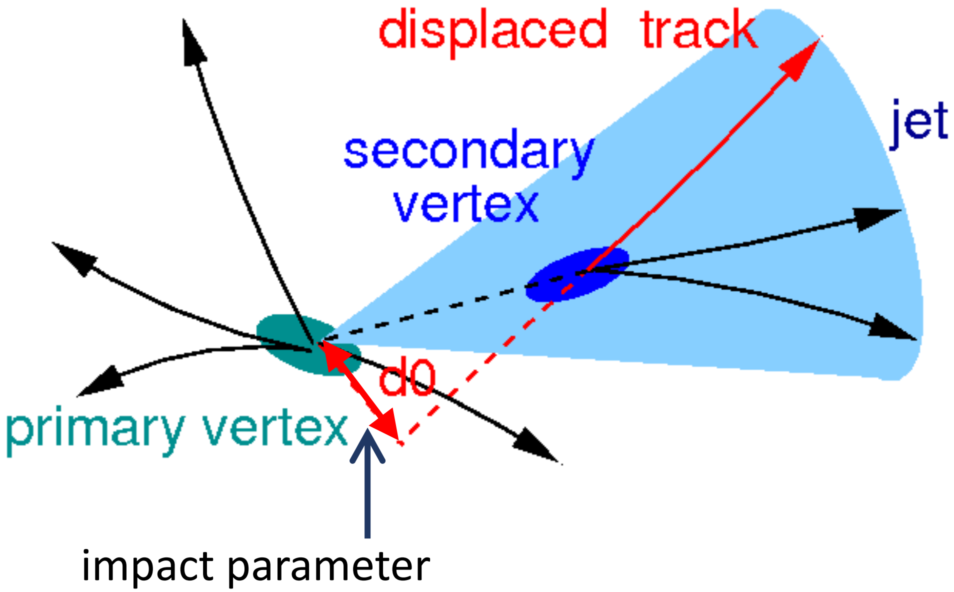


Secondary vertex reconstruction

- Important for top quark and Higgs boson physics
  Identification of
  - b-quark jets
  - τ leptons
- Long liftetime: τ (b-Hadron) $\approx$ 1.5 ps $\rightarrow c\tau \approx 450\ \mu$m
  τ (τ-Lepton) $\approx$ 0.3 ps

Requirement of a secondary vertex:

$\rightarrow$ 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

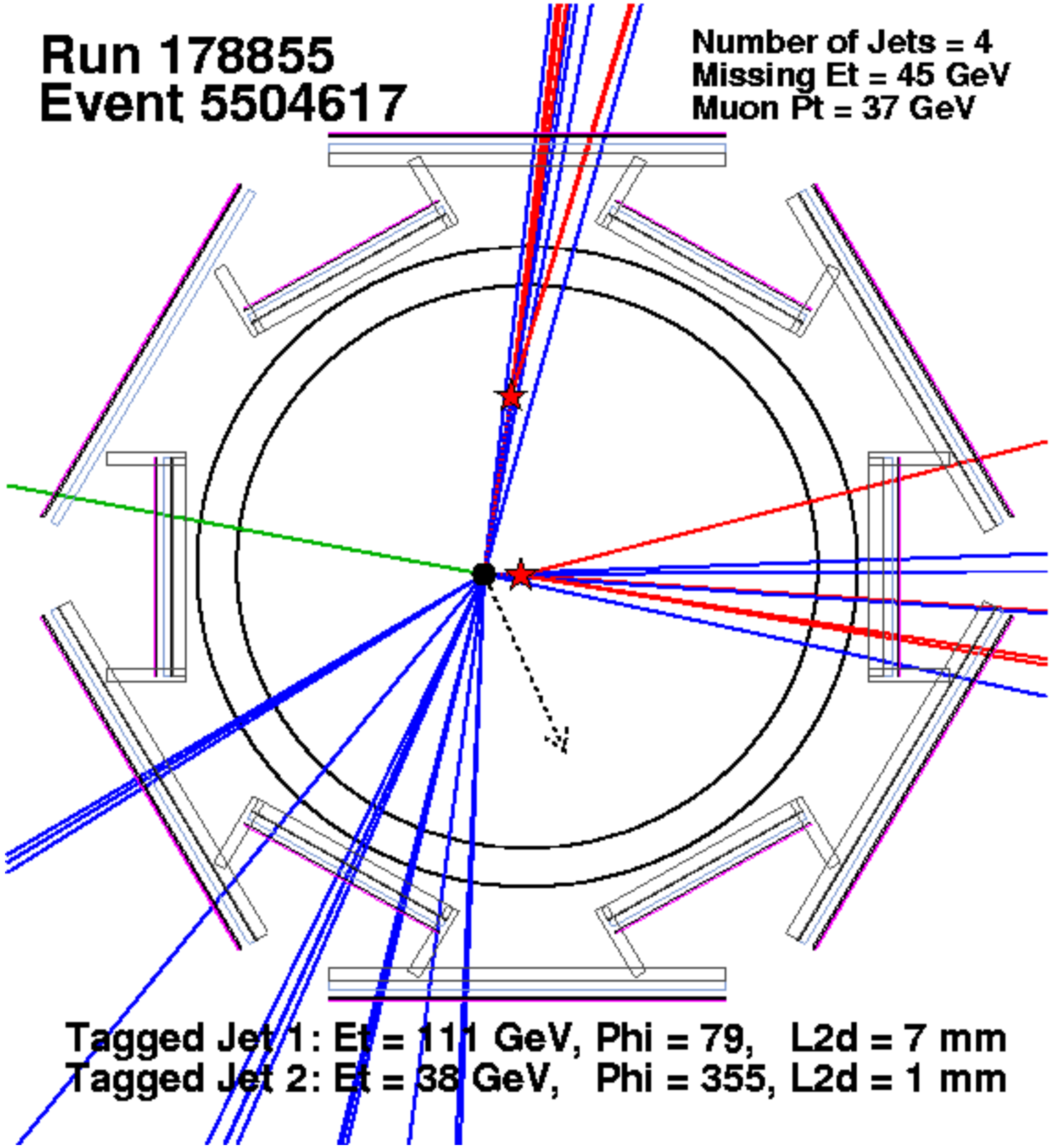
$\propto L$ Distance of the first measurement layer

Top-quark-antiquark pair candidate event …

BERGISCHE UNIVERSITÄT WUPPERTAL

… with two reconstructed secondary vertices

CDF experiment at Fermilab

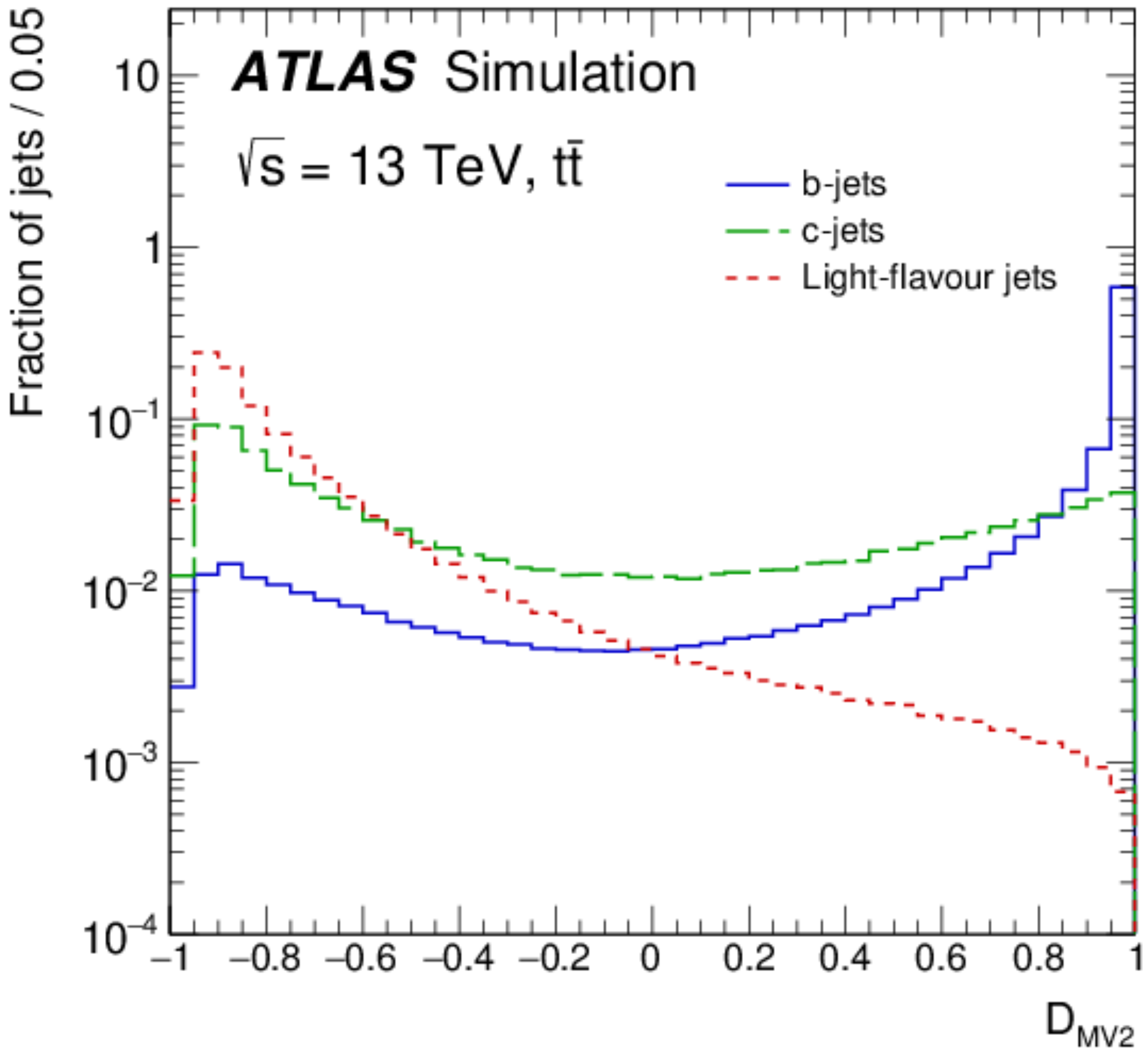


Flavour-tagging with multivariate techniques

BERGISCHE UNIVERSITÄT WUPPERTAL

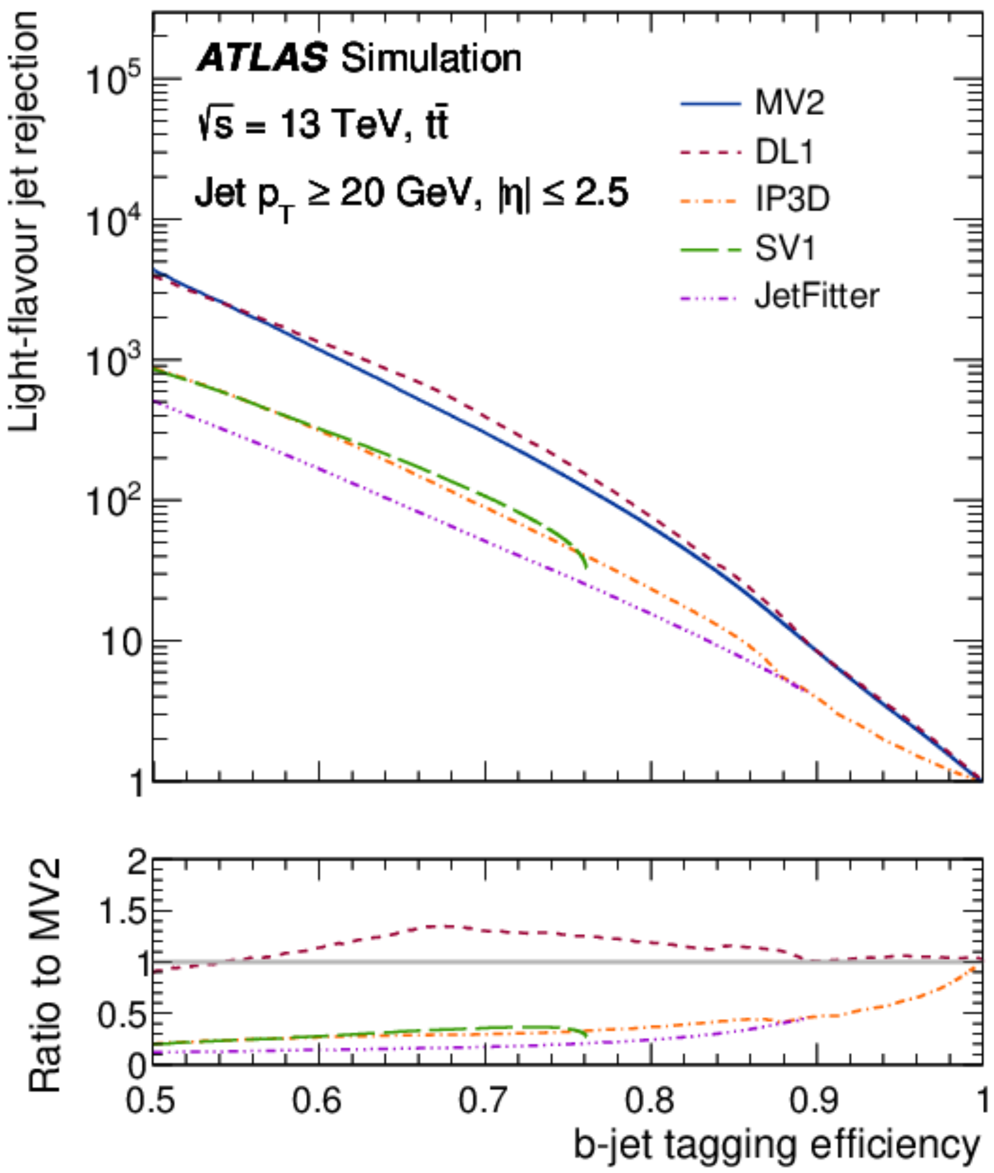
Use many discriminating features of b-jets, c-jets and light-jets to identify them.

arXiv:1907.05120



Performance of flavour-tagging algorithms

BERGISCHE UNIVERSITÄT WUPPERTAL



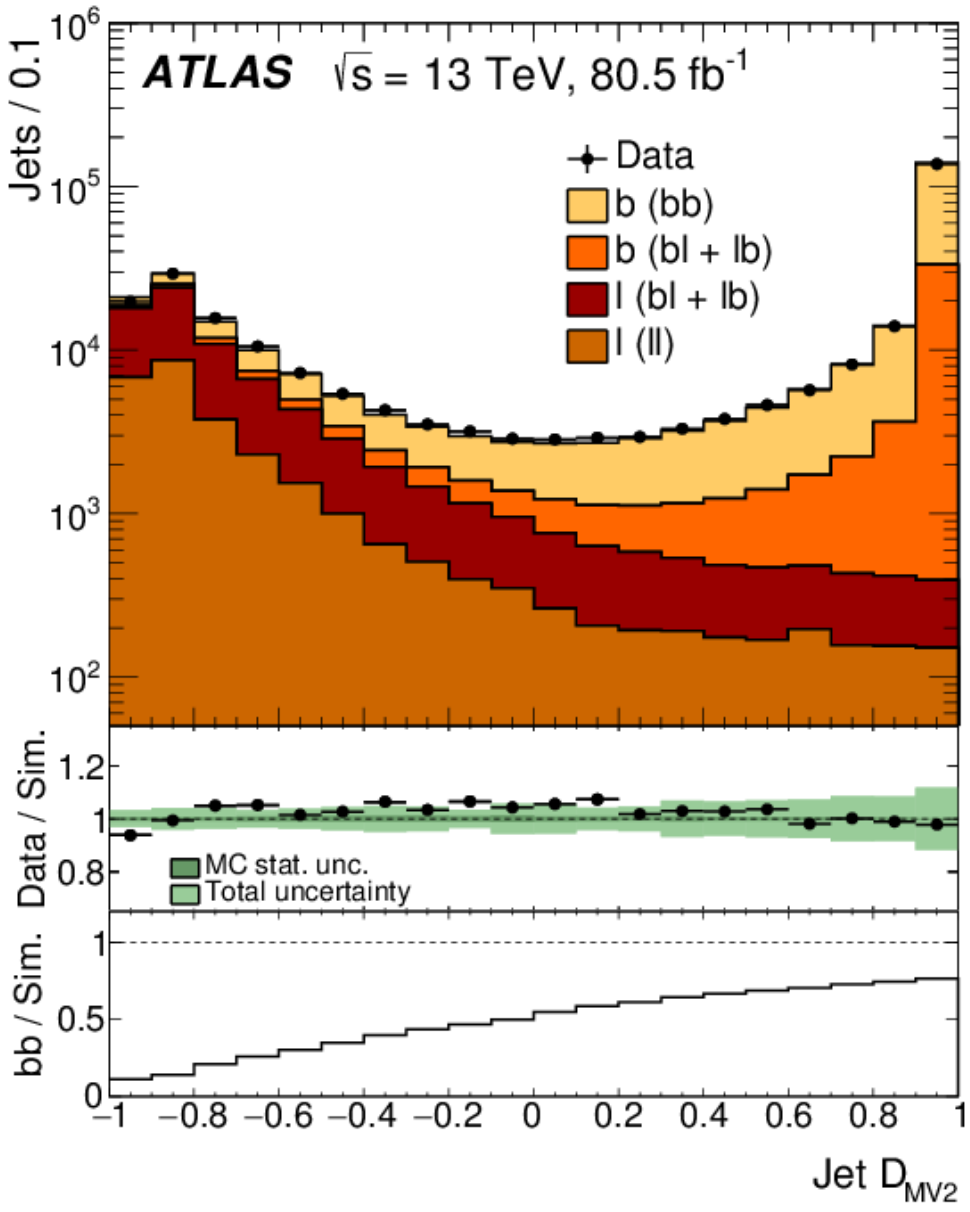
Multivariate tagger algorithms improve rejection of light-flavour jets by more than one order of magnitude.

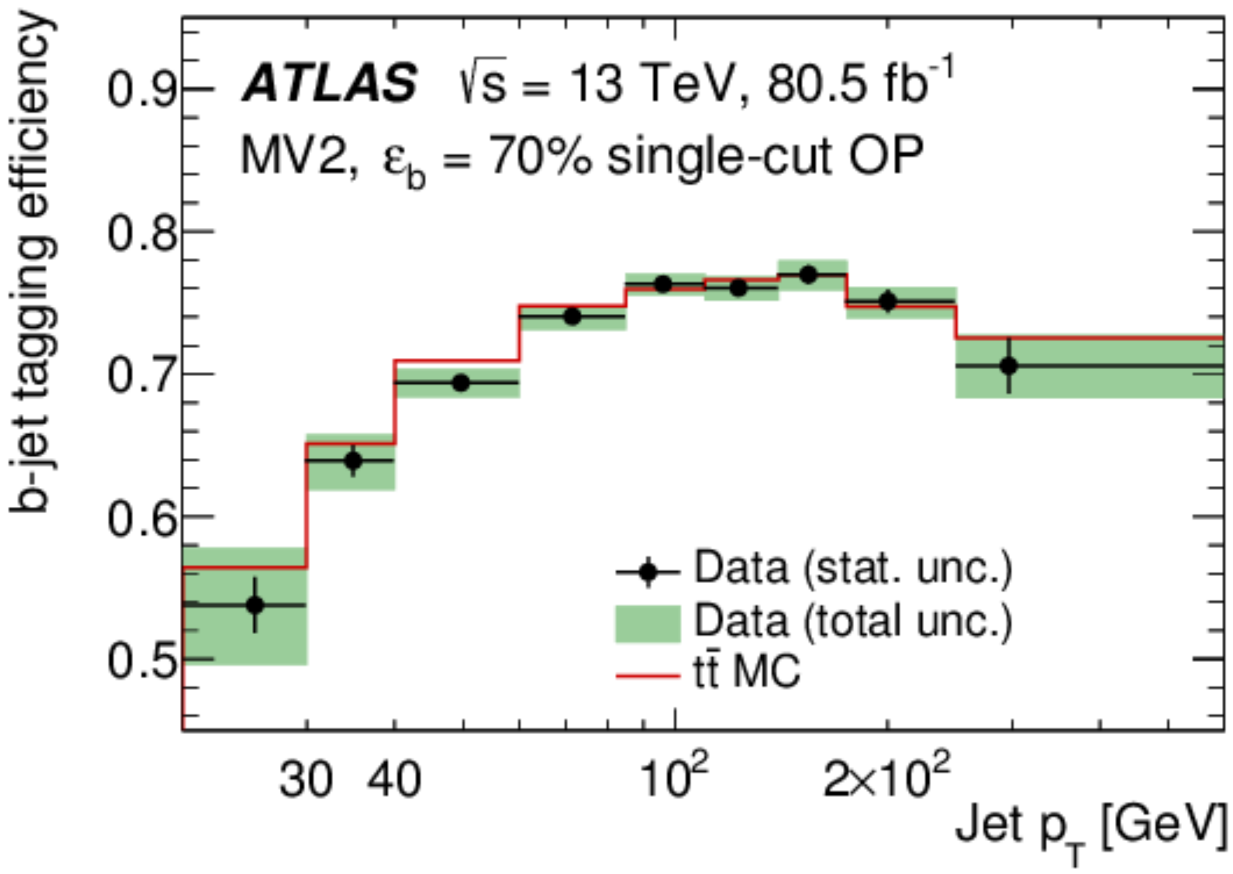
MV2 = Boosted Decision Tree (BDT)
DL1 = Deep Neural Network

Conventional tagging algorithms:
IP3D = Track impact parameter based tagger
SV1 = Reconstruction of a secondary vertex
JetFitter =

Data Monte-Carlo comparison (calibration)

BERGISCHE UNIVERSITÄT WUPPERTAL





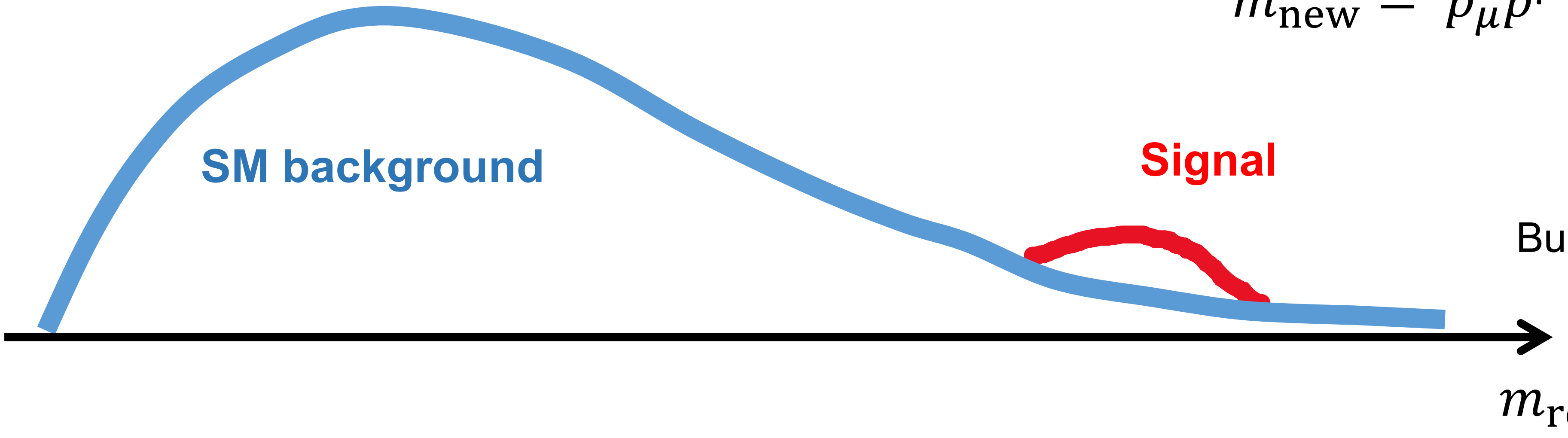
MC-to-data scale factor is close to 1.

Chapter 3

Direct searches for new particles

(So-called on-shell production)

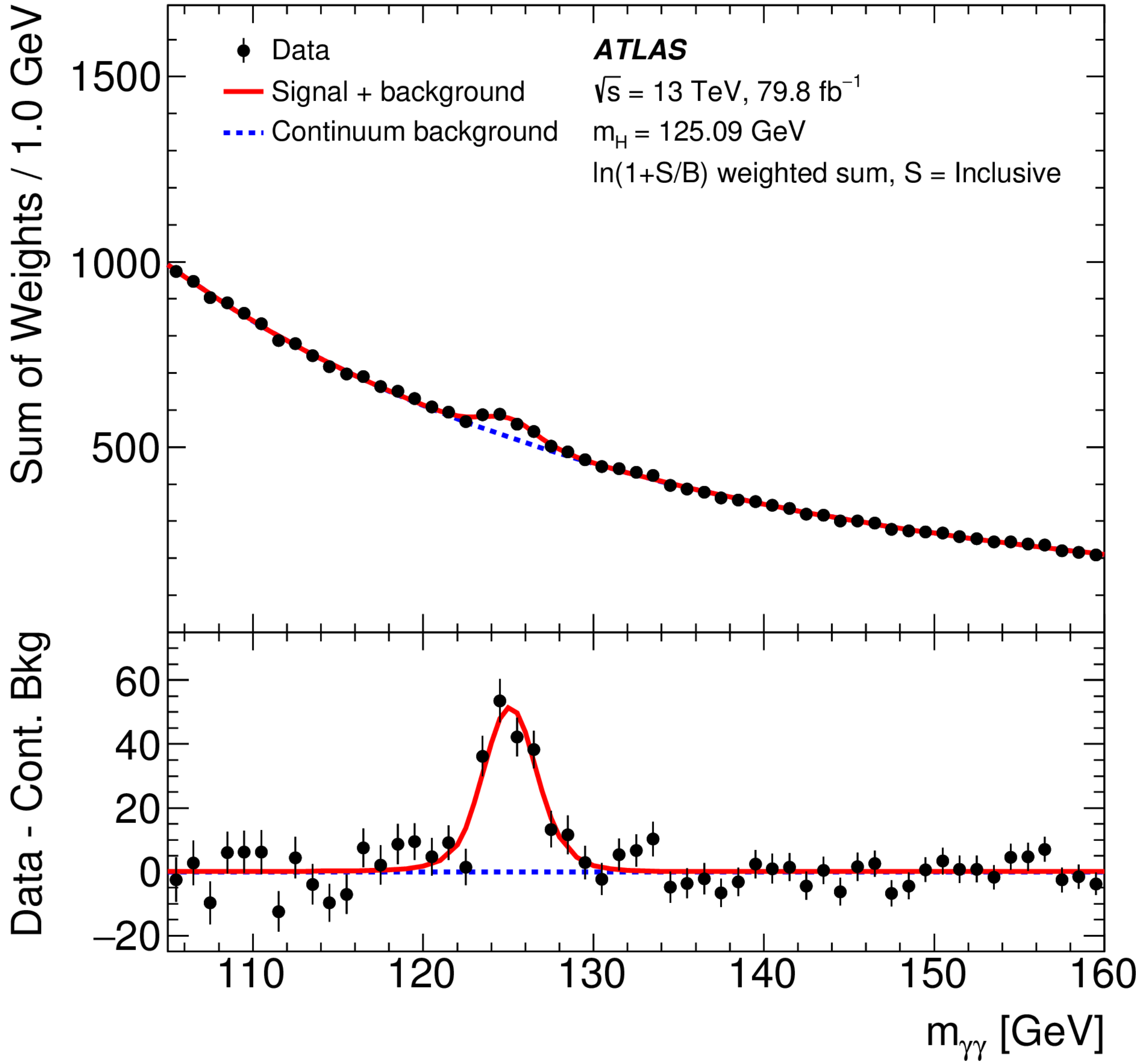
$$m_{\text{new}}^2 = p_\mu p^\mu = E^2 - \vec{p} \cdot \vec{p}$$



Bump search

Prime example of a bump search:

Observation and subsequent measurement of the SM Higgs boson in the
$H \rightarrow \gamma\gamma$
decay channel.



Content of Chapter 3

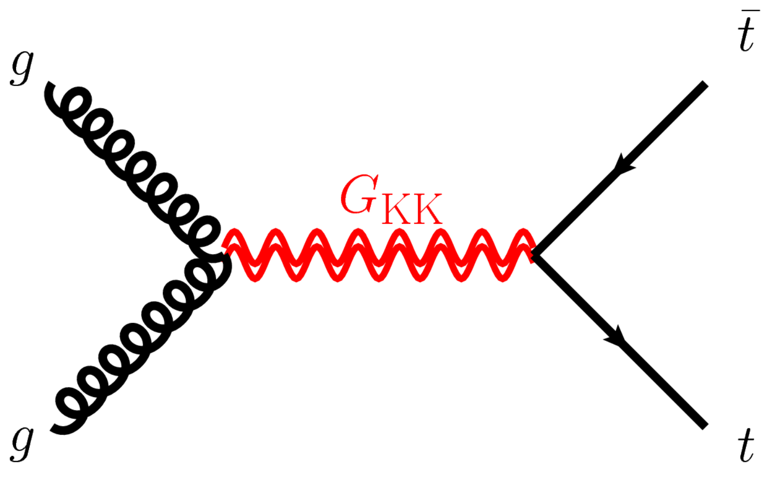
BERGISCHE
UNIVERSITÄT
WUPPERTAL

Direct searches for

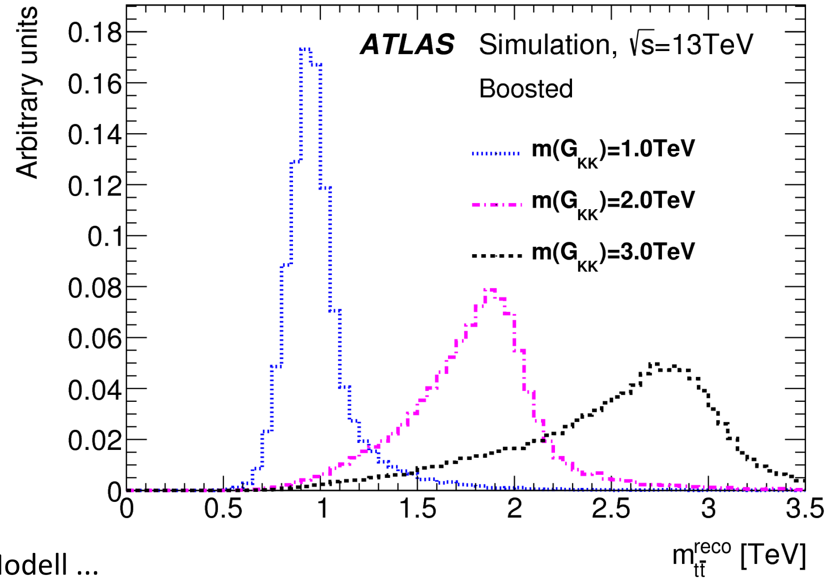
1) $t\bar{t}$ resonances
2) Supersymmetric partners of top quarks, bottom quarks and gluons decaying to $t\bar{t}$ pairs
3) Vector-like top quarks
4) Lepto-quarks decaying to 3rd generation quarks and leptons

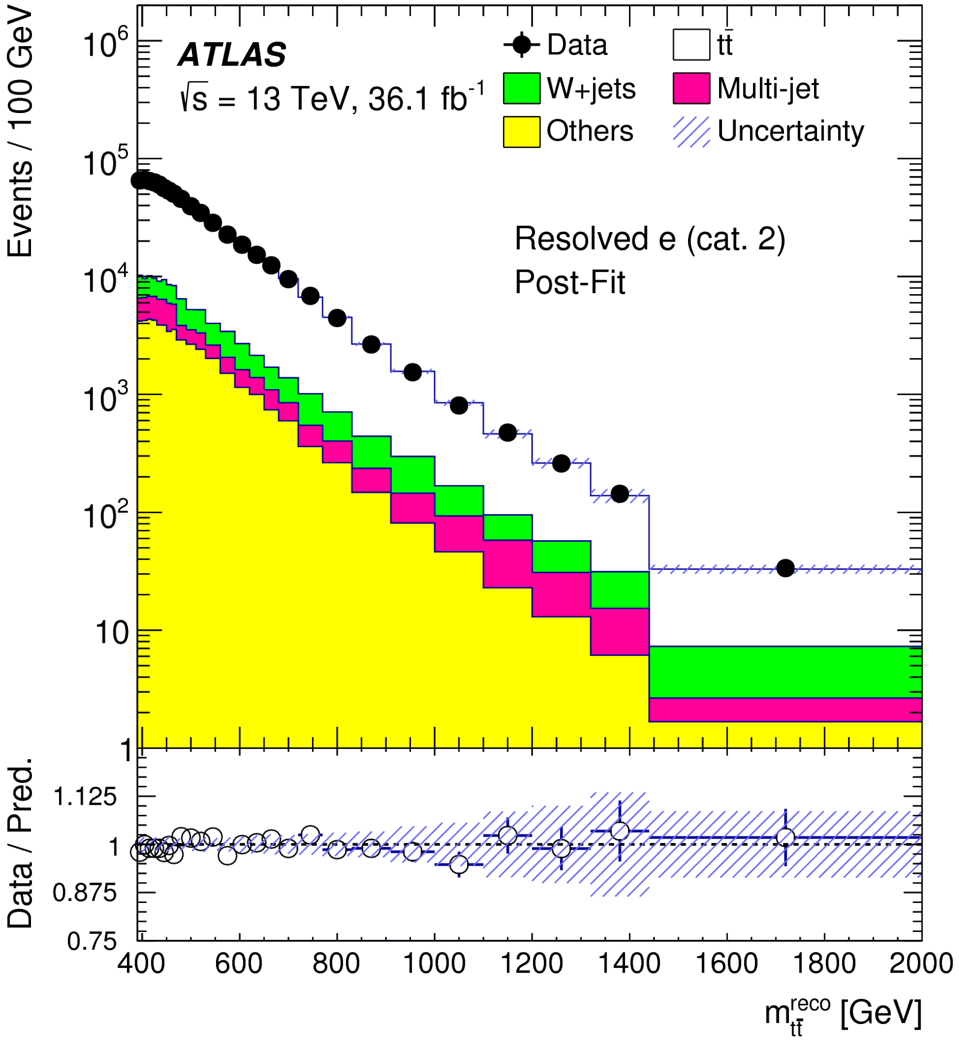
Search for $t\bar{t}$ resonances

Higher symmetry than SM $\rightarrow$ more gauge bosons



Important for discovery if decay to $t\bar{t}$ is enhanced.



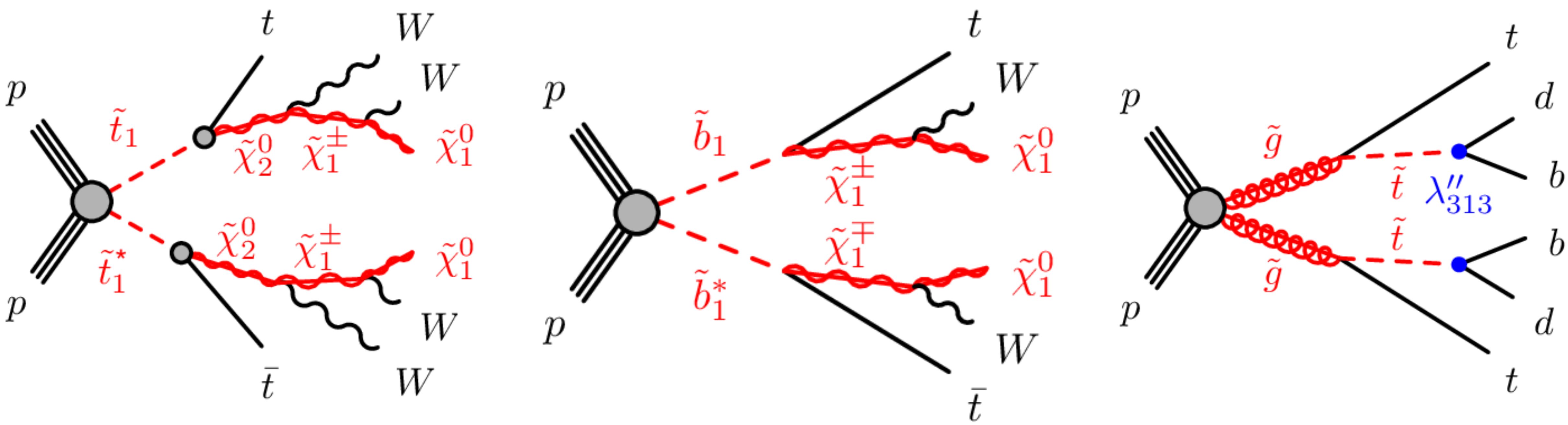


arXiv: 1804.10823

Eur. Phys. J. C 78 (2018) 565

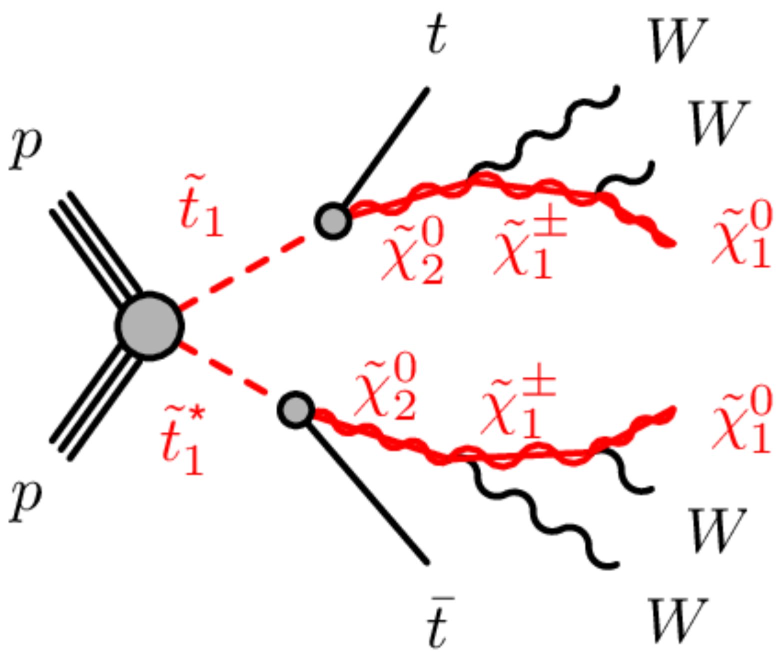
Search for top squarks and bottom squarks

$\tilde{t}_1$ and $\tilde{b}_1$: the lightest eigenstates of the (scalar) supersymmetric top and bottom partners.



- Production of $t\bar{t} + X$
- Events contain multiple leptons and jets, and large missing transverse momentum.

General strategy in (most) SUSY searches



- Do not attempt to reconstruct four-momentum of supersymmetric particle ($\tilde{t}_1$, $\tilde{b}_1$, $\tilde{g}$, …).
- Define global variables capturing the key features of the signal events:
  - Large missing transverse momentum $E_\mathrm{T}^\mathrm{miss}$ due to neutralinos in R-parity conserving SUSY models.
  - Large effective mass

    $$m_\mathrm{eff} = \sum_\mathrm{jets} p_T + \sum_\mathrm{leptons} p_T + E_\mathrm{T}^\mathrm{miss}$$

    (scalar sum!)

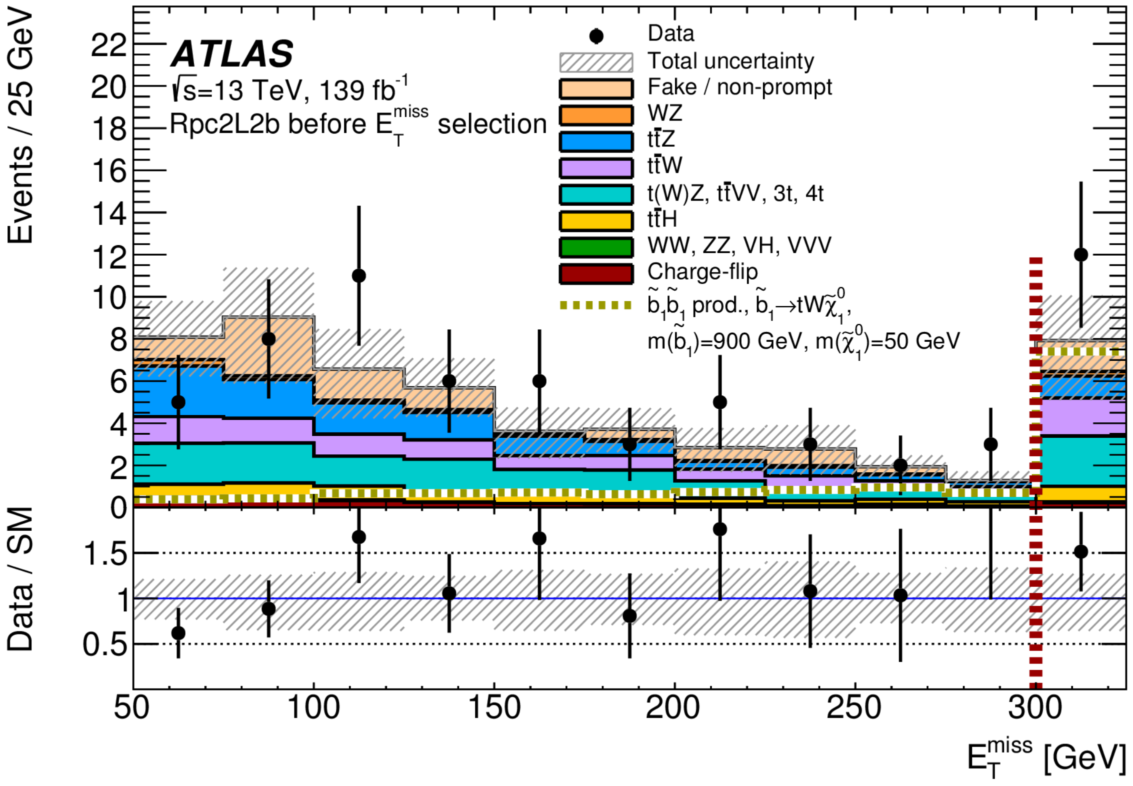
ATLAS two-same-sign-leptons search

Define 5 signal regions with $\ell^{\pm}\ell^{\pm}$ pair and ≥ 6 jets.

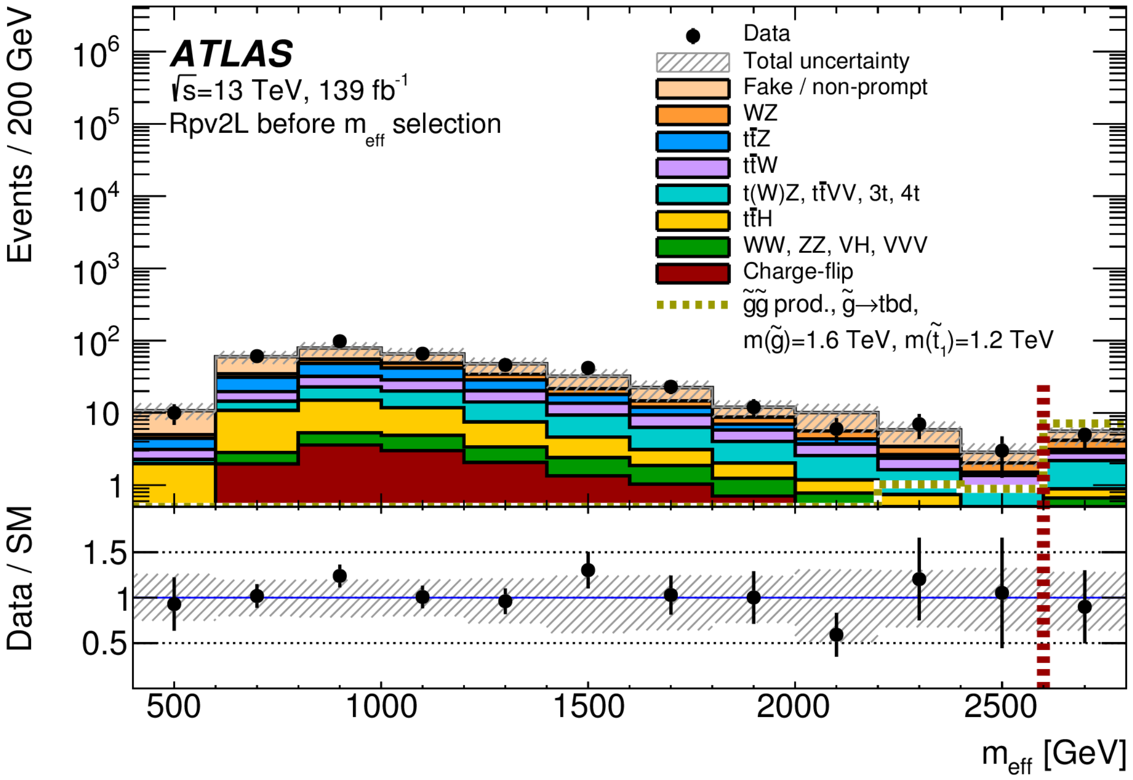
arXiv: 1909.08457

SR Rpc2L2b:
$E_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV and $m_{\mathrm{eff}} > 1600$ GeV

SR Rpv2L: $m_{\mathrm{eff}} > 2600$ GeV
no $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement

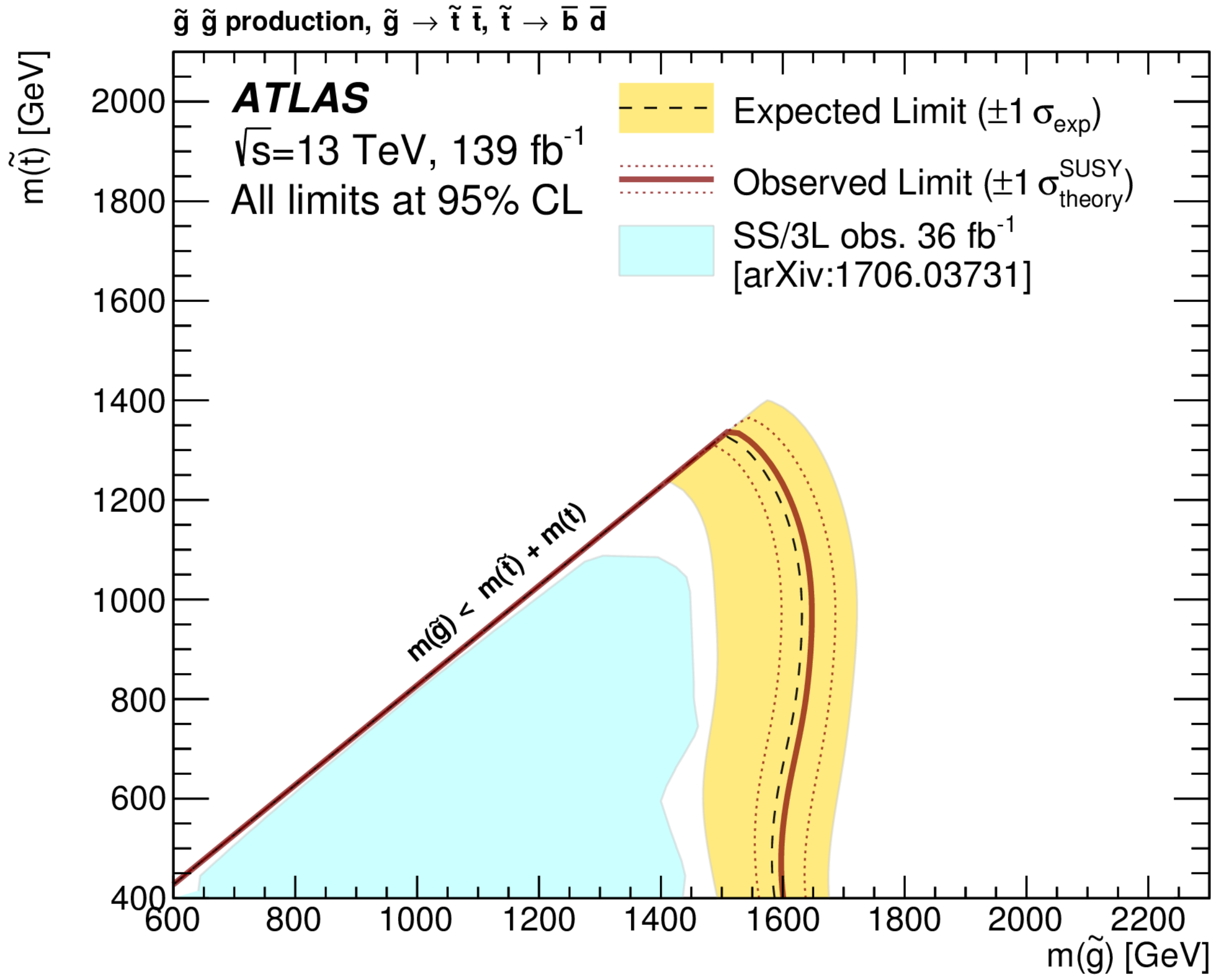


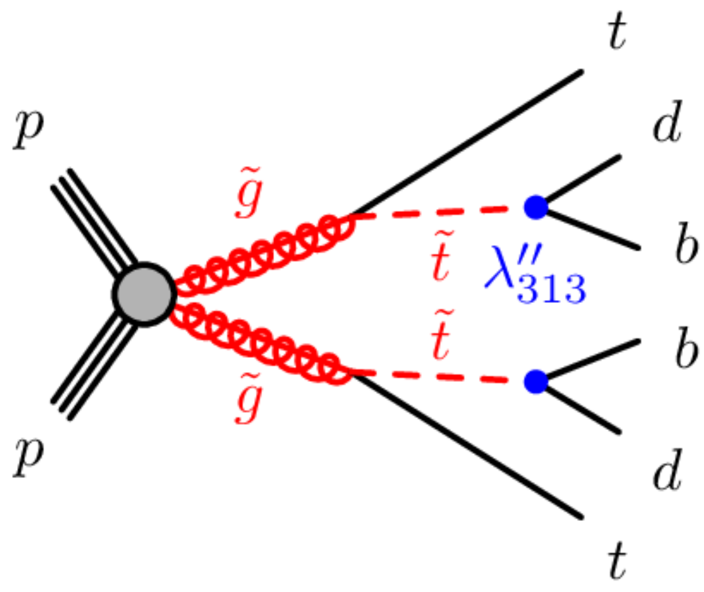
Sensitive to $\tilde{b}_1 \rightarrow tW\tilde{\chi}_1^0$ and $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$.



Sensitive to $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ with $\tilde{\chi}_1^0 \rightarrow 3q$ and $\tilde{g} \rightarrow t\tilde{t}_1^*$.

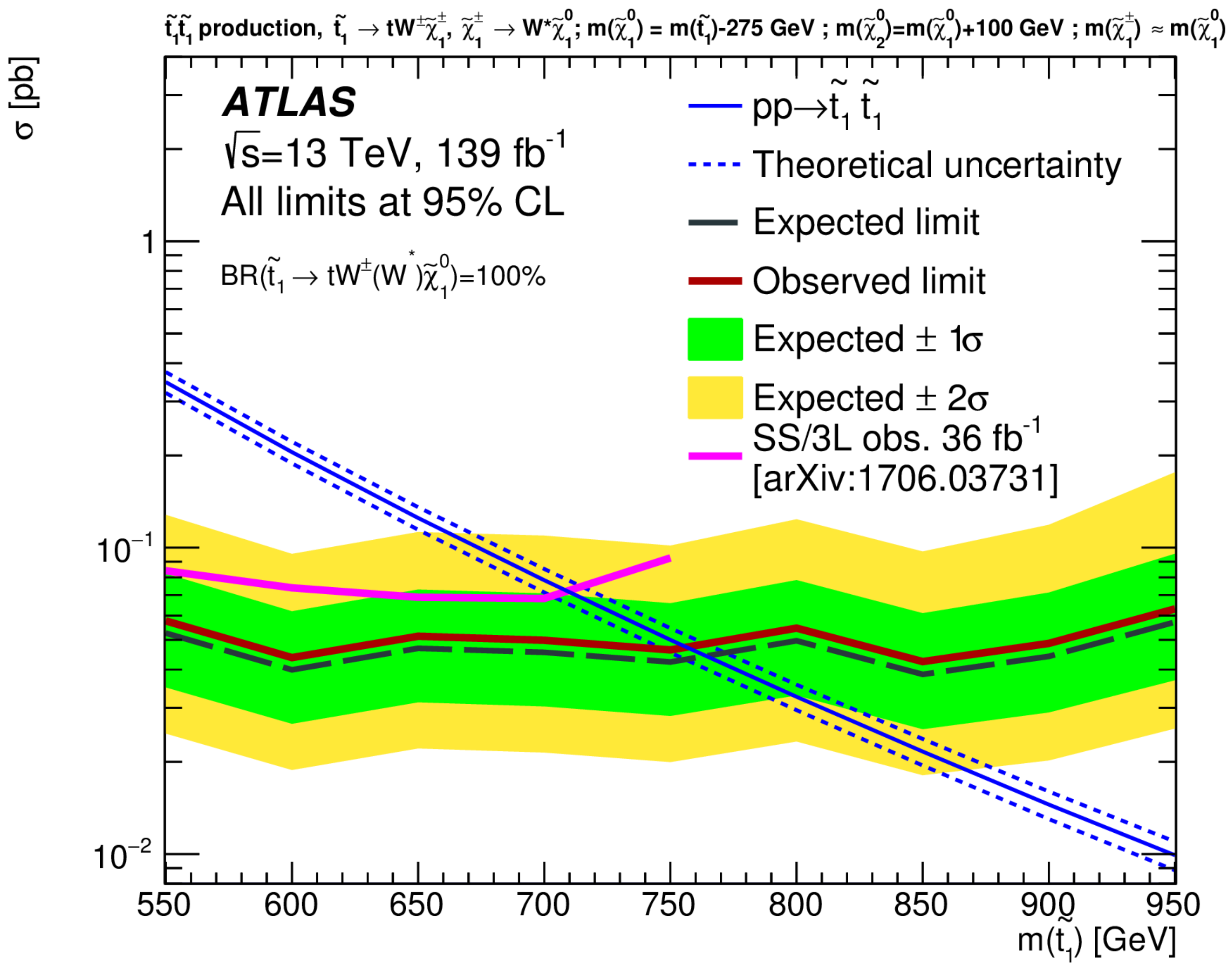
Exclusion limits

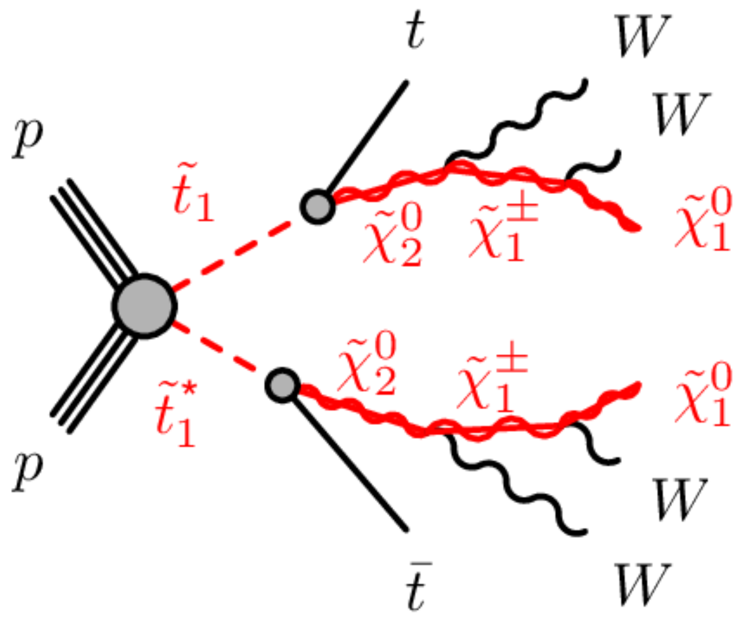




- R-parity violating model
- SR Rpv2L
- $\tilde{g} \rightarrow tbd$

Exclusion limits

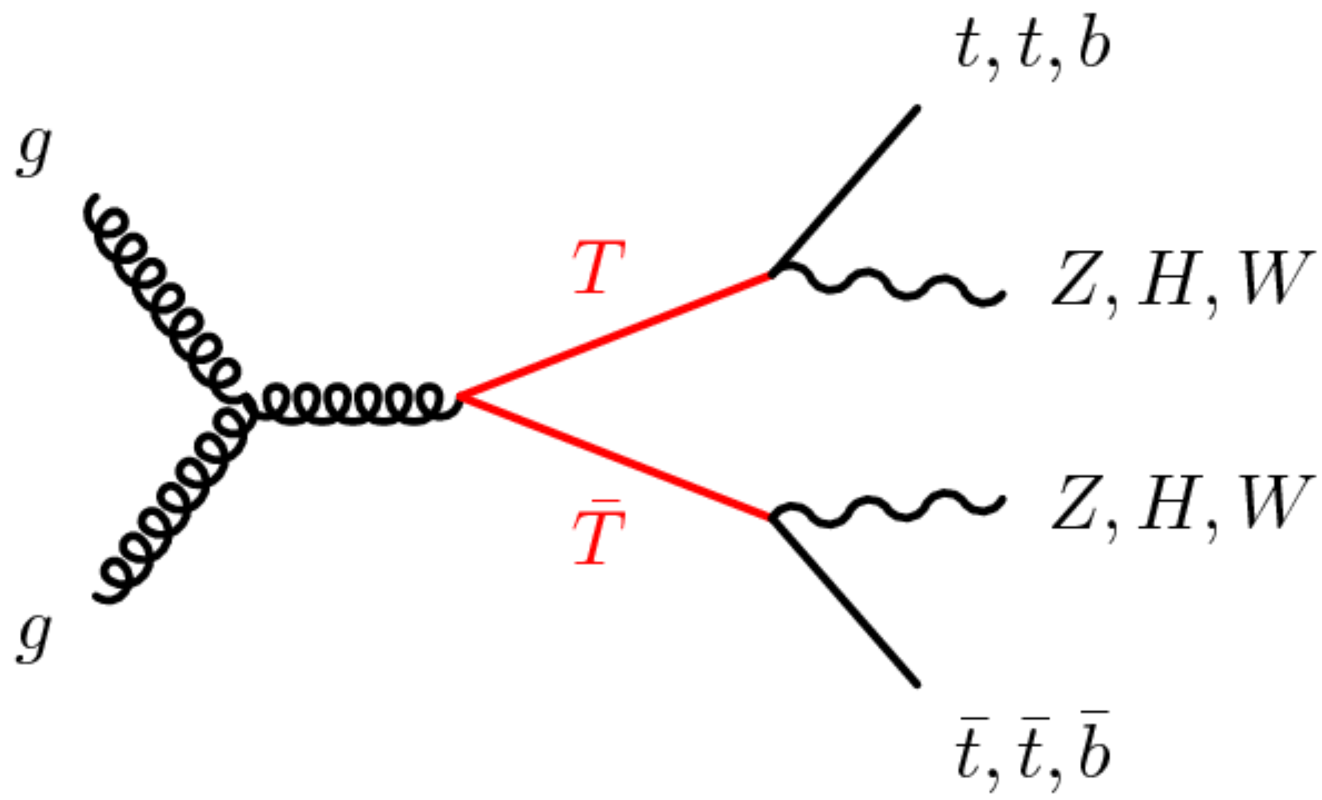




- R-parity conserving model
- SR Rpc3LSS1b
- $\tilde{t}_1 \rightarrow tW^{\mp}\tilde{\chi}_1^{\pm}$

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.

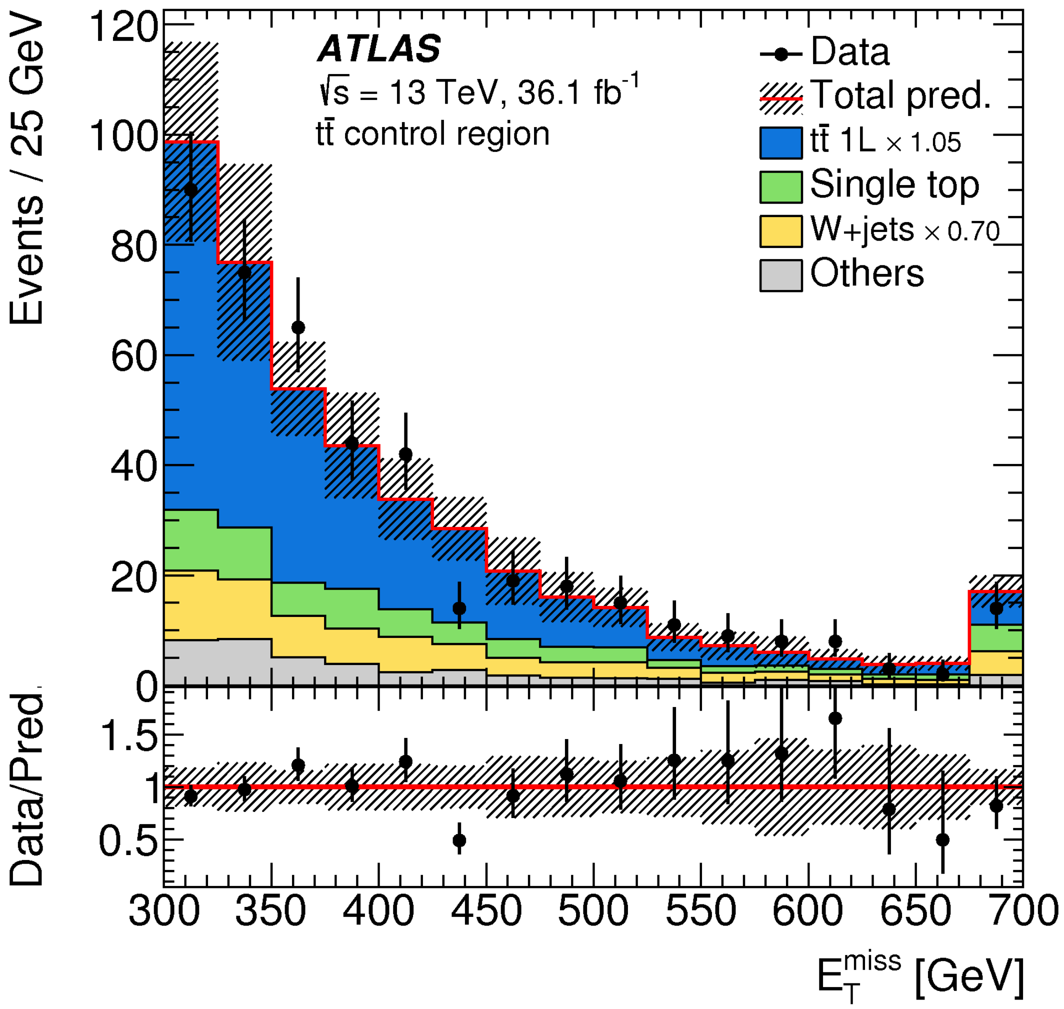
Search in the $T\bar{T} \to Zt + X$ with $Z \to \nu\bar{\nu}$ channel

arXiv:1705.10751 JHEP 08 (2017) 052

Basic event selection:

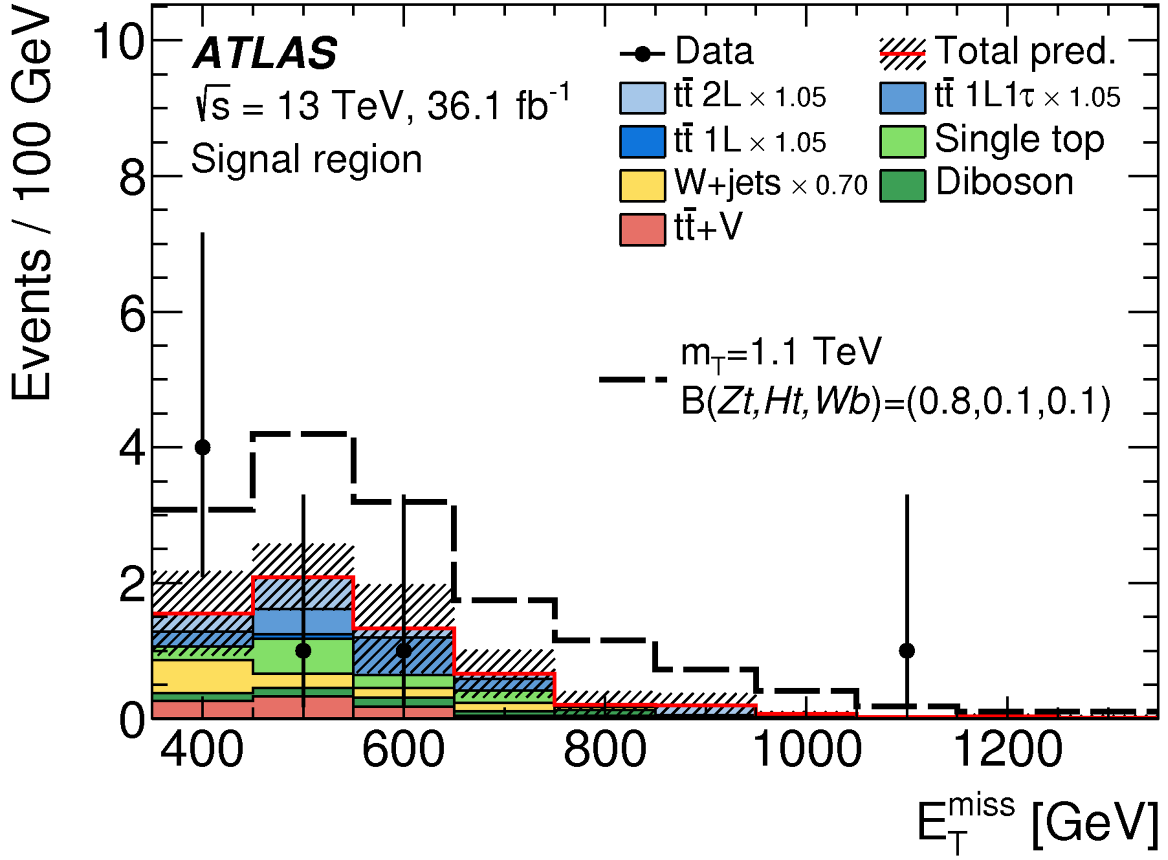
- $E_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV
- exactly 1 charged lepton
- ≥ 4 jets with (small) $R = 0.4$
- Re-cluster jets to large-R jets with $R = 1.0$: ≥ 2 large-R jets

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



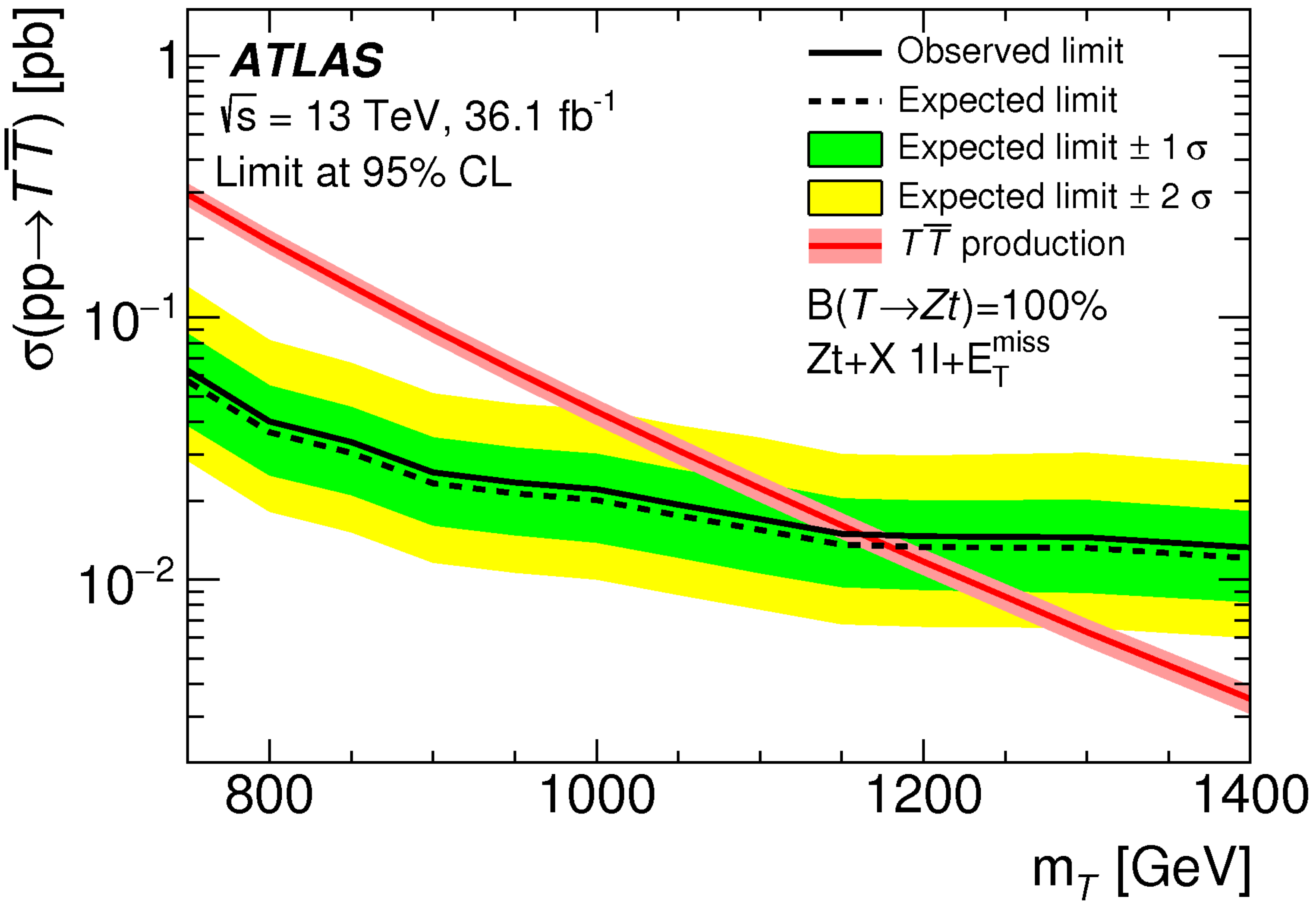
Signal region

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 $T\bar{T} \to Zt + X$

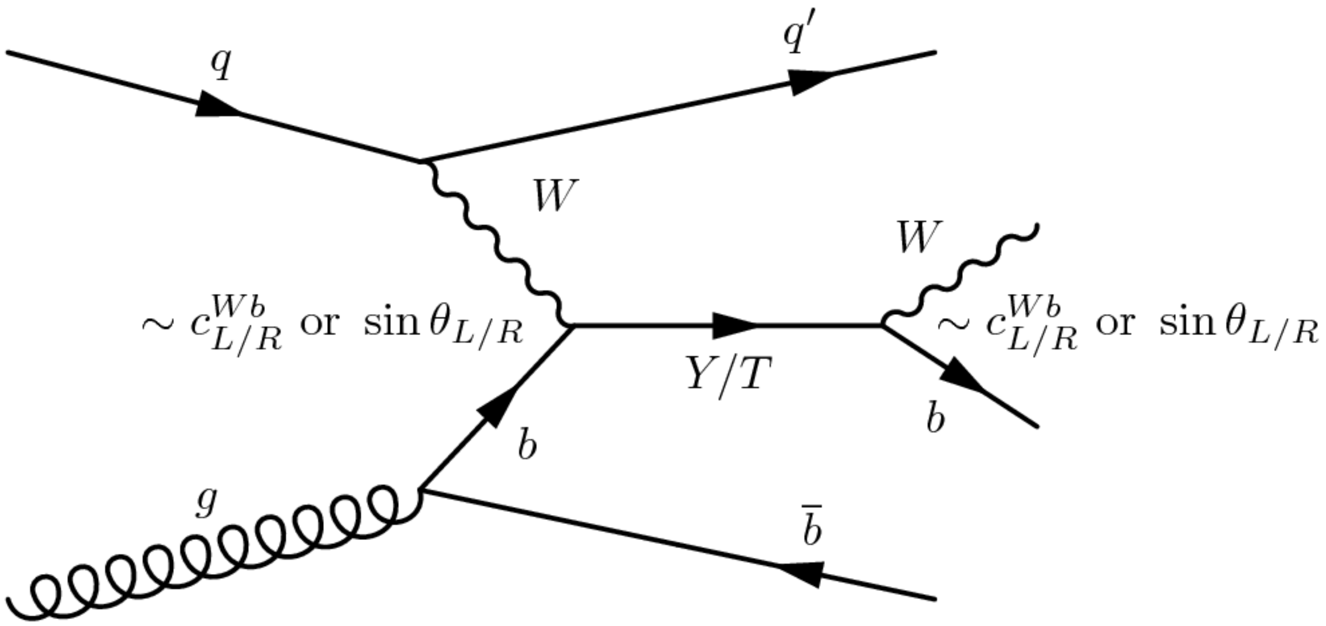


- T quarks with $m_T < 1.16$ TeV are excluded if $\mathcal{B}(T \to Zt) = 100\%$ is assumed.
- Account for other decay modes ($T \to Ht$ and $T \to Wb$):
  - Single model: $m_T < 0.87$ TeV
  - Double model: $m_T < 1.05$ TeV

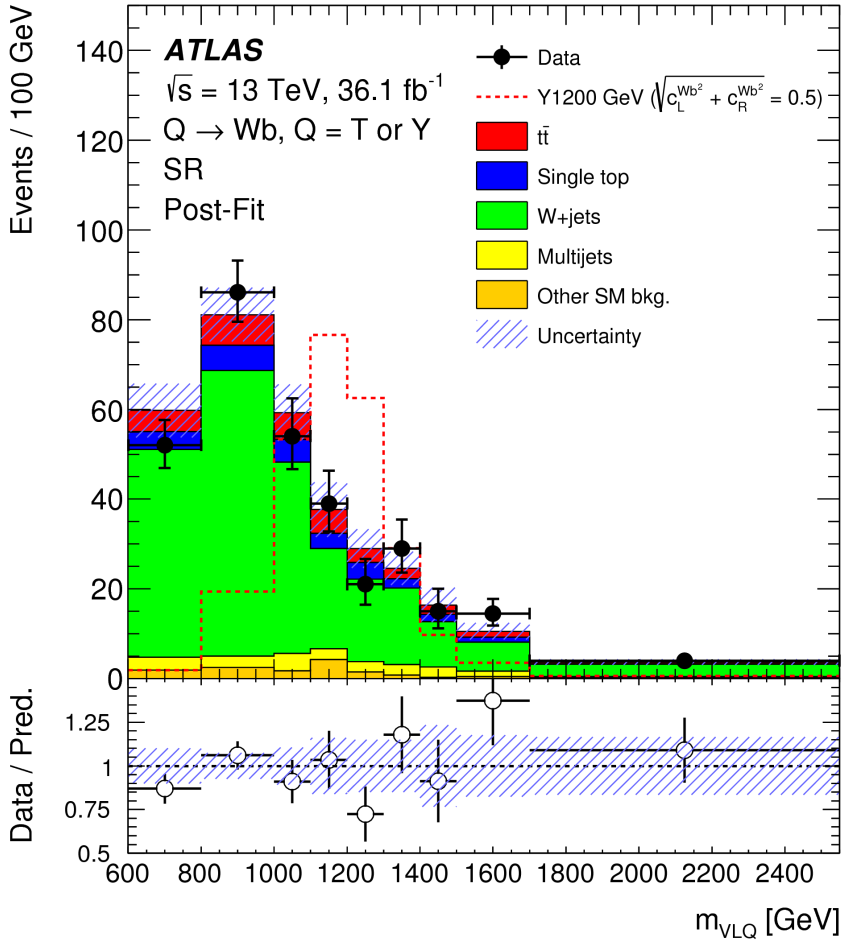
Single production of vector-like top quarks

[arXiv: 1812.07343](https://arxiv.org/abs/1812.07343) JHEP 05 (2019) 164

$T \rightarrow Wb$ channel (and Y quarks with $Q_Y = -\frac{4}{3}$)



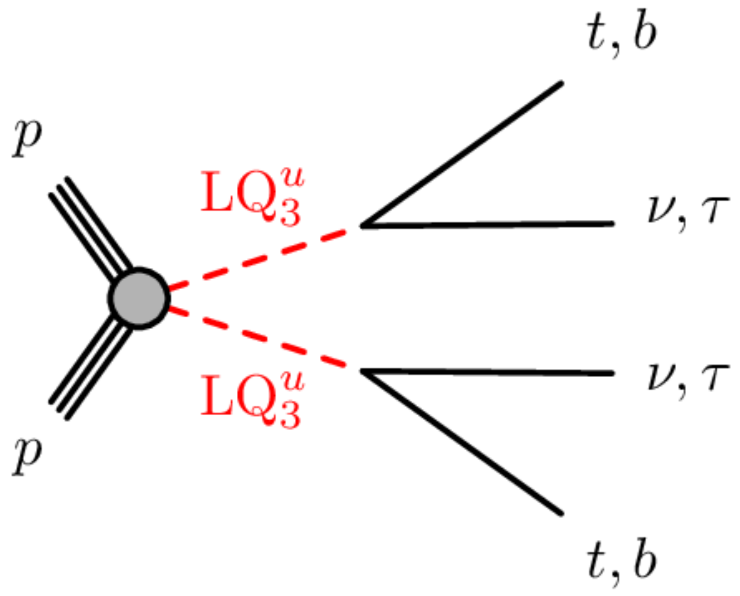
Reconstructed mass distribution of the T(Y) candidate

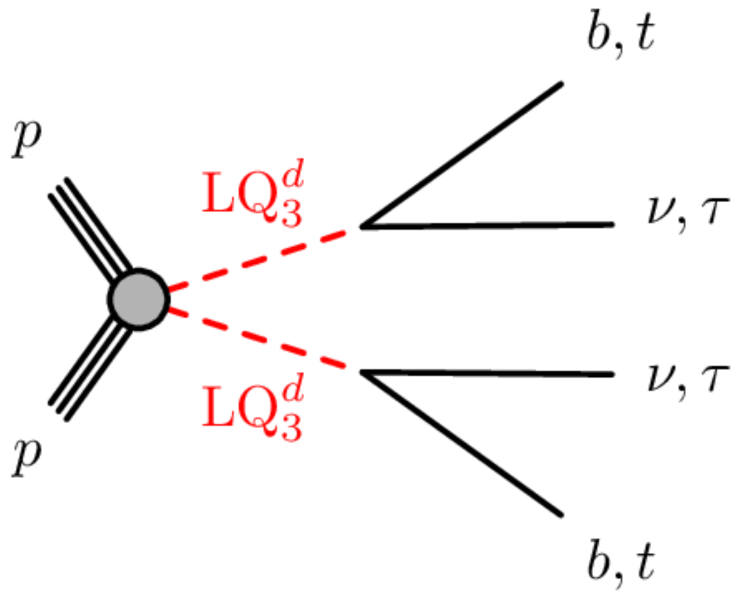


Production cross section scales with a coupling squared.

Searches for lepto-quarks

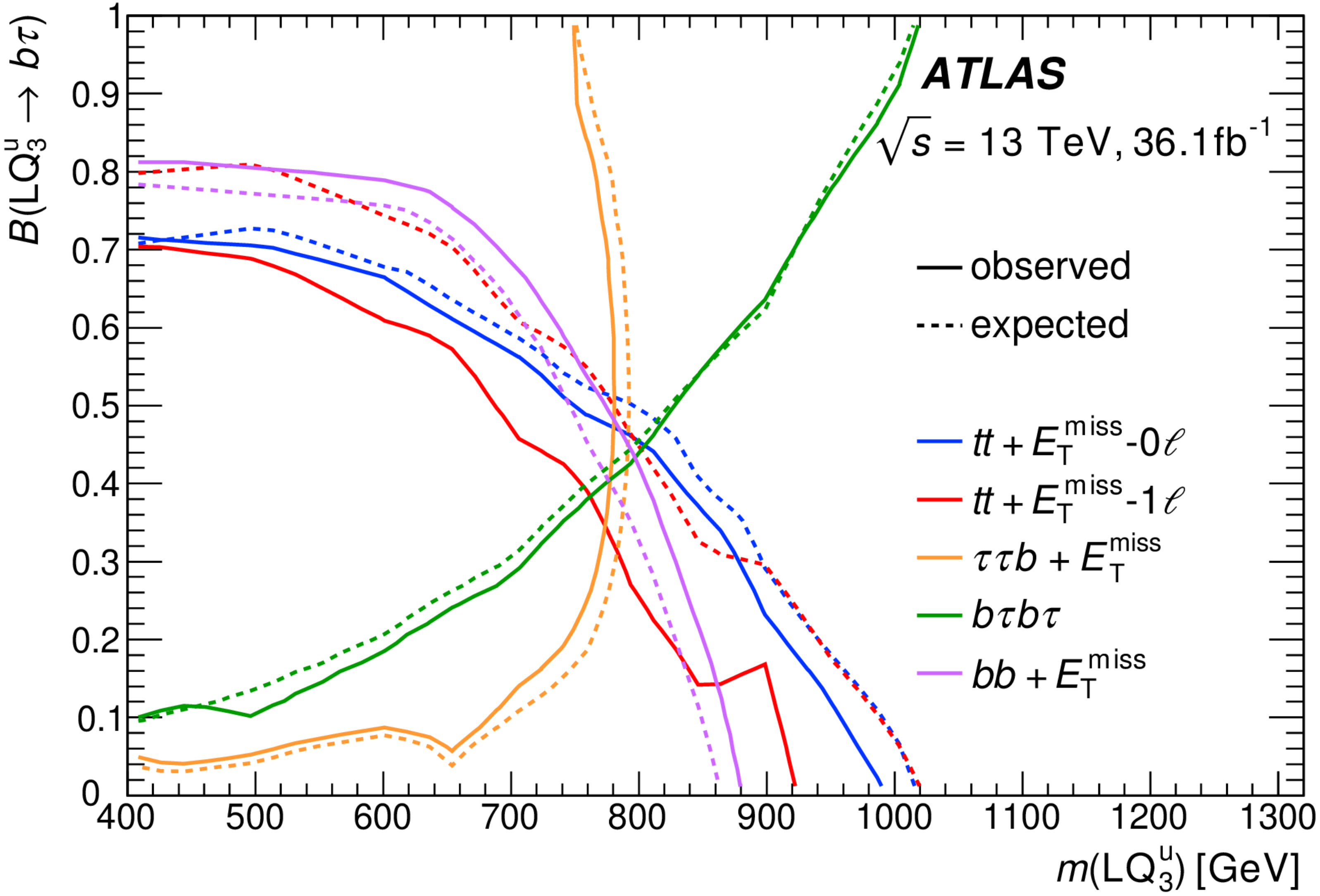
- Lepto-quarks occur in many extensions of the SM based on a larger symmetry group.
- Bosons
- Carry colour charge and electrical charge.
- Connect quark and lepton sector.
- Carry non-zero baryon and lepton numbers.
- Decay into a lepton-quark pair.
- Consider up-type lepto-quark LQ_3^u and down-type lepto-quark LQ_3^d
- Decay into fermions of the 3rd generation.





Exclusion limits

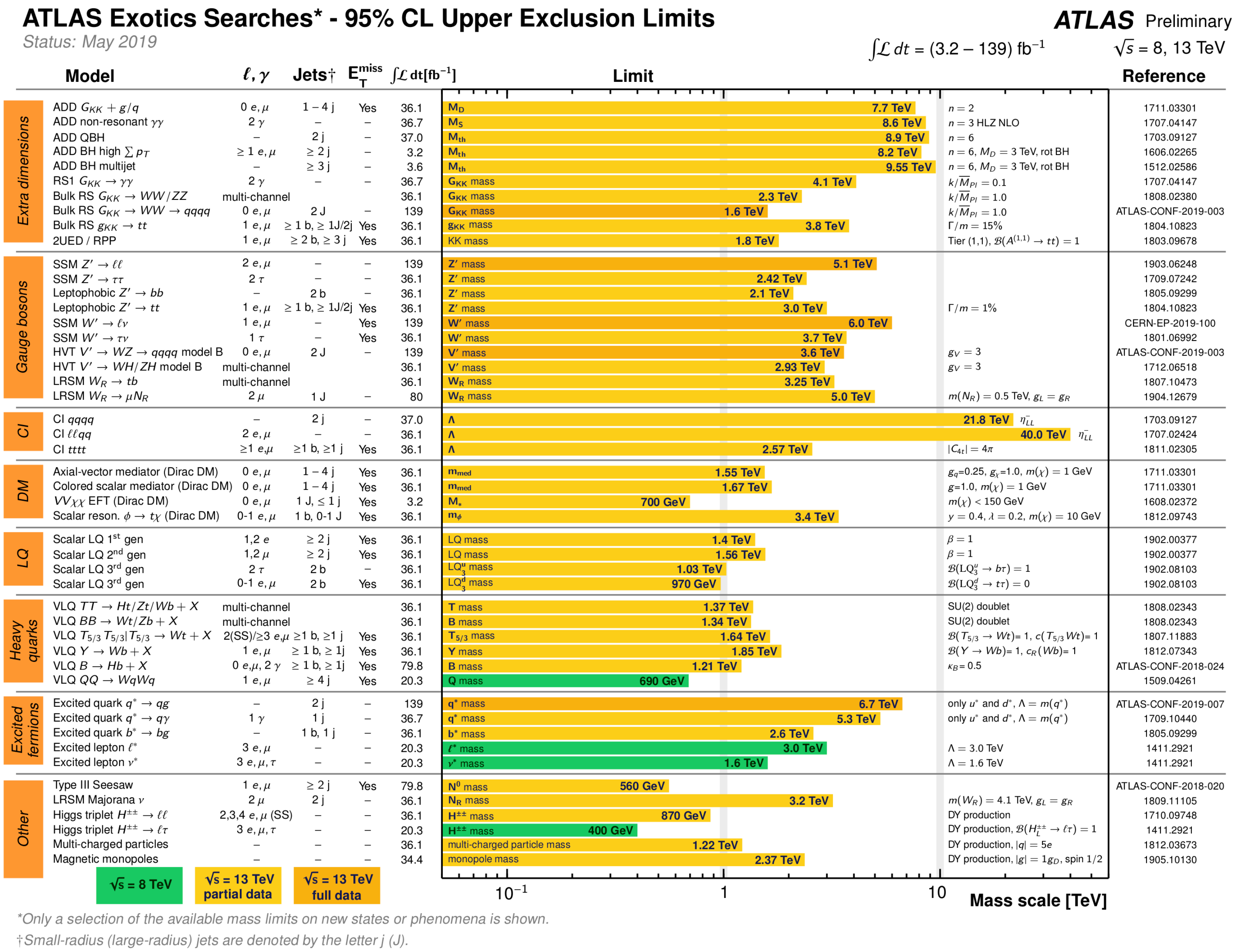
arXiv: 1902.08103 JHEP 06 (2019) 144



Indirect vs. direct Searches for New Physics

BERGISCHE UNIVERSITÄT WUPPERTAL

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



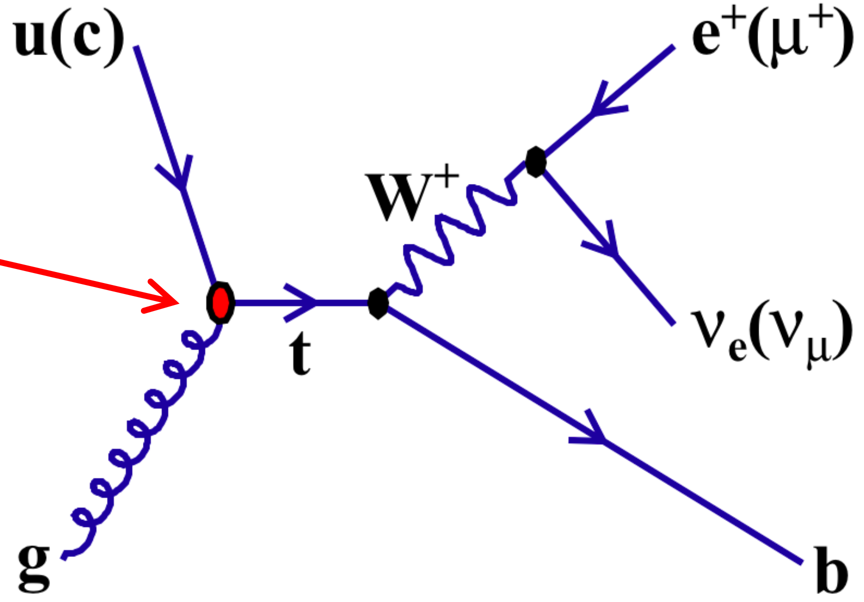
Access higher mass scales by deviations in coupling measurements and search for rare processes.

Chapter 4

Indirect searches / searches for anomalous couplings

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

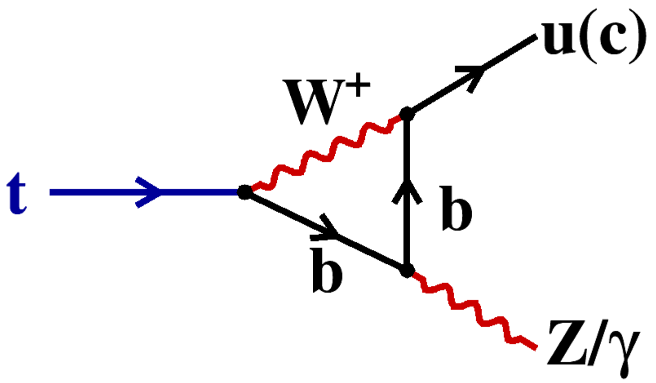
→ Recall Fermi theory of nuclear beta decay



Decays via flavour-changing neutral currents (FCNC)

BERGISCHE UNIVERSITÄT WUPPERTAL

- 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.



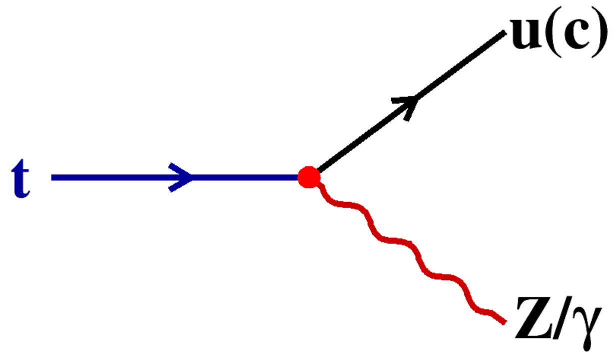
	$Br(t \to q\gamma)$	$Br(t \to qZ)$	$Br(t \to qg)$
$q = u$	3.7×10^{-16}	8×10^{-17}	3.7×10^{-14}
$q = c$	4.6×10^{-14}	1×10^{-14}	4.6×10^{-12}

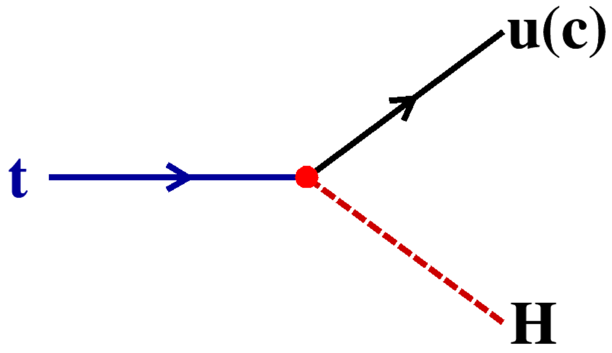
FCNC in theories beyond the SM

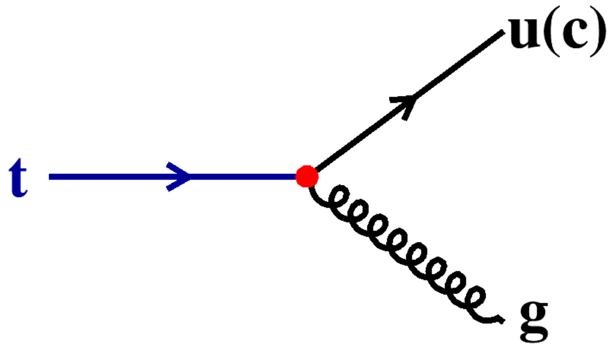
Branching ratios of top-quark decays in SM and BSM theories:

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





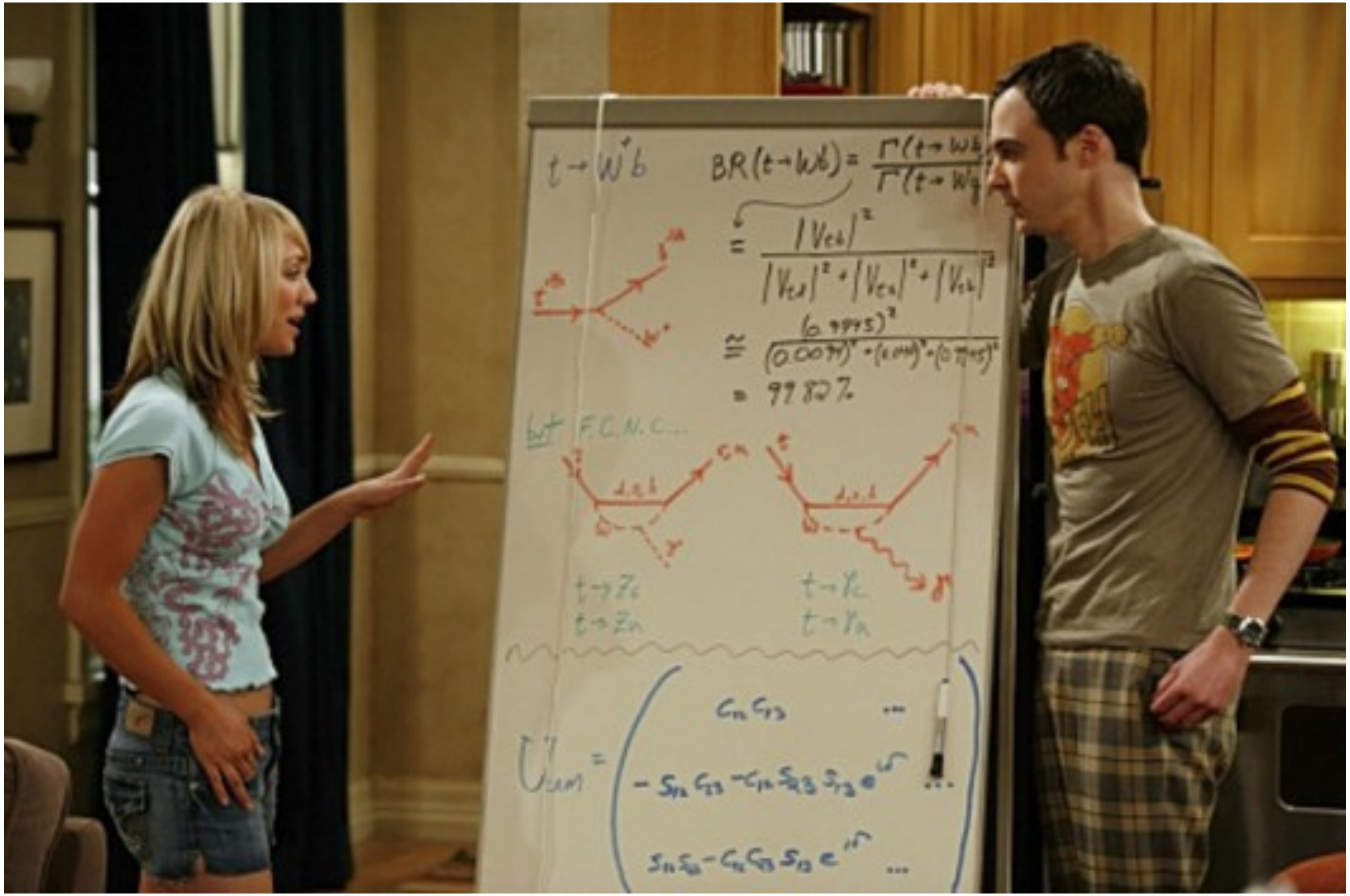


Strong enhancement!

Any FCNC signal is evidence for BSM physics!

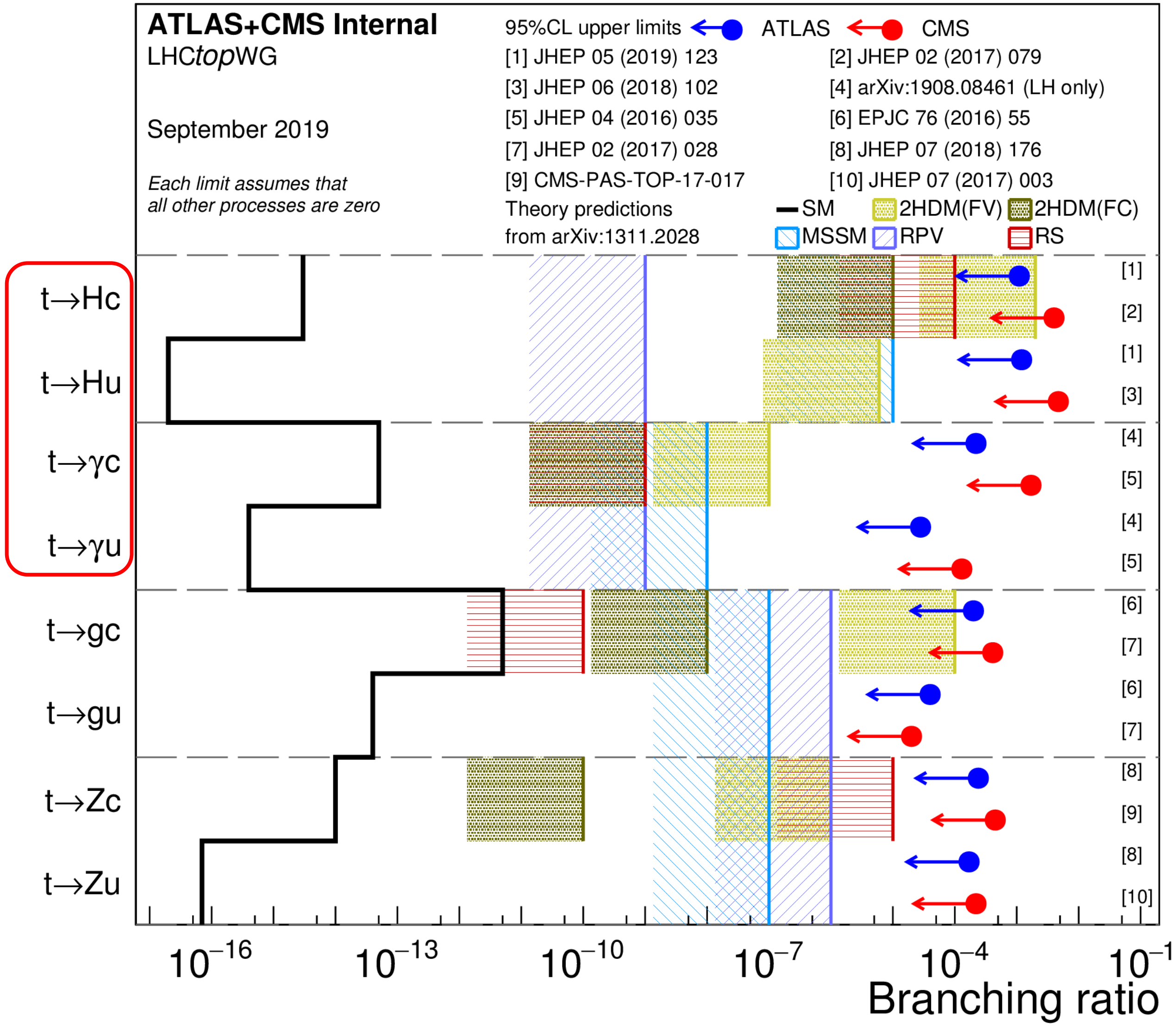
Even Hollywood knows: FCNC are exiting!

BERGISCHE
UNIVERSITÄT
WUPPERTAL



Status of FCNC limits

BERGISCHE UNIVERSITÄT WUPPERTAL



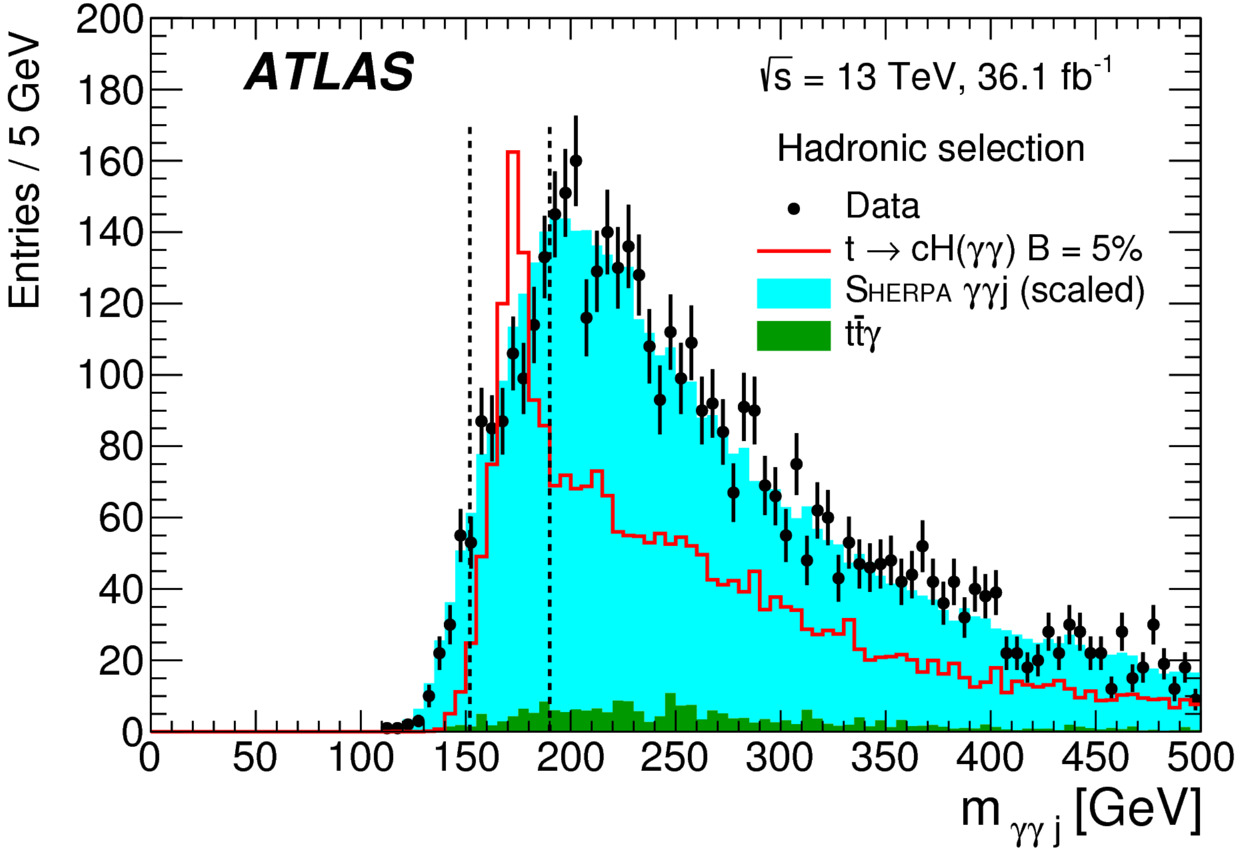
Latest ATLAS analysis

Search for $t \to qH$ with $H \to \gamma\gamma$

- Select $t\bar{t}$ candidate events.
- Assume one top-quark decays via $t \to q\gamma\gamma$ and one via the SM mode $t \to Wb$
- Consider $W \to q\bar{q}'$ and $W \to \ell\nu$

arXiv: 1707.01404

JHEP 10 (2017) 129

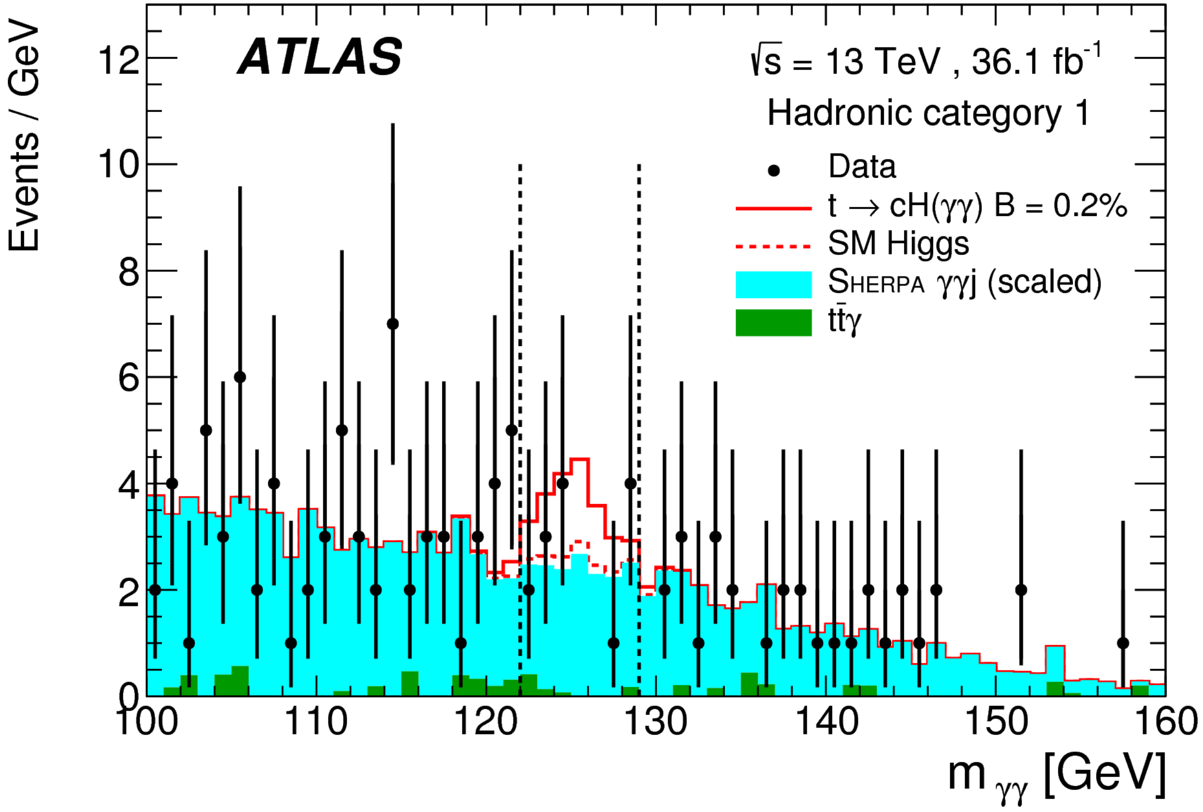


- Reconstruct top-quark mass:

  $m(\gamma\gamma j)$ and $m(jjj)$
- Place mass window cuts.

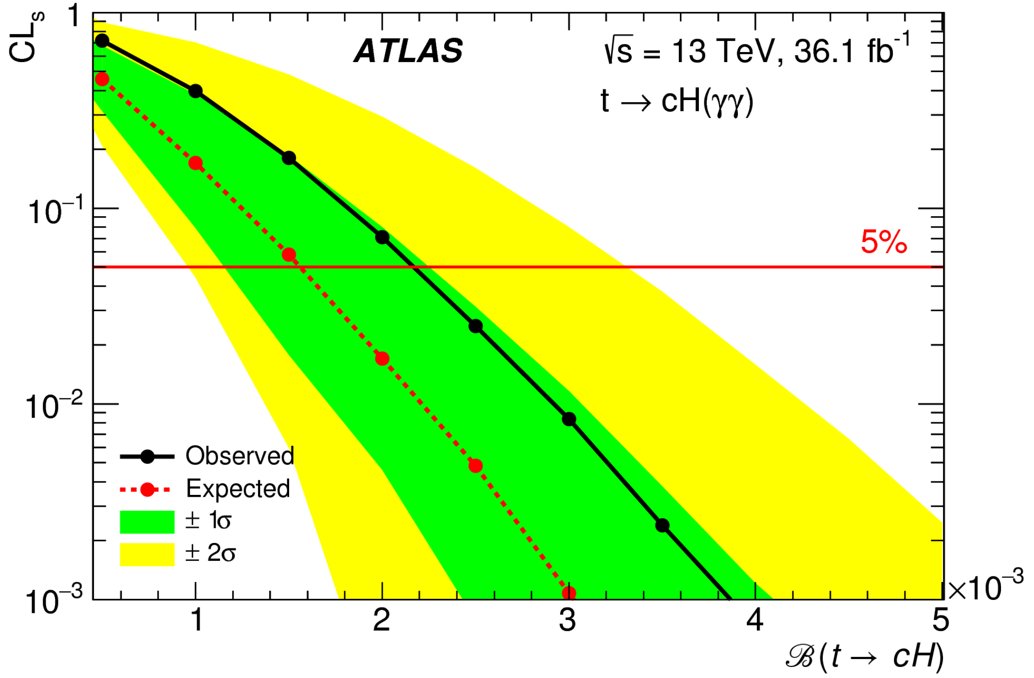
Limits on $t \to qH$ with $H \to \gamma\gamma$

BERGISCHE UNIVERSITÄT WUPPERTAL



- Look at $m(\gamma\gamma)$ spectrum.
- Normalise background to data in side bands.
- Obtained limits:

$\mathcal{B}(t \to cH) \leq 2.2\ 10^{-3}$ and $\mathcal{B}(t \to uH) \leq 2.4\ 10^{-3}$



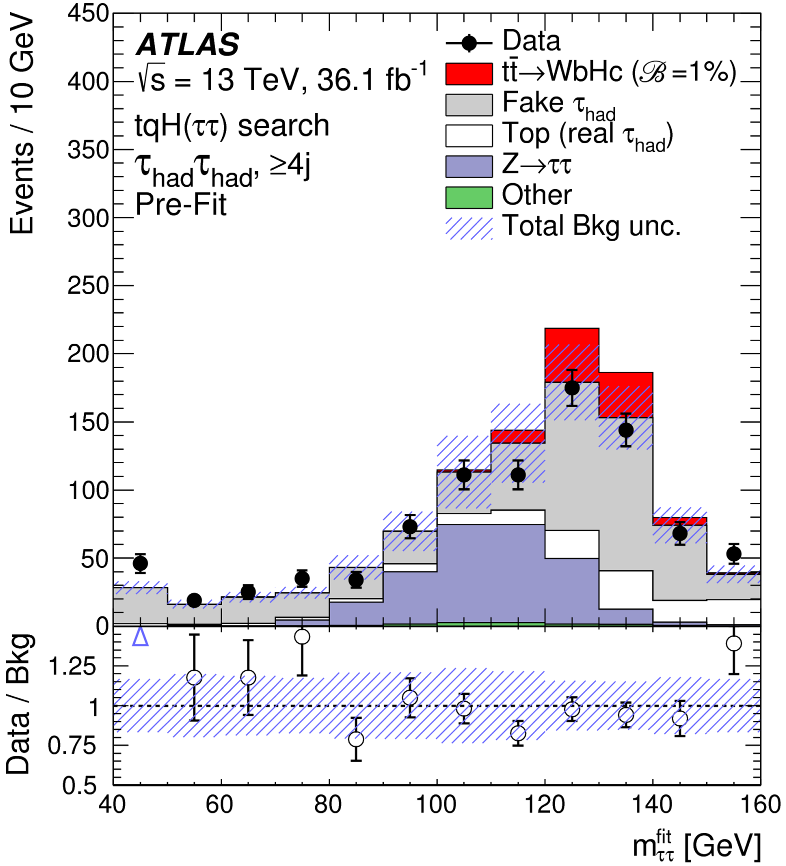
Search for $t \rightarrow qH$ with $H \rightarrow \tau^+\tau^-$

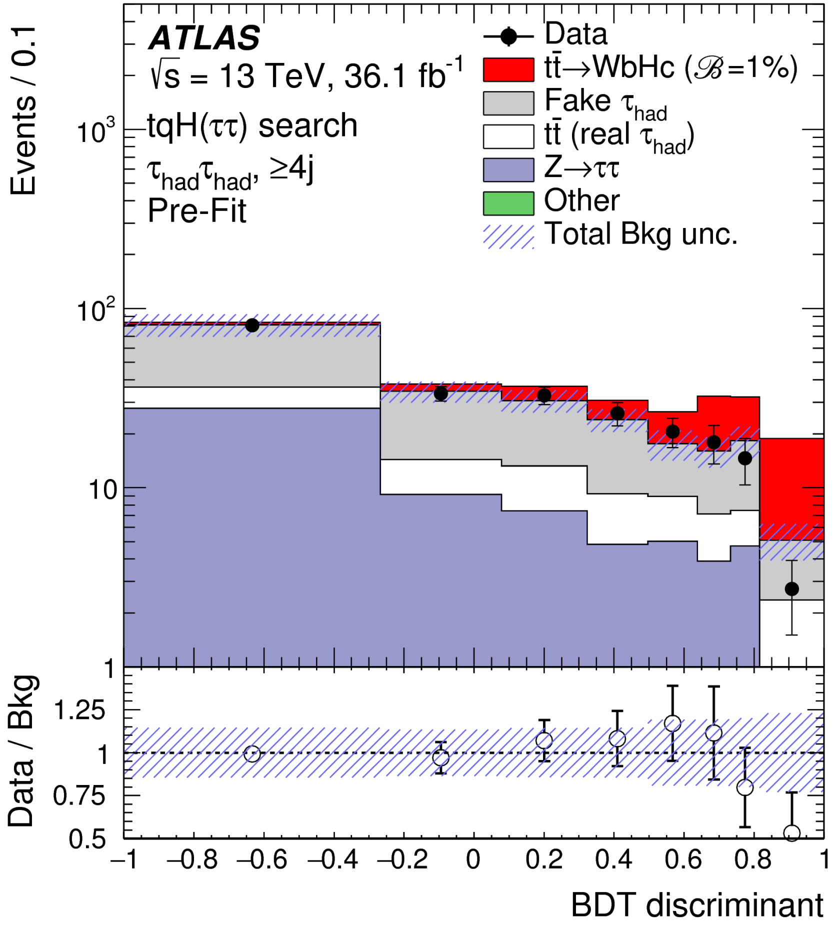
- τ leptons are reconstructed in their leptonic and hadronic decay modes
- Boosted decision trees (BDTs) are used to separate signal and background.

arXiv: 1812.11568

JHEP 05 (2019) 123

One of the input variables to the BDT:
The reconstructed Higgs boson mass.

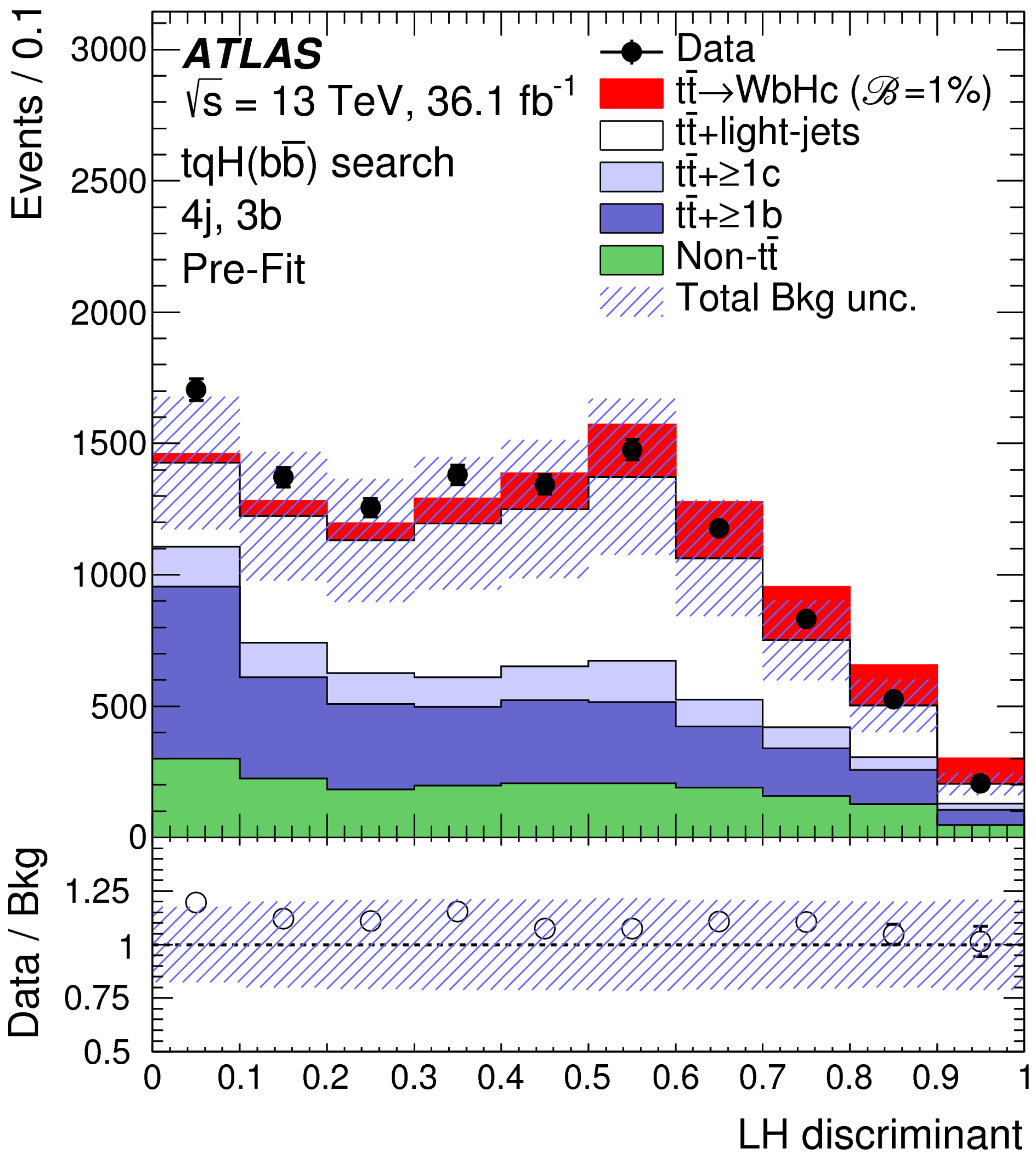




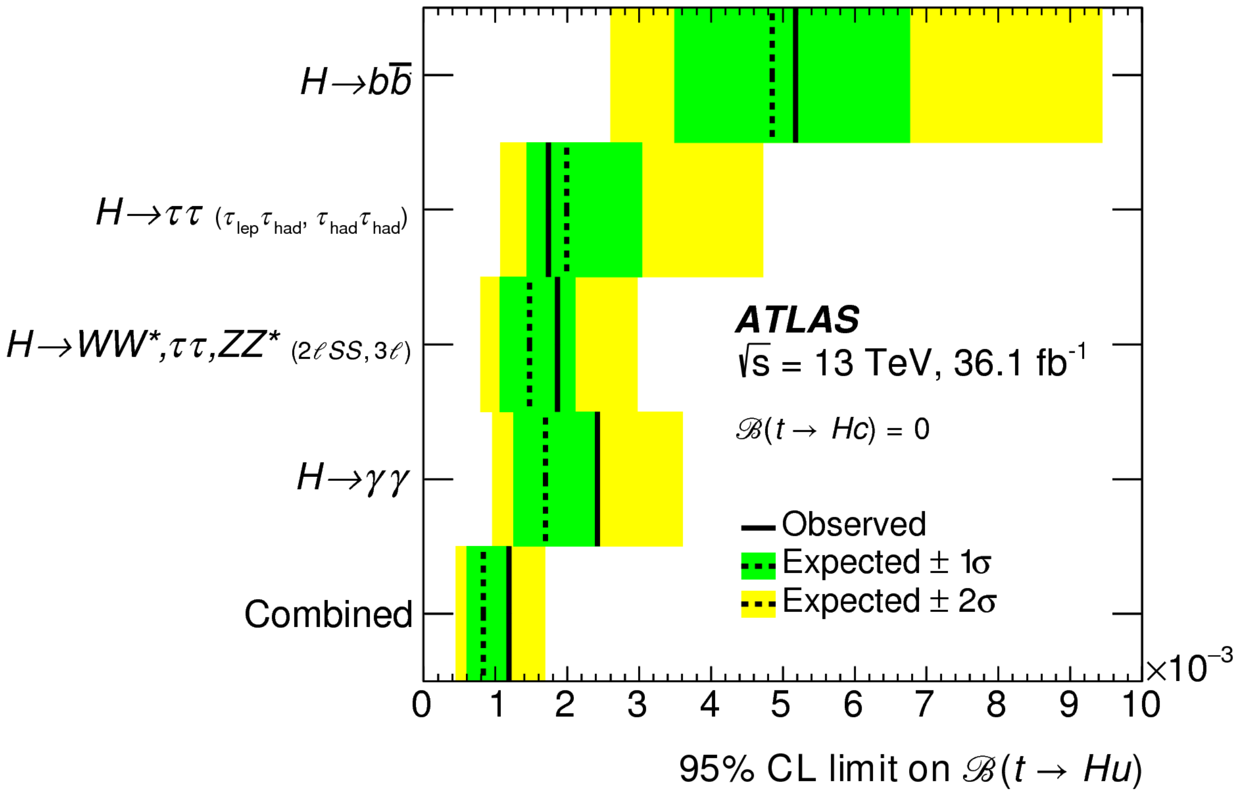
Search for $t \to qH$ with $H \to b\bar{b}$

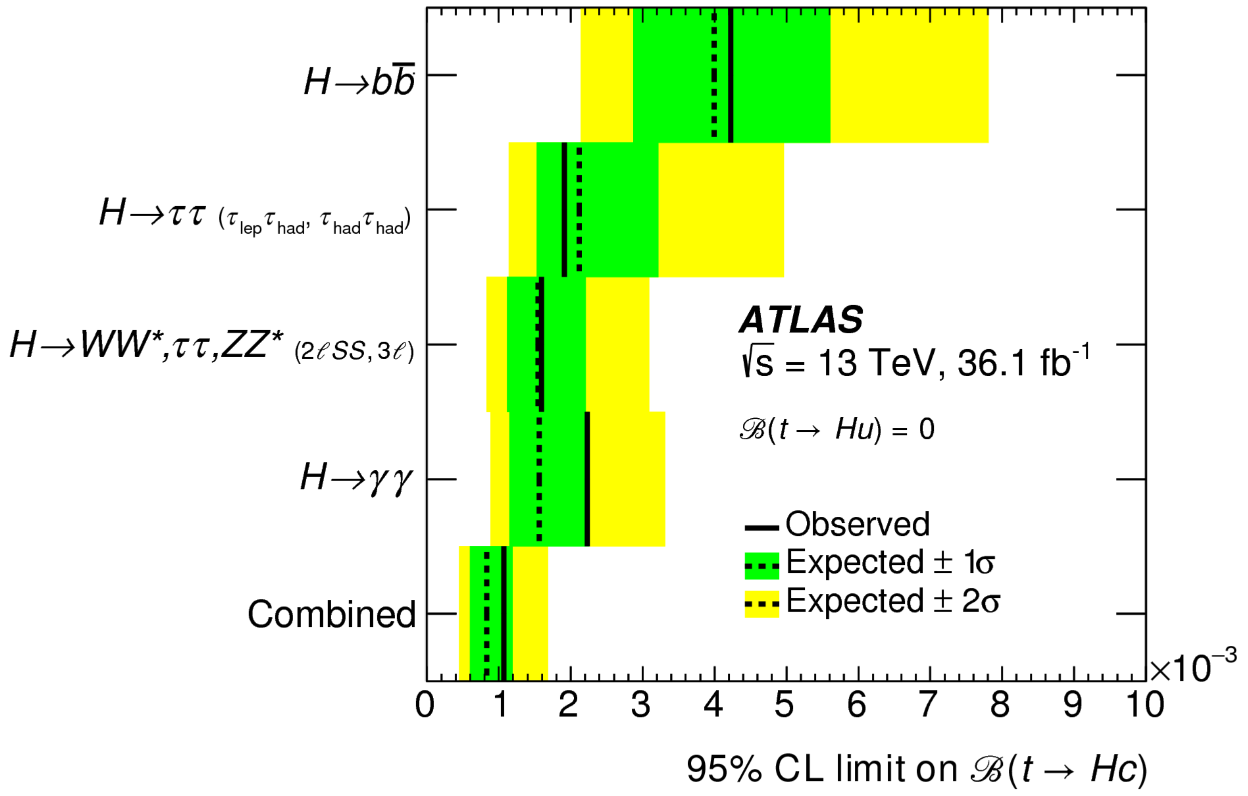
Combine several kinematic variables with a likelihood ratio.

$$L(\vec{x}) = \frac{p_{\text{sig}}(\vec{x})}{p_{\text{sig}}(\vec{x})+p_{\text{bkg}}(\vec{x})}$$



Upper limits on $\mathcal{B}(t \to qH)$



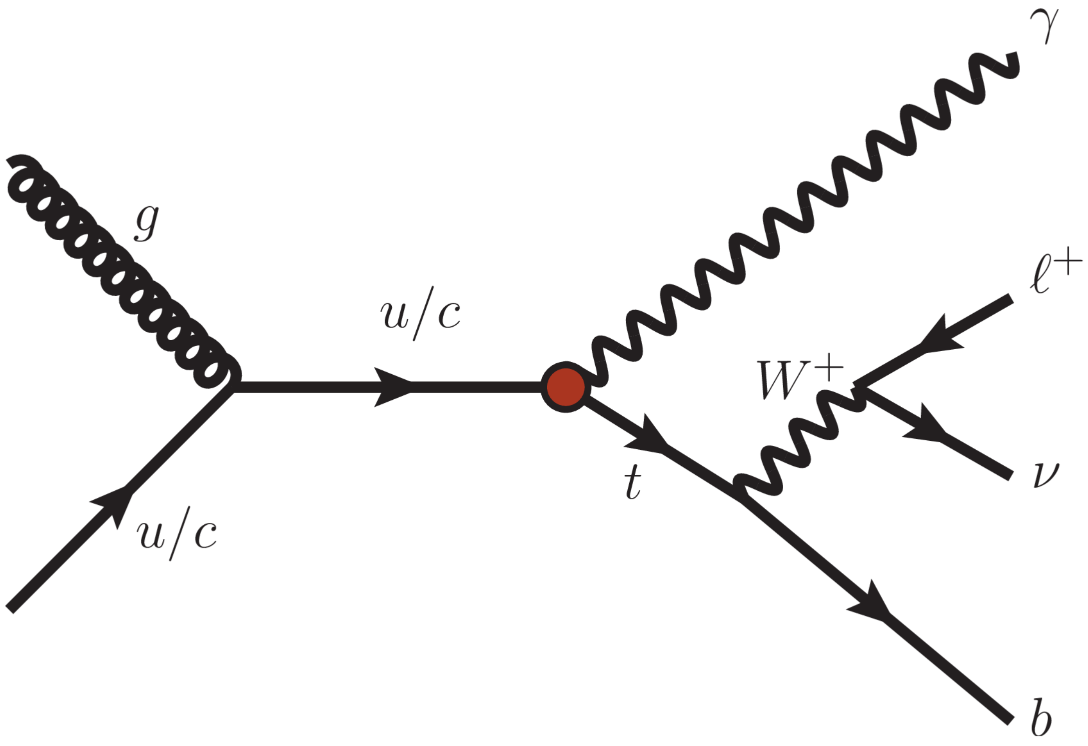


$\mathcal{B}(t \to uH) < 1.2 \cdot 10^{-3}$

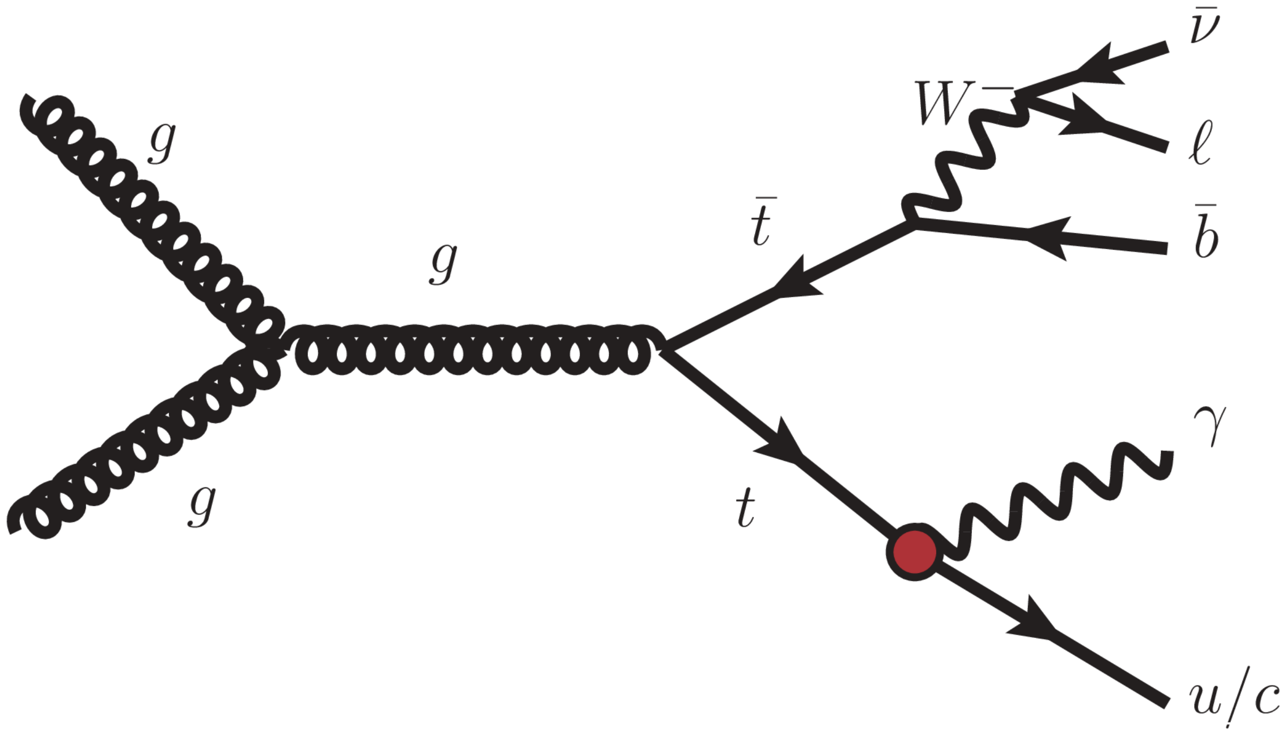
$\mathcal{B}(t \to cH) < 1.1 \cdot 10^{-3}$

Search for $t\gamma$ FCNC

$t\gamma$ production



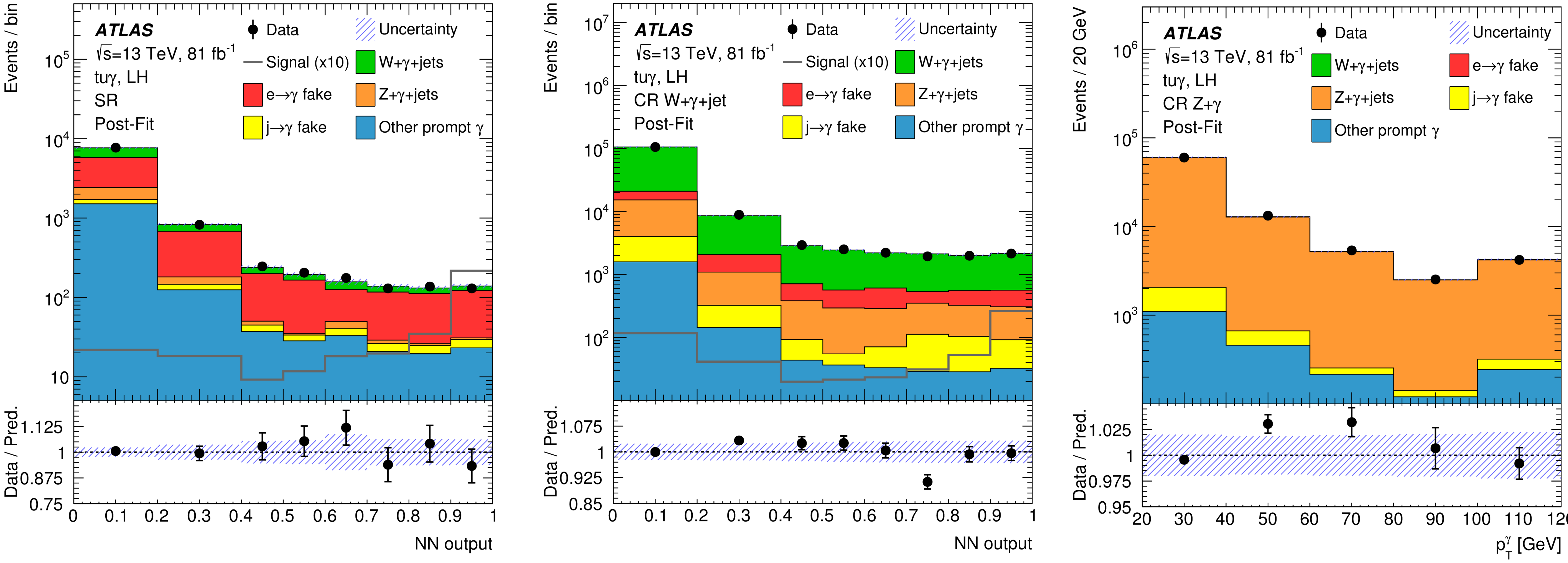
$t \rightarrow q\gamma$ decay



Postfit distributions

- Train neural networks wot separate signal and background.
- Use control regions for two backgrounds.
- Consider different chiral couplings: left-handed and right-handed.

arXiv: 1908.08461



$t\gamma$ FCNC results

Observable	Vertex	Coupling	Obs.	Exp.
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*} \rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)} \rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*} \rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)} \rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

Upper limits on ...

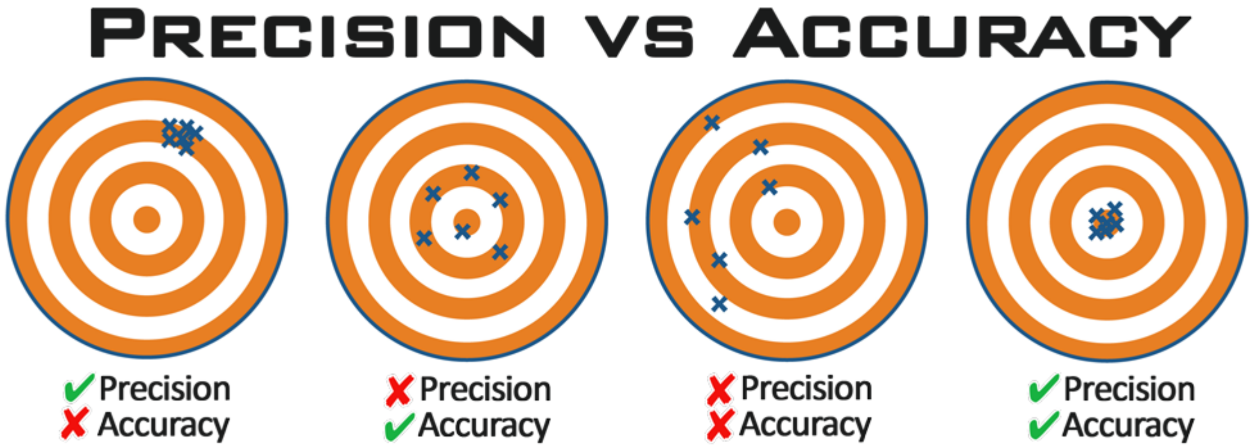
Effective operator coefficients

Cross sections

Branching ratios

Chapter 5

Precision measurements of top-quark properties

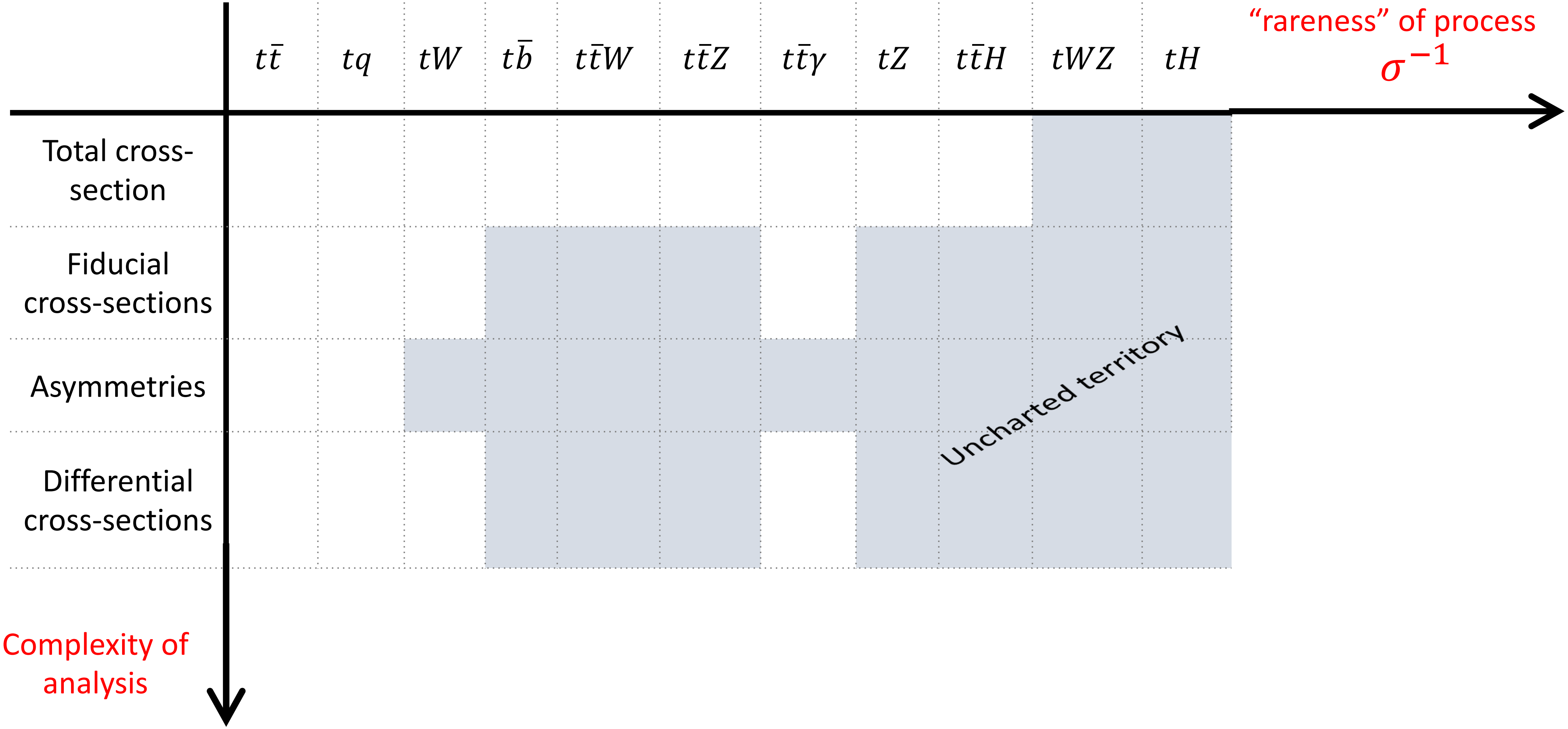


Discussed analyses:

1) Measurement of $t\bar{t}$ cross-section in the electron muon channel
2) Measurement of $t\bar{t}$ cross-section in the lepton+jets channel
3) Charge asymmetry in $t\bar{t}$ events
4) Spin correlations in $t\bar{t}$ events

Pushing the frontiers of complexity

BERGISCHE
UNIVERSITÄT
WUPPERTAL



Precision measurement of $\sigma(t\bar{t})$

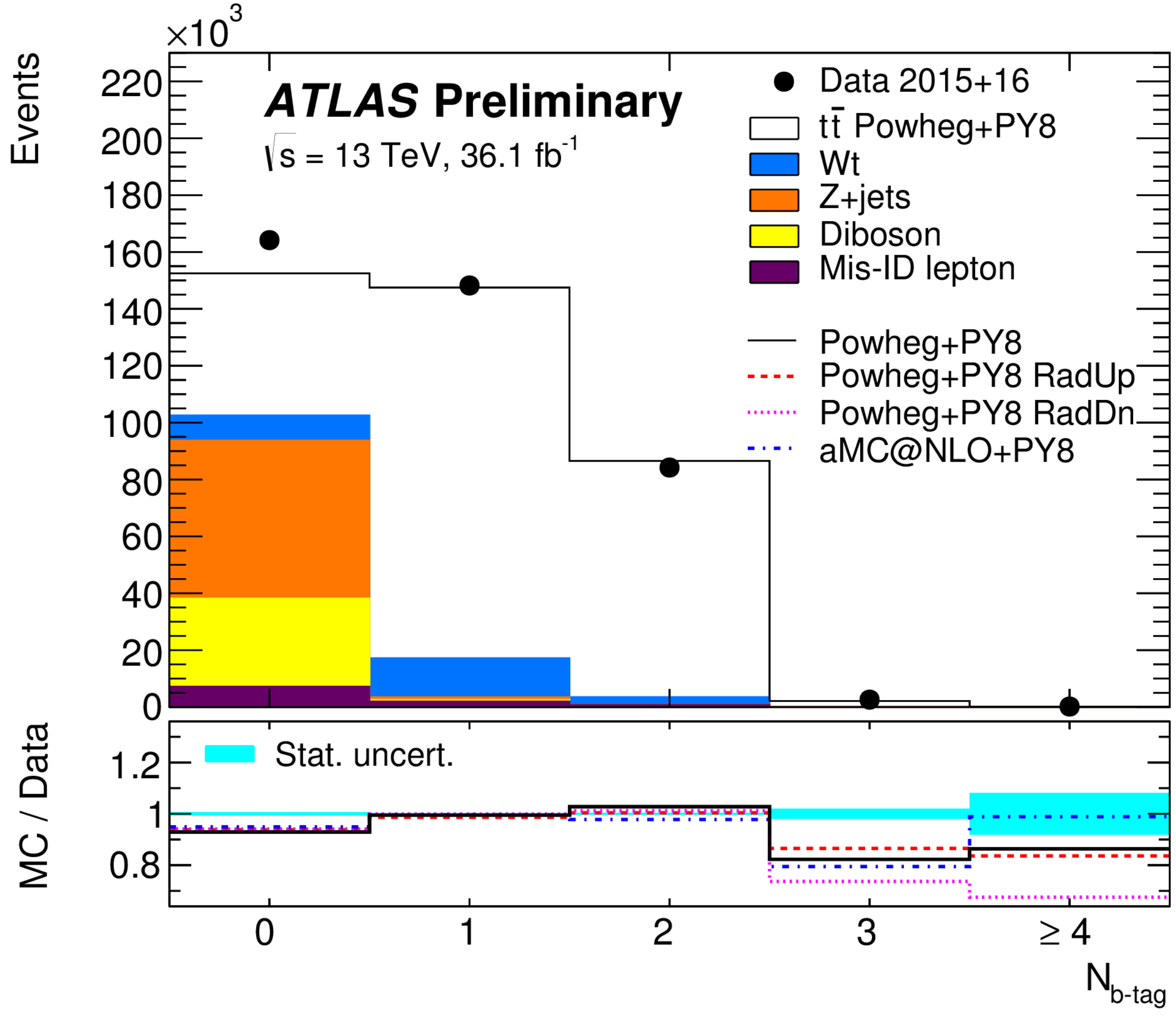
- Use electron-muon final state.
- Low background
- Counting experiment
- Determine b-tagging efficieny by using the 1-tag and 2-tag rates.

$$N_1 = \mathcal{L}_{\text{int}}\,\sigma(t\bar{t})\,\epsilon_{e\mu}\,2\,\epsilon_b\,(1 - C_b\epsilon_b) + N_1^{\text{bkg}}$$

$$N_2 = \mathcal{L}_{\text{int}}\,\sigma(t\bar{t})\,\epsilon_{e\mu}\,C_b\,\epsilon_b^2 + N_2^{\text{bkg}}$$

- The lepton isolation efficiency is recalibrated in the context of this analysis.

ATLAS-CONF-2019-041

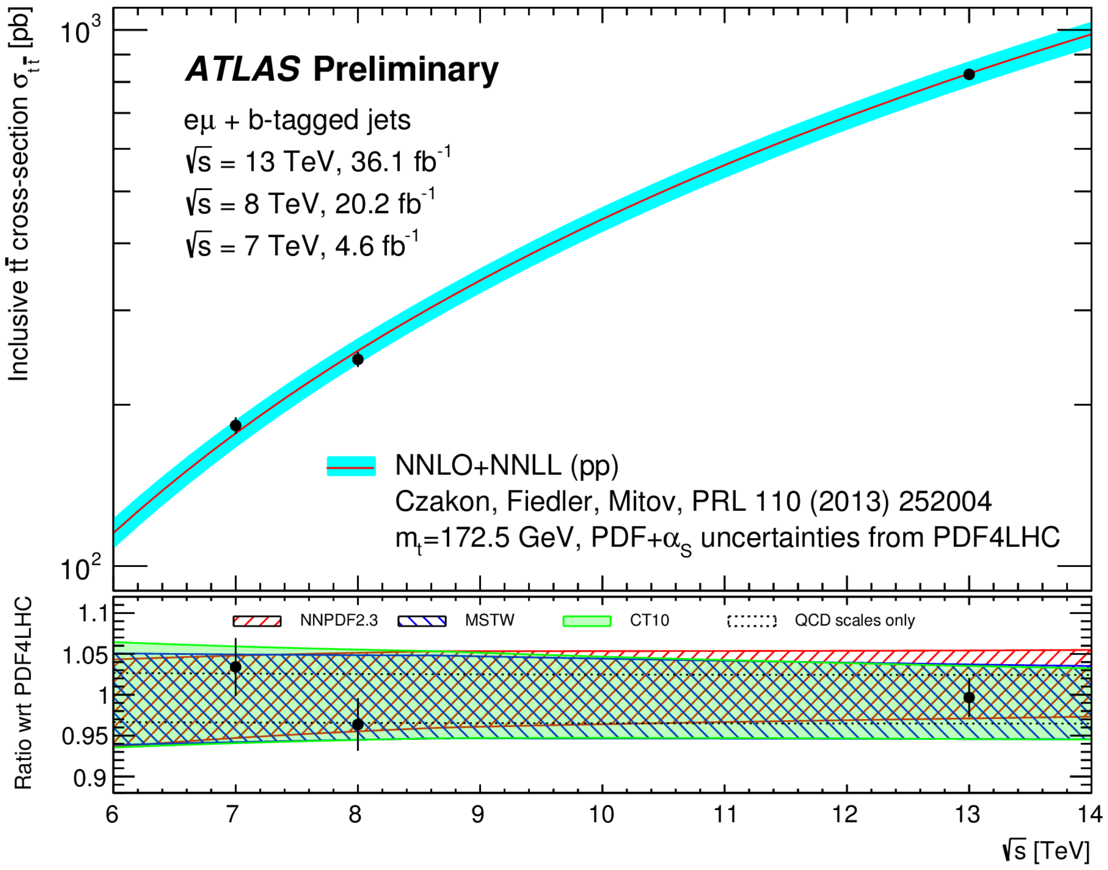


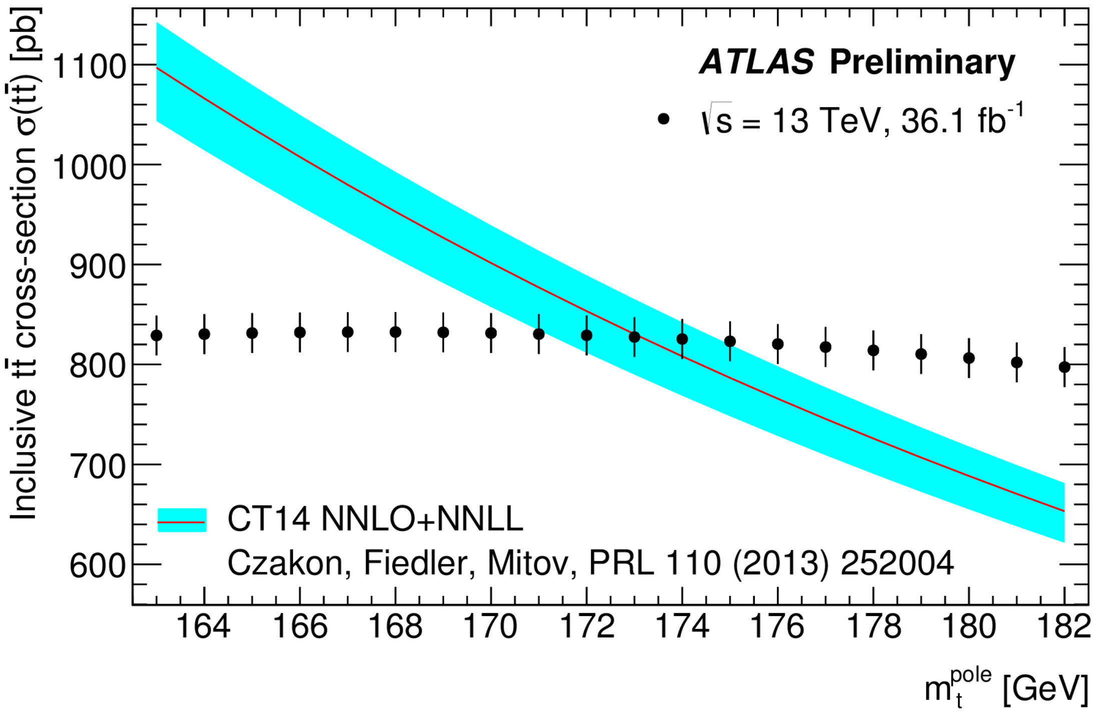
Total cross-section result

$\sigma(t\bar{t}) = 826.4\ \pm 3.6\ (\mathrm{stat}) \pm 11.5\ (\mathrm{syst}) \pm 1.9\ (\mathrm{beam})$

2.4% precision

Precision of theory prediction @ NNLO: 5.5%



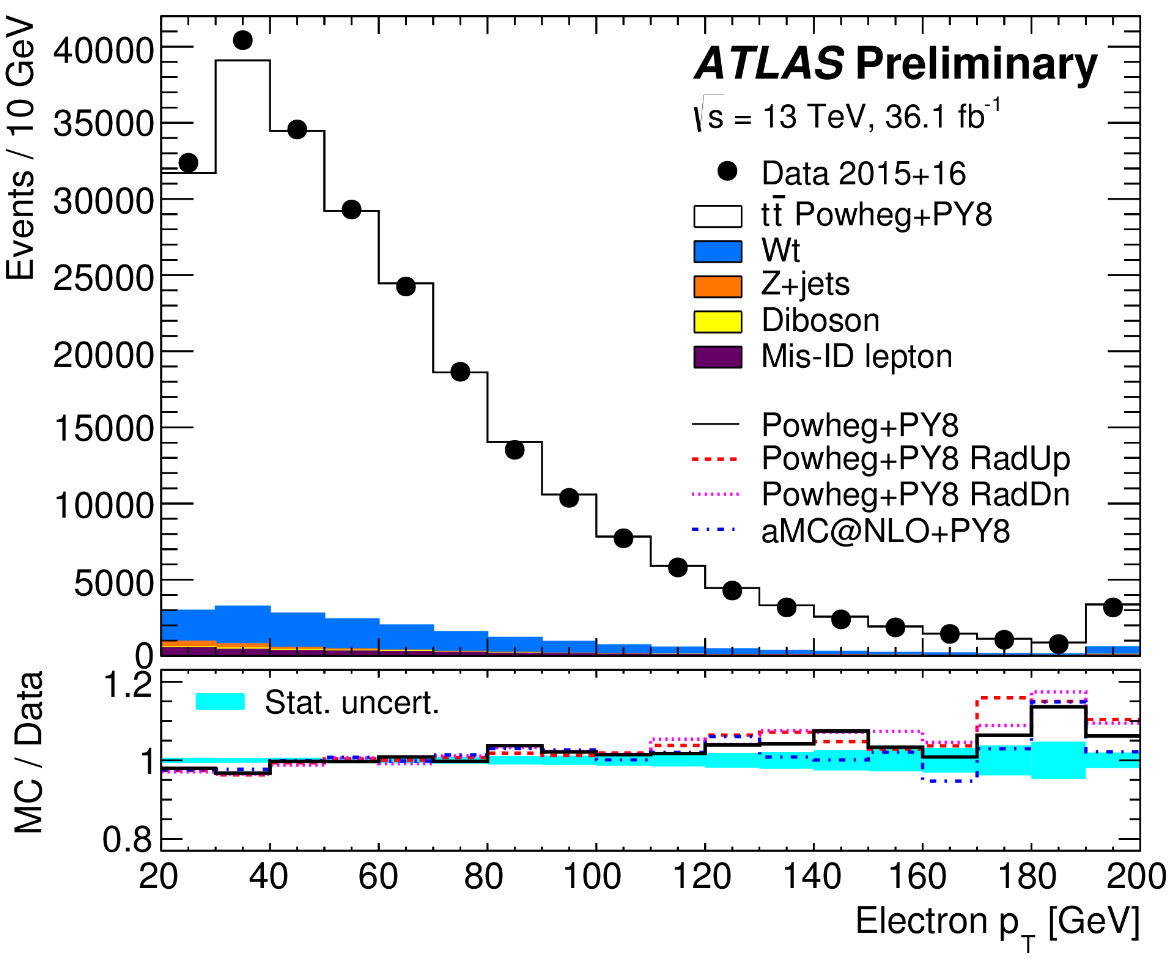


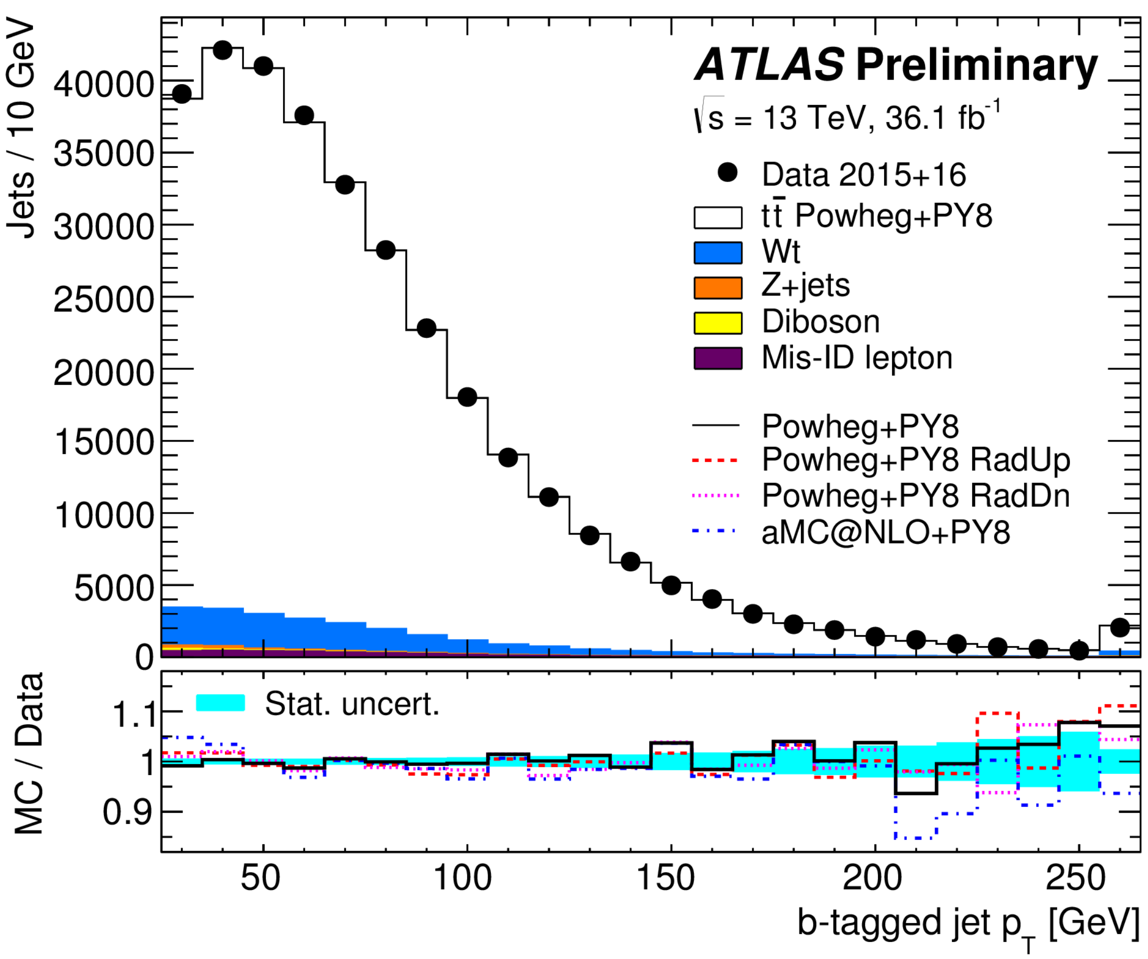
Extract the pole mass from the dependence of $\sigma(t\bar{t})$ on m_t:

$m_t^{\mathrm{pole}} = 173.1^{+2.0}_{-2.1}$ GeV

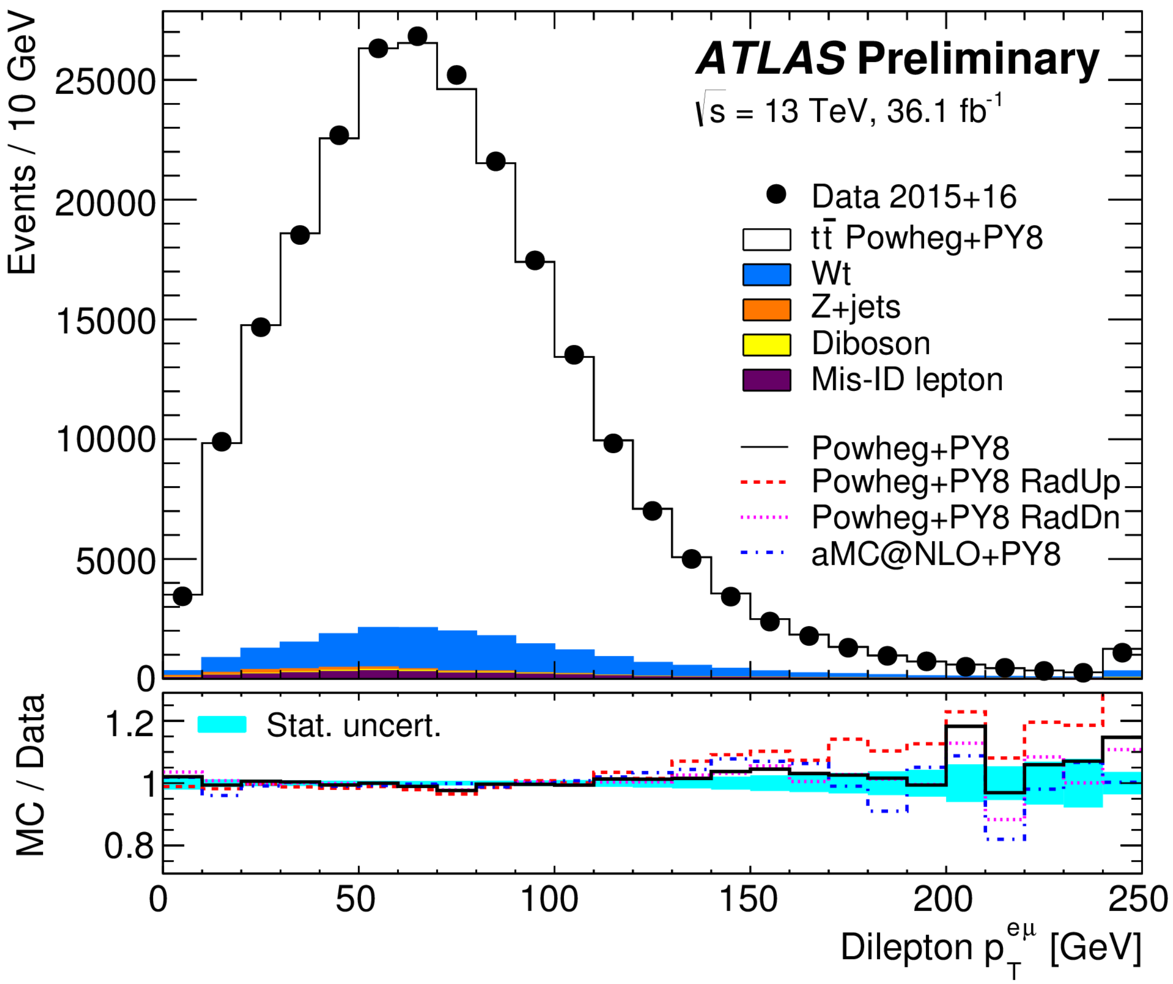
p_T spectra

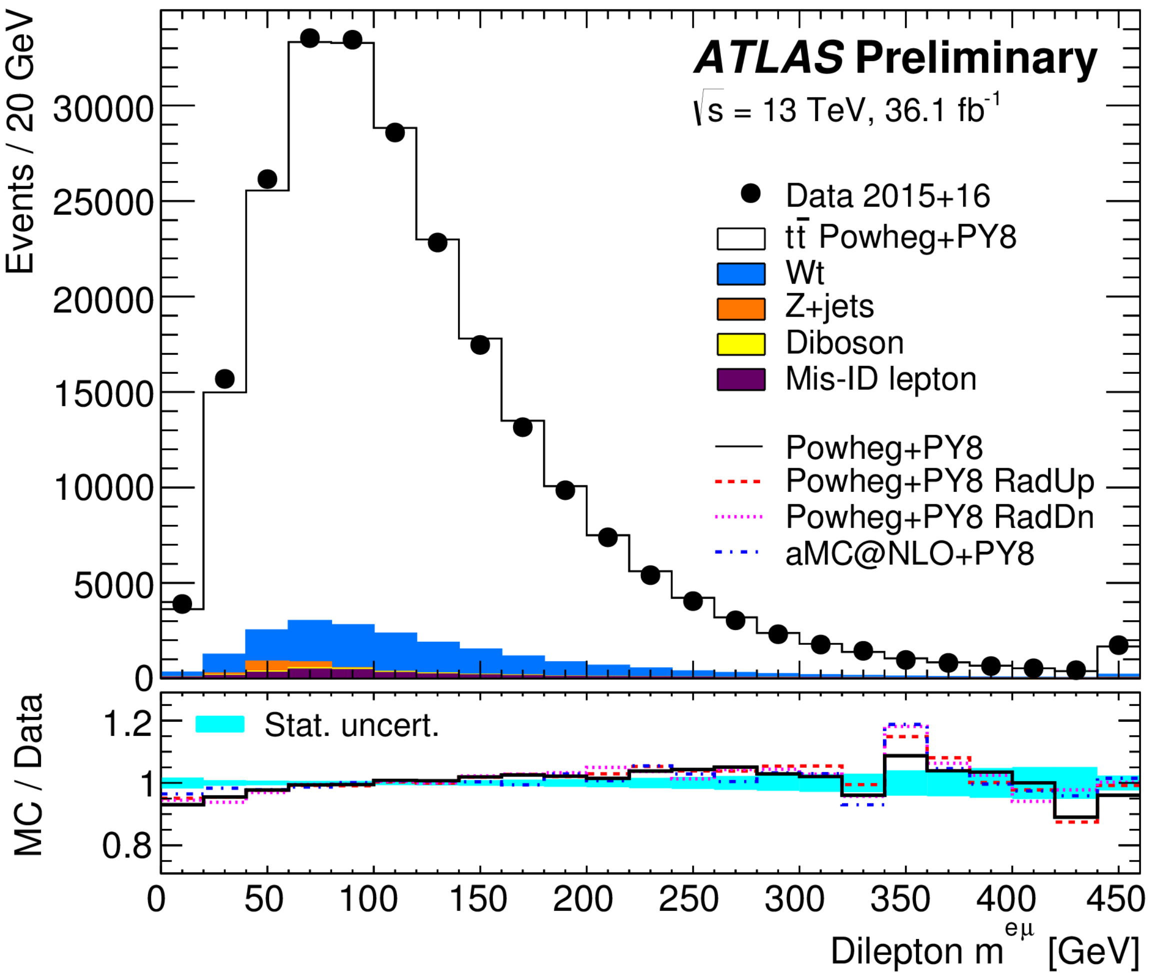
BERGISCHE UNIVERSITÄT WUPPERTAL





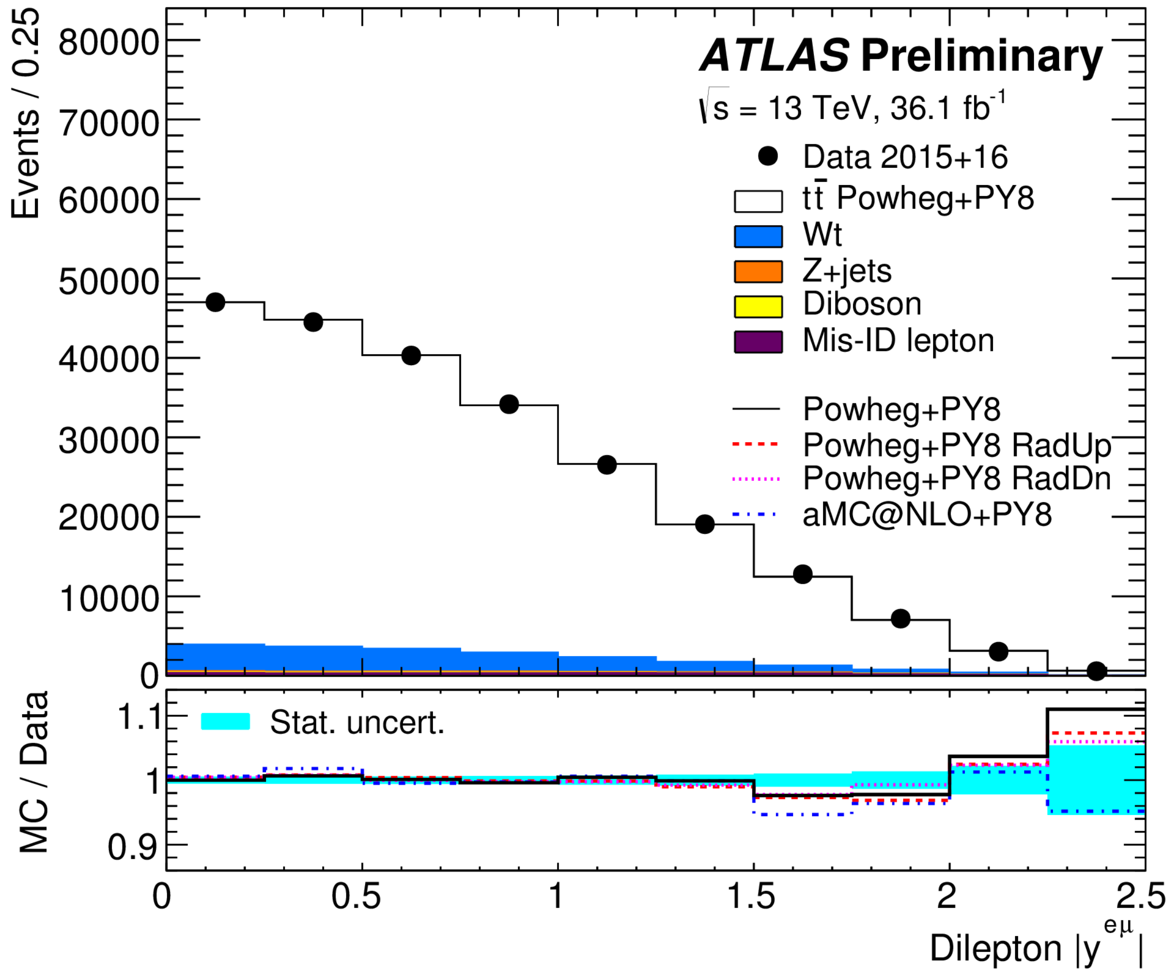
Dilepton quantities

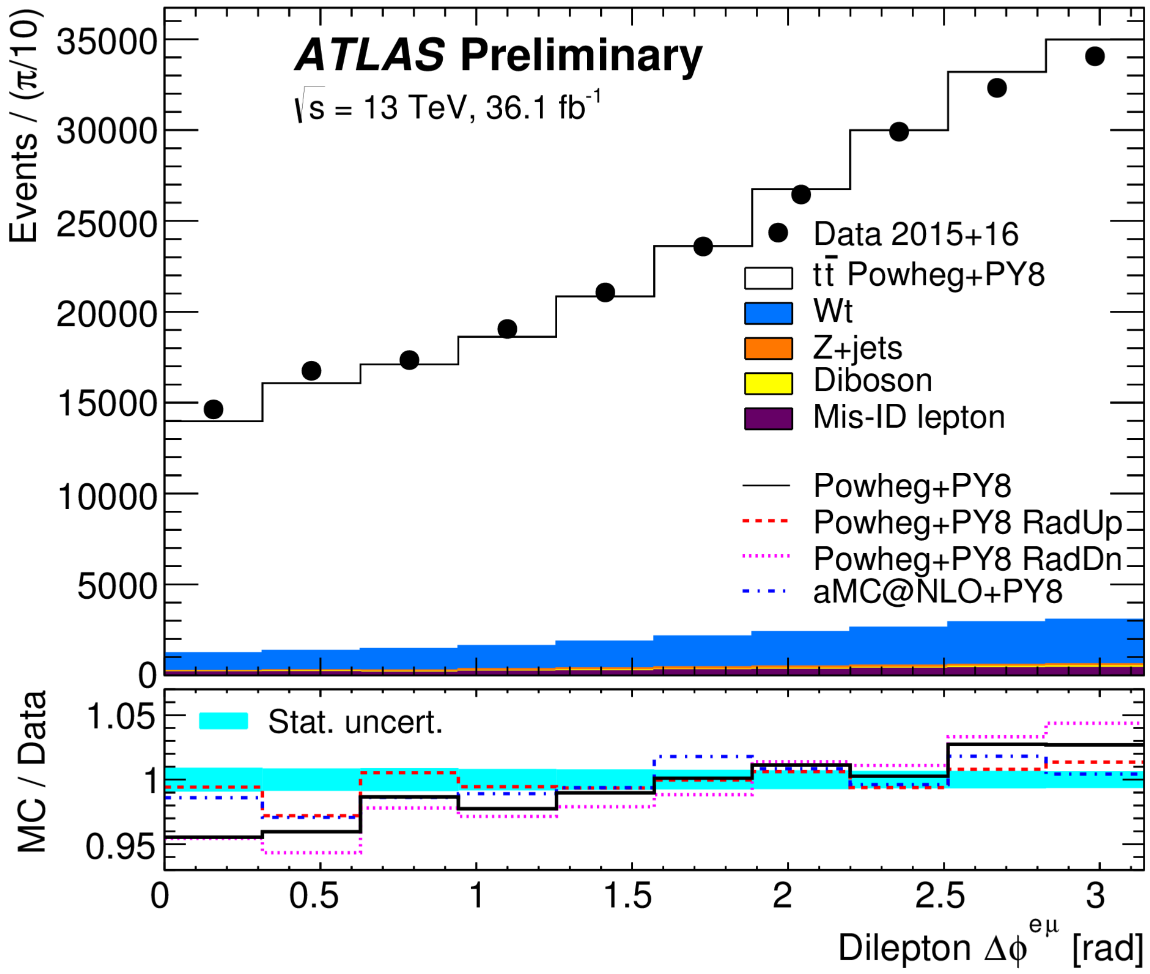




Angular distributions

BERGISCHE UNIVERSITÄT WUPPERTAL



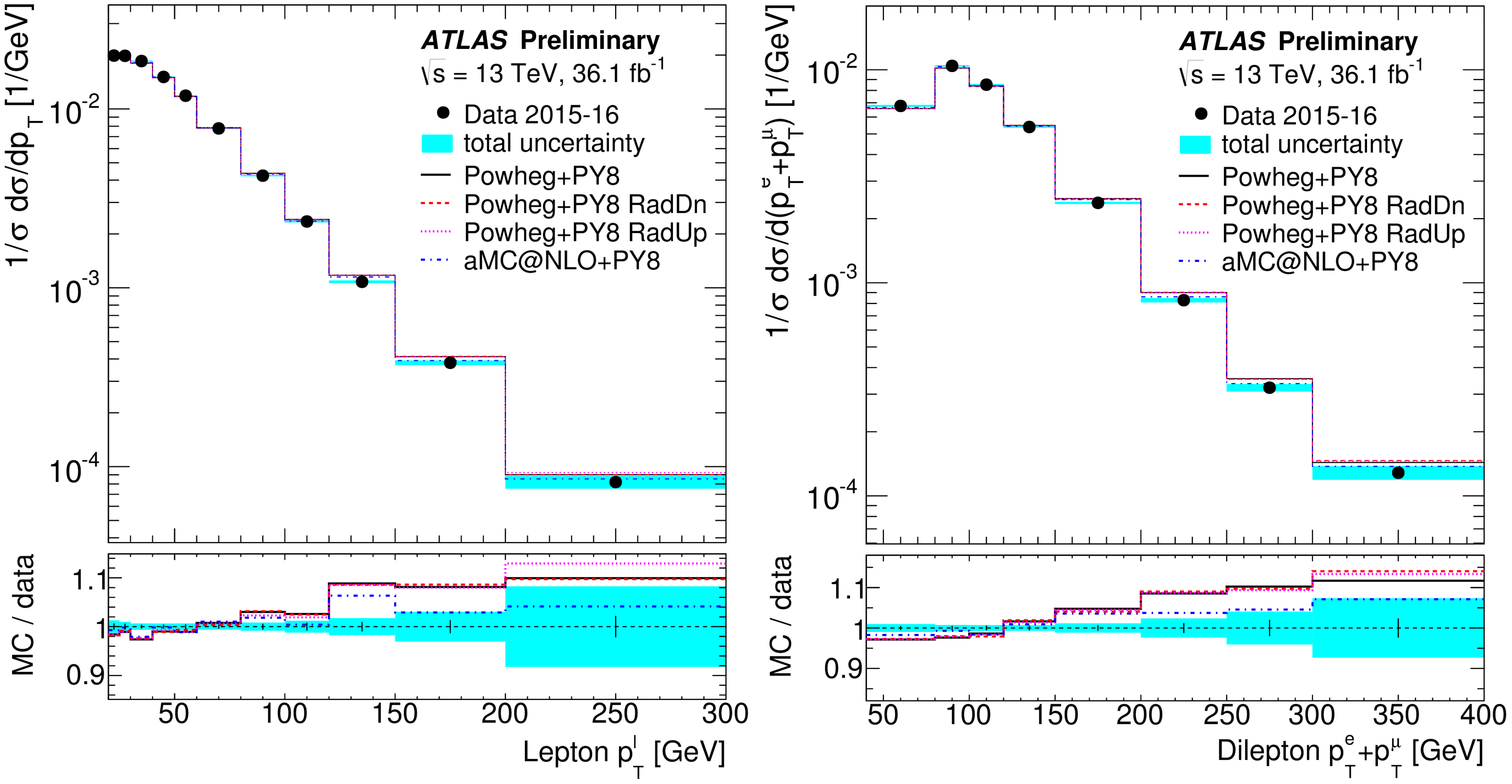


Discrepancy between MC prediction and data (more on this later).

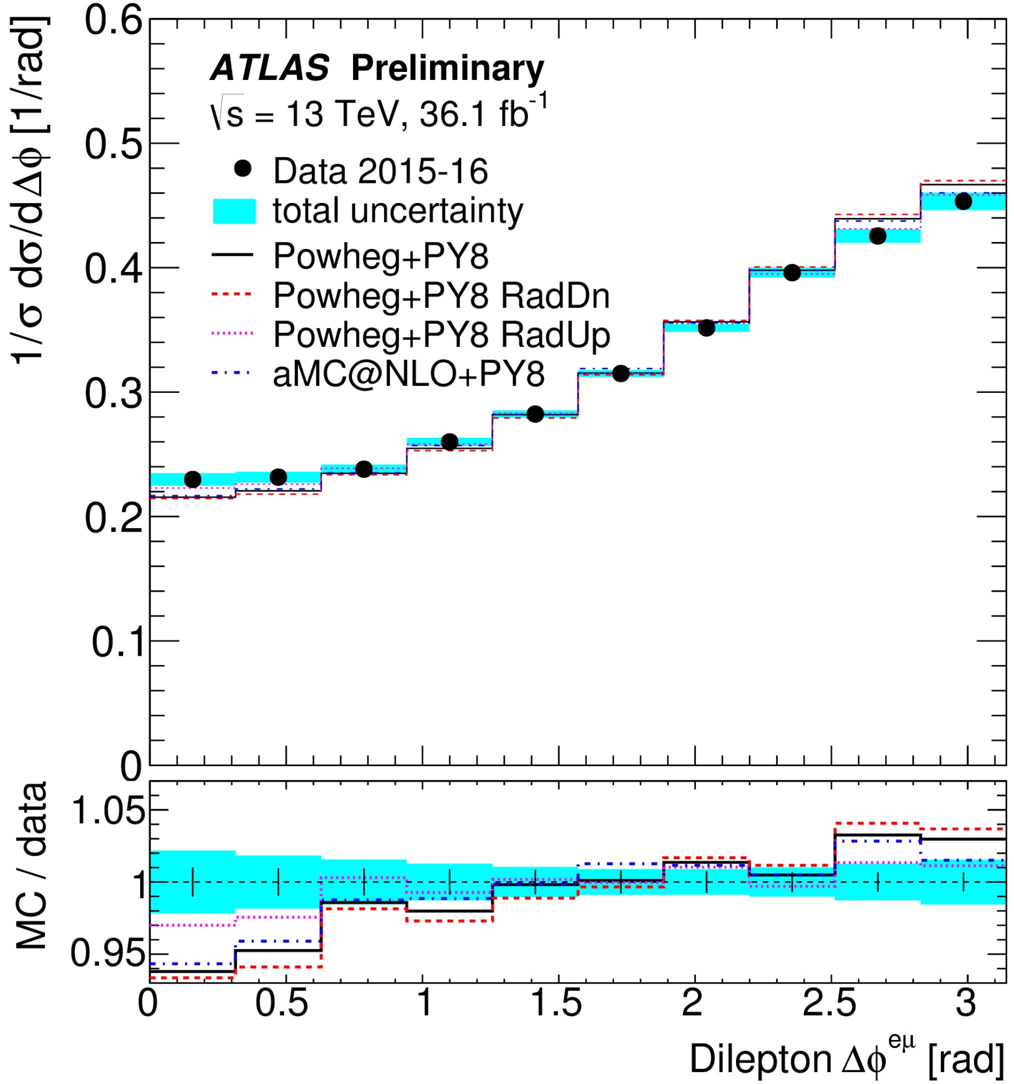
Differential cross sections

Apply the tagging equations bin-by-bin in a distribution.

Data are softer than predictions by MC generators.

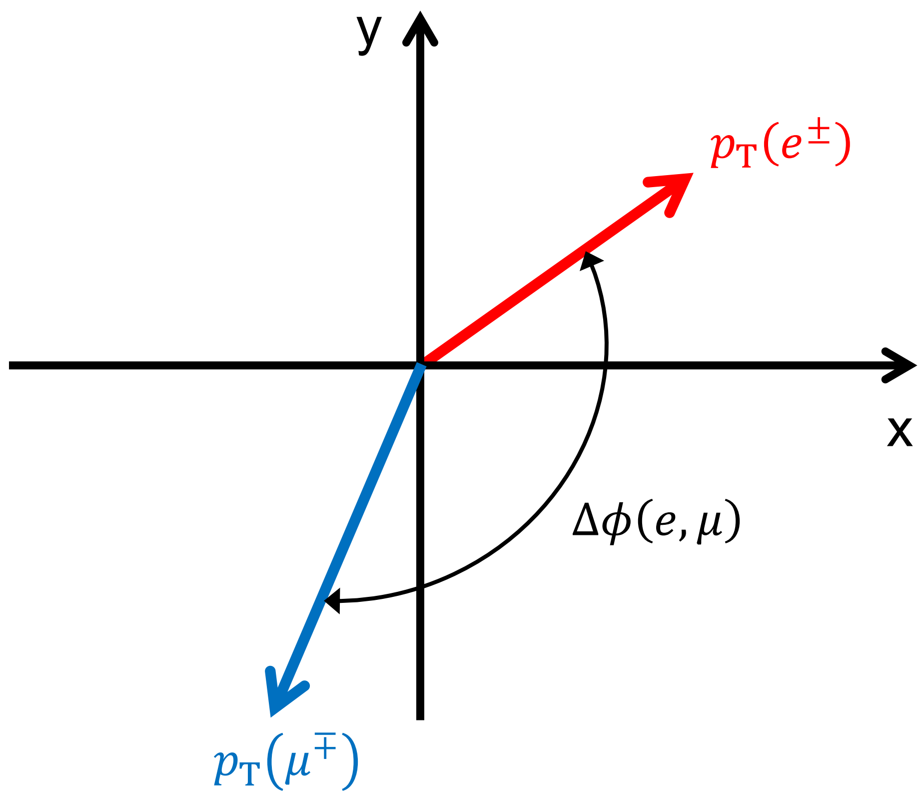


$\Delta\phi(e,\mu)$

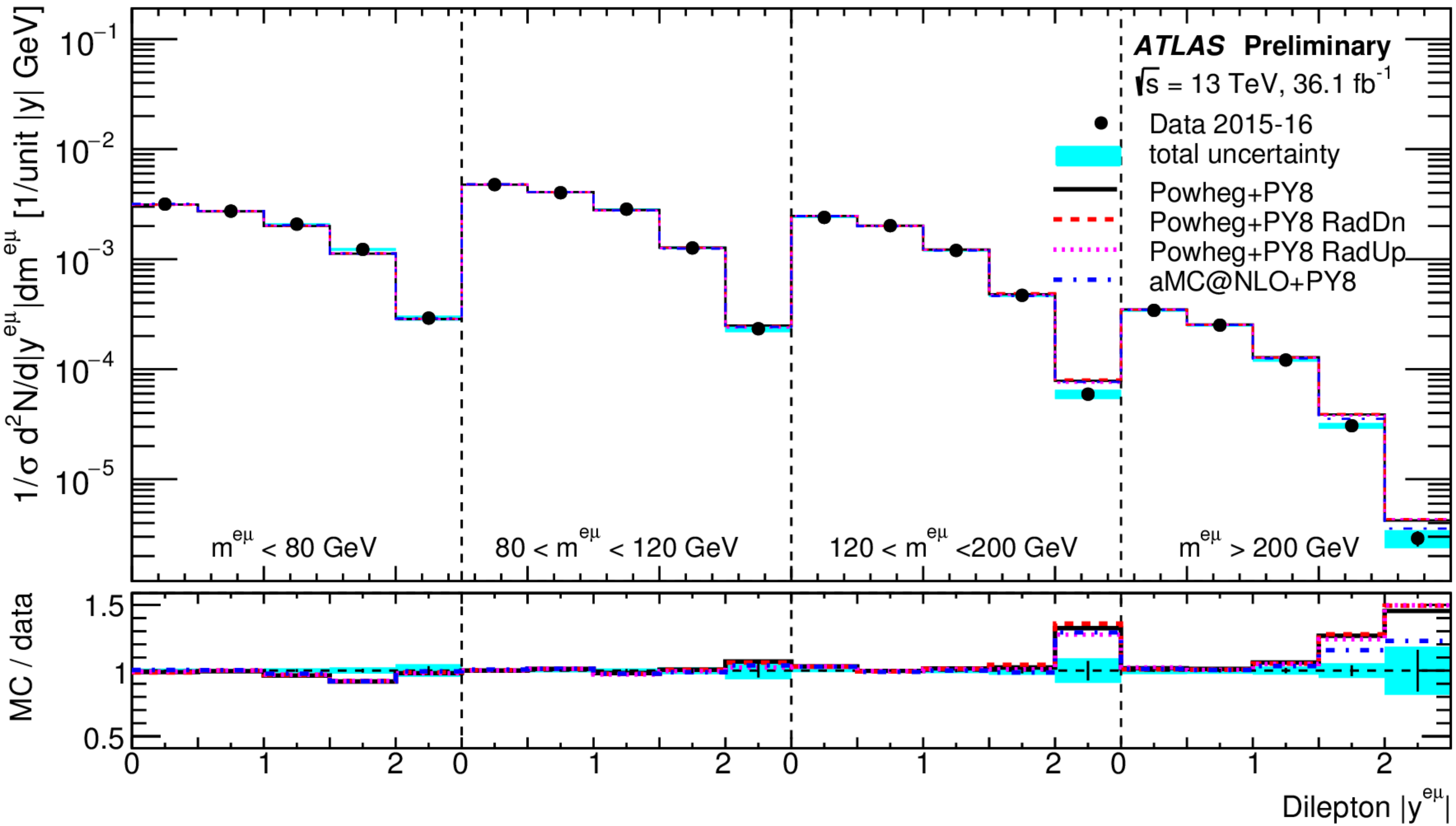


Difference in the azimuthal angle ϕ between electron and muon

Transverse plane:



Double differential cross-sections



Some discrepancies for higher $m(e\mu)$ and $|y^{e\mu}|$.

Goodness of fit

	Generator	p_T^ℓ	$\lvert\eta^\ell\rvert$	$p_T^{e\mu}$	$m^{e\mu}$	$\lvert y^{e\mu}\rvert$	$\Delta\phi^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
	N_{dof}	10	8	8	11	8	9	7	9
χ^2 values	POWHEG + PY8	43.7	19.5	8.6	44.3	11.4	14.4	32.5	18.4
	POWHEG + PY6 CT10	36.1	7.9	9.3	33.0	16.2	16.2	21.9	30.5
	POWHEG + HW7	34.8	15.9	11.5	62.7	9.4	17.3	23.0	14.7
	POWHEG + PY8 p_T rew.	20.2	14.7	2.3	38.3	8.4	12.7	9.4	14.0
	POWHEG + PY8 RadDn	40.0	24.2	6.1	44.3	9.2	16.3	29.0	20.1
	POWHEG + PY8 RadUp	33.0	16.3	21.9	35.3	12.3	6.4	26.7	16.5
	POWHEG + PY8 $\mu_{F,R} \times 2$	46.5	21.6	6.2	42.6	8.5	16.5	28.9	17.1
	POWHEG + PY8 $\mu_{F,R} \times 0.5$	39.8	17.3	11.4	38.0	10.7	10.9	27.6	14.2
	POWHEG + PY8 PDF4LHC15	43.4	14.6	7.4	39.0	6.2	13.5	28.0	15.9
	POWHEG + PY8 CT14	44.1	9.3	7.6	37.0	8.2	13.5	28.5	18.2
	POWHEG + PY8 MMHT	41.2	17.7	6.9	39.0	6.3	13.2	26.3	14.3
	aMC@NLO + PY8	26.2	25.7	11.4	19.7	16.7	13.2	12.5	14.0
	aMC@NLO + PY8 CT10	24.9	11.7	10.6	16.9	10.0	13.4	12.0	19.0
	aMC@NLO + PY8 HERA2	17.1	96.6	6.9	26.0	68.5	12.5	6.1	38.4
χ^2 probabilities	POWHEG + PY8	$4 \cdot 10^{-6}$	0.012	0.37	$6 \cdot 10^{-6}$	0.18	0.11	$3 \cdot 10^{-5}$	0.030
	POWHEG + PY6 CT10	$8 \cdot 10^{-5}$	0.45	0.32	$5 \cdot 10^{-4}$	0.039	0.062	$3 \cdot 10^{-3}$	$4 \cdot 10^{-4}$
	POWHEG + HW7	$1 \cdot 10^{-4}$	0.043	0.18	$3 \cdot 10^{-9}$	0.31	0.045	$2 \cdot 10^{-3}$	0.098
	POWHEG + PY8 p_T rew.	0.028	0.065	0.97	$7 \cdot 10^{-5}$	0.39	0.18	0.23	0.12
	POWHEG + PY8 RadDn	$2 \cdot 10^{-5}$	$2 \cdot 10^{-3}$	0.64	$6 \cdot 10^{-6}$	0.32	0.060	$1 \cdot 10^{-4}$	0.017
	POWHEG + PY8 RadUp	$3 \cdot 10^{-4}$	0.038	$5 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	0.14	0.70	$4 \cdot 10^{-4}$	0.057
	POWHEG + PY8 $\mu_{F,R} \times 2$	$1 \cdot 10^{-6}$	$6 \cdot 10^{-3}$	0.62	$1 \cdot 10^{-5}$	0.39	0.056	$1 \cdot 10^{-4}$	0.048
	POWHEG + PY8 $\mu_{F,R} \times 0.5$	$2 \cdot 10^{-5}$	0.027	0.18	$8 \cdot 10^{-5}$	0.22	0.28	$3 \cdot 10^{-4}$	0.12
	POWHEG + PY8 PDF4LHC15	$4 \cdot 10^{-6}$	0.067	0.49	$5 \cdot 10^{-5}$	0.62	0.14	$2 \cdot 10^{-4}$	0.068
	POWHEG + PY8 CT14	$3 \cdot 10^{-6}$	0.32	0.47	$1 \cdot 10^{-4}$	0.42	0.14	$2 \cdot 10^{-4}$	0.033
	POWHEG + PY8 MMHT	$1 \cdot 10^{-5}$	0.024	0.55	$5 \cdot 10^{-5}$	0.62	0.15	$5 \cdot 10^{-4}$	0.11
	aMC@NLO + PY8	$3 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	0.18	0.049	0.034	0.15	0.086	0.12
	aMC@NLO + PY8 CT10	$5 \cdot 10^{-3}$	0.16	0.23	0.11	0.27	0.15	0.10	0.025
	aMC@NLO + PY8 HERA2	0.073	0	0.54	$6 \cdot 10^{-3}$	0	0.19	0.53	$1 \cdot 10^{-5}$

$\sigma(t\bar{t})$ in the lepton+jets channel

BERGISCHE UNIVERSITÄT WUPPERTAL

New for TOP2019

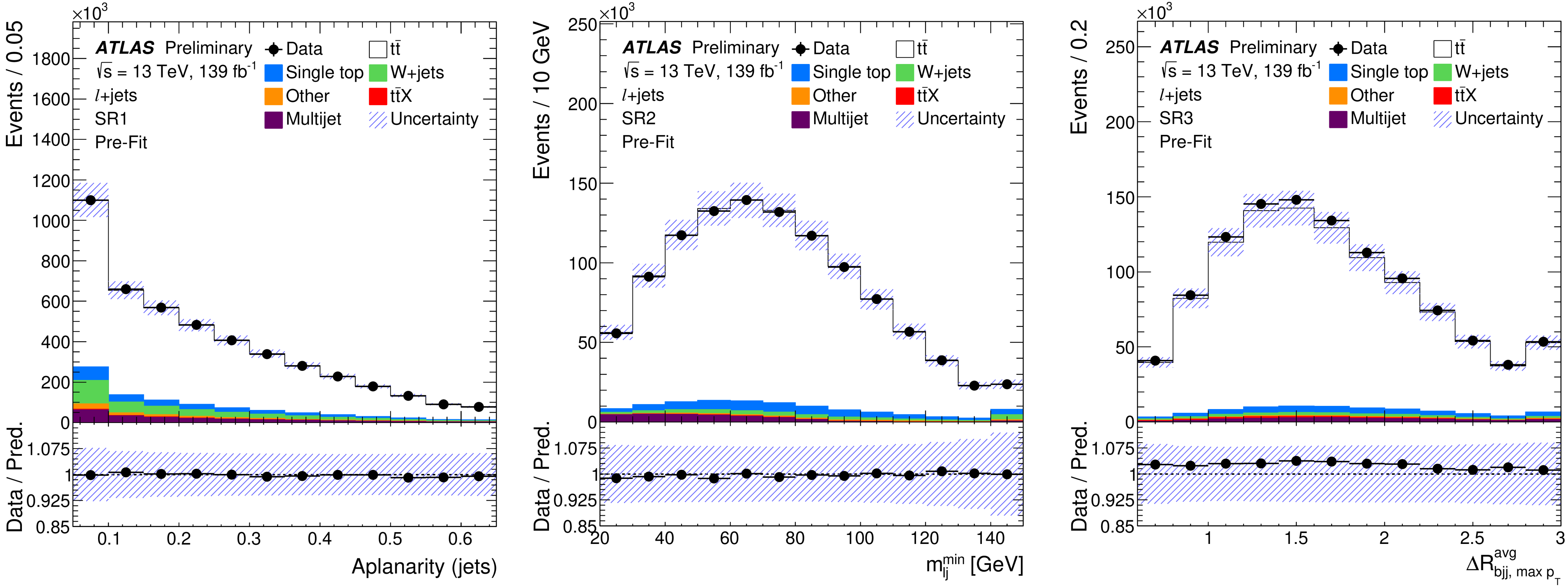
Use kinematic variables in 3 channels

ATLAS-CONF-2019-044

≥ 4 jets and = 1 b-tag

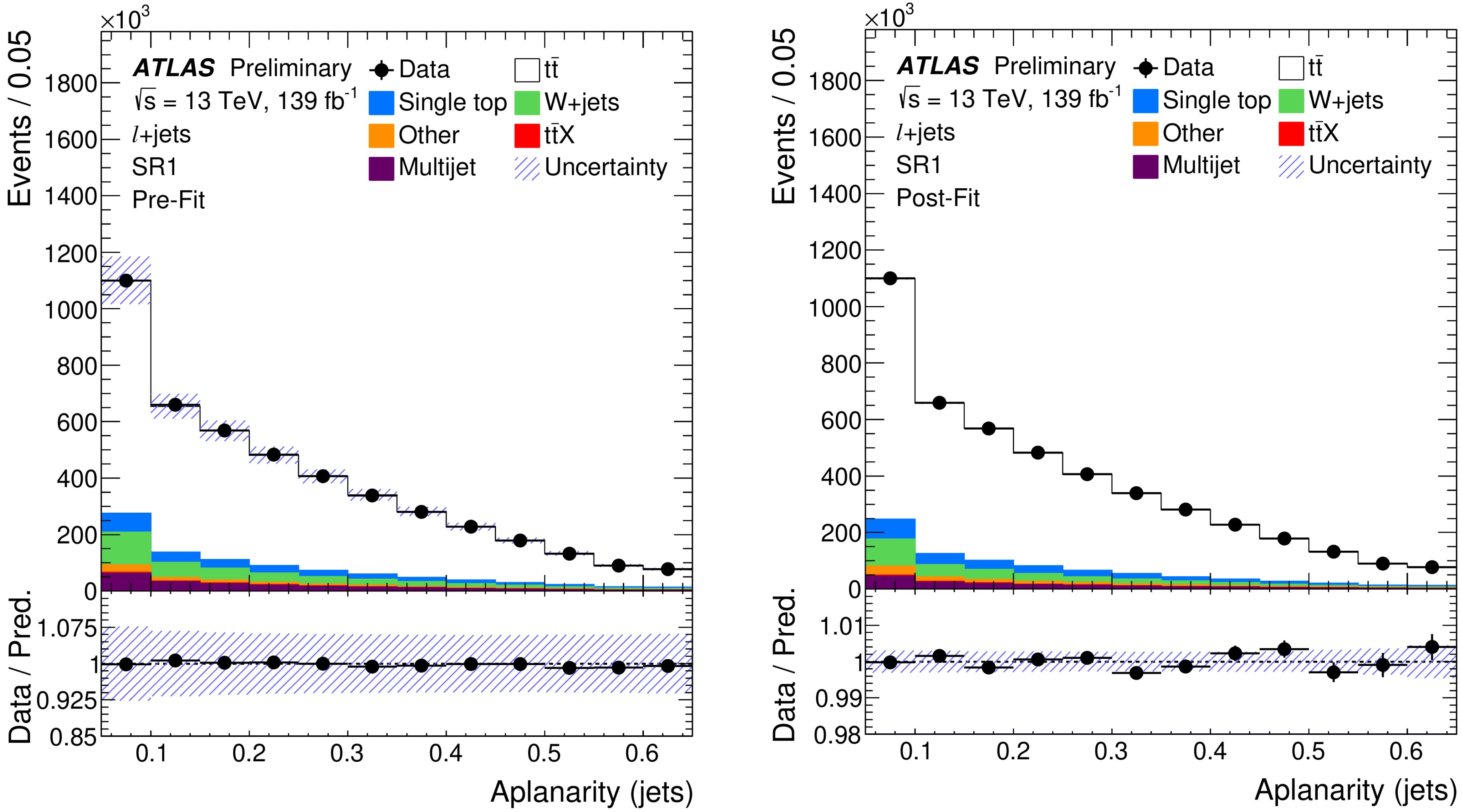
= 4 jets and = 2 b-tags

≥ 5 jets and = 2 b-tags



Profile likelihood fit

Uncertainties are reduced as a result of the fit.



$\sigma(t\bar{t})$ result

BERGISCHE UNIVERSITÄT WUPPERTAL

$\sigma(t\bar{t}) = 830.4 \pm 0.4\,(\text{stat.})\,^{+38.2}_{-37.0}\,(\text{syst.})$

4.6% precision

Theory prediction:

$\sigma(t\bar{t}) = 832\,^{+20}_{-29}\,(\text{scale}) \pm 35\,(\text{PDF} + \alpha_s)$

Dominating uncertainties are due to modelling of the $t\bar{t}$ process by event generators.

Category	$\frac{\Delta\sigma_{\text{fid}}}{\sigma_{\text{fid}}}$ [%]		$\frac{\Delta\sigma_{\text{inc}}}{\sigma_{\text{inc}}}$ [%]	
Signal modelling				
$t\bar{t}$ shower/hadronisation	+2.1	−1.9	+2.7	−2.7
$t\bar{t}$ scale variations	+2.0	−1.8	+2.5	−2.6
Background modelling				
MC background modelling	+1.8	−1.7	+1.6	−1.8
Multijet background	+0.5	−0.6	+0.6	−0.7
Detector modelling				
Jet reconstruction	+2.4	−2.3	+2.5	−2.3
Luminosity	+1.8	−1.7	+1.8	−1.6
Flavour tagging	+1.4	−1.4	+1.5	−1.4
E_T^{miss} + pile-up	+0.3	−0.2	+0.5	−0.5
Muon reconstruction	+0.4	−0.6	+0.4	−0.5
Electron reconstruction	+0.4	−0.2	+0.2	−0.4
Simulation stat. uncertainty	+0.7	−0.6	+0.9	−0.9
Total systematic uncertainty	+4.1	−3.9	+4.6	−4.5
Data stat. uncertainty	+0.05	−0.05	+0.05	−0.05
Total uncertainty	+4.1	−3.9	+4.6	−4.5

Charge asymmetry in $t\bar{t}$ production

BERGISCHE UNIVERSITÄT WUPPERTAL

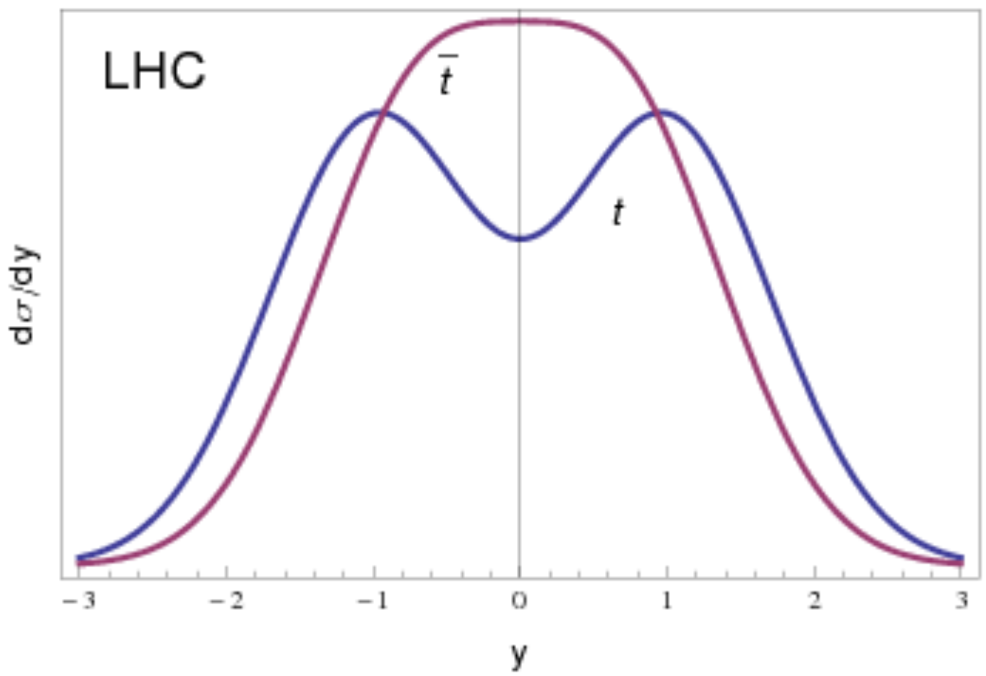
- Top-quarks are produced slightly more forward than top-antiquarks.
  → central-forward asymmetry
- Only the $q\bar{q}$ initial state contributes.
- Quantum interference effect involving NLO amplitudes, in particular ISR and FSR for $q\bar{q} \rightarrow t\bar{t}g$.
- Observable:

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

with $\Delta|y| = |y_t| - |y_{\bar{t}}|$

- SM Prediction at QCD NLO + EWK NLO precision:

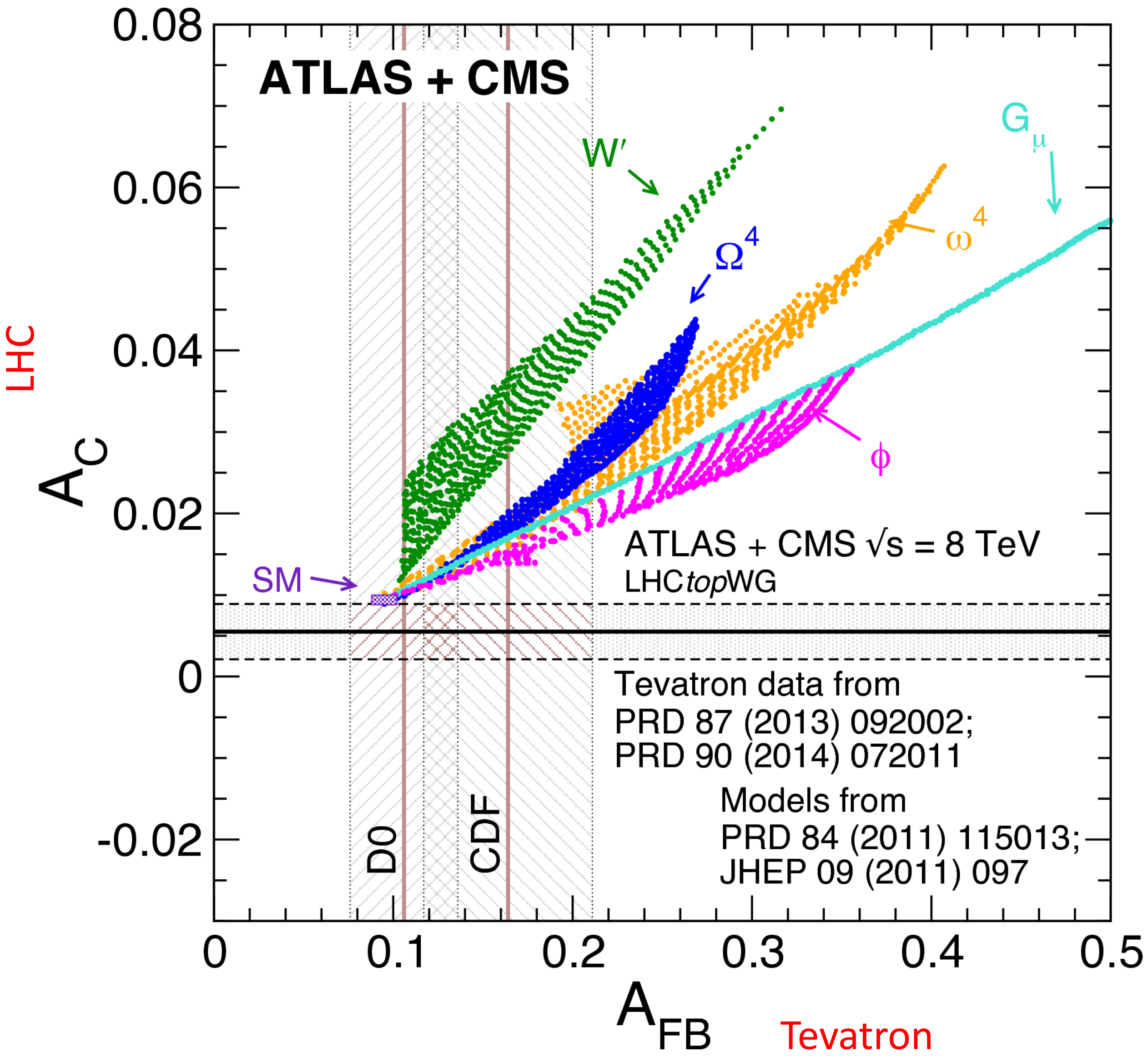
@ 7 TeV: $A_c = 0.0123 \pm 0.0005$
@ 8 TeV: $A_c = 0.0111 \pm 0.0004$
@ 13 TeV: $A_c = 0.0 \pm 0.000$



(Effect strongly exaggerated for illustration)

- SM effect is quite small, but
- Sensitive to new physics contributions
- Tevatron observed large forward-backward asymmetries ($p\bar{p}$ initial state), but tensions have eased in the meanwhile.

Impact on BSM physics

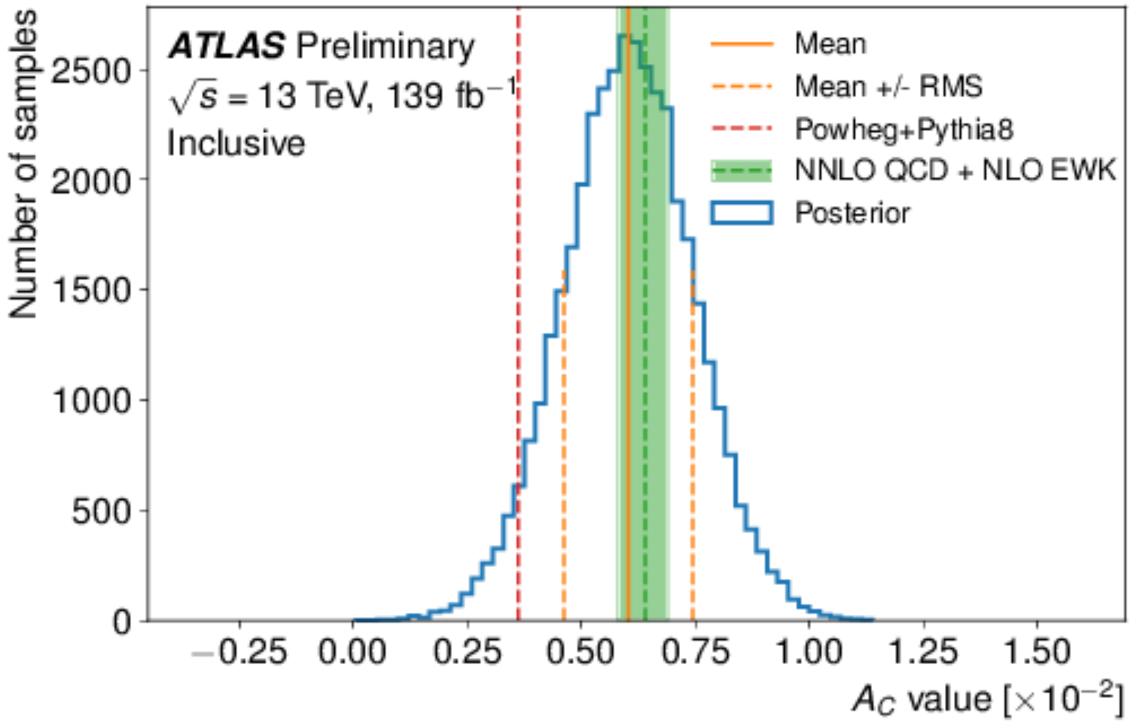


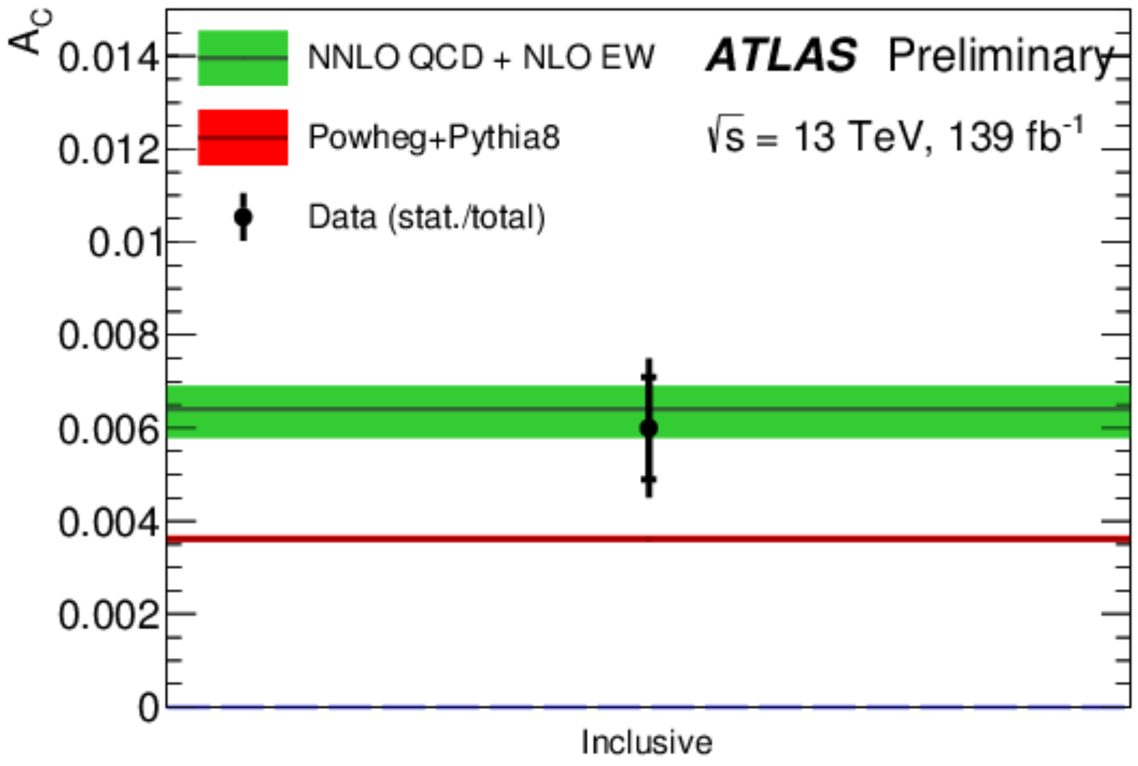
Tested models:

- W’ boson
- Heavy axi-gluon G_μ
- Scalar isodoublet ϕ
- Colour triplet scalar ω^4
- Colour sextet scalar Ω^4

Charge asymmetry: results

- Use fully Bayesian unfolding (FBU)
- Integrate out nuisance parameters of systematic uncertainties in the likelihood function



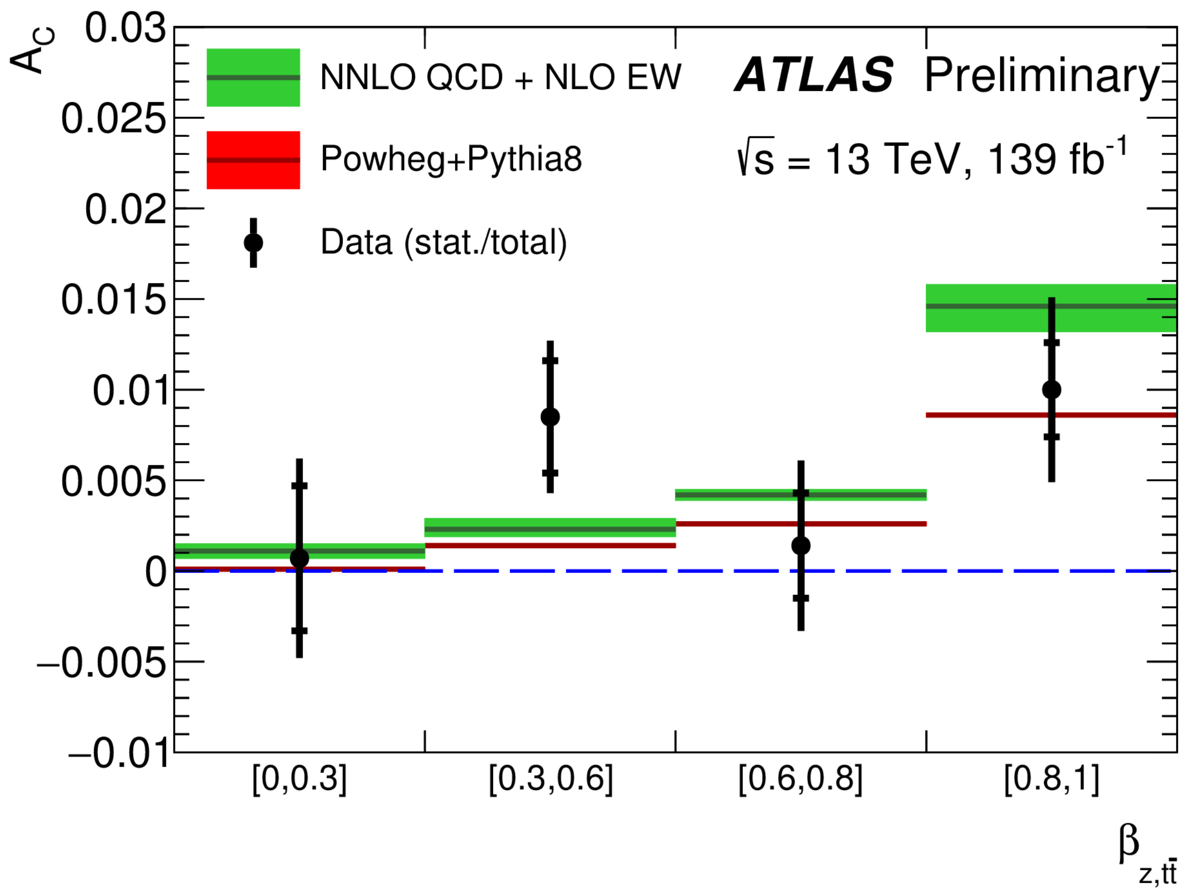


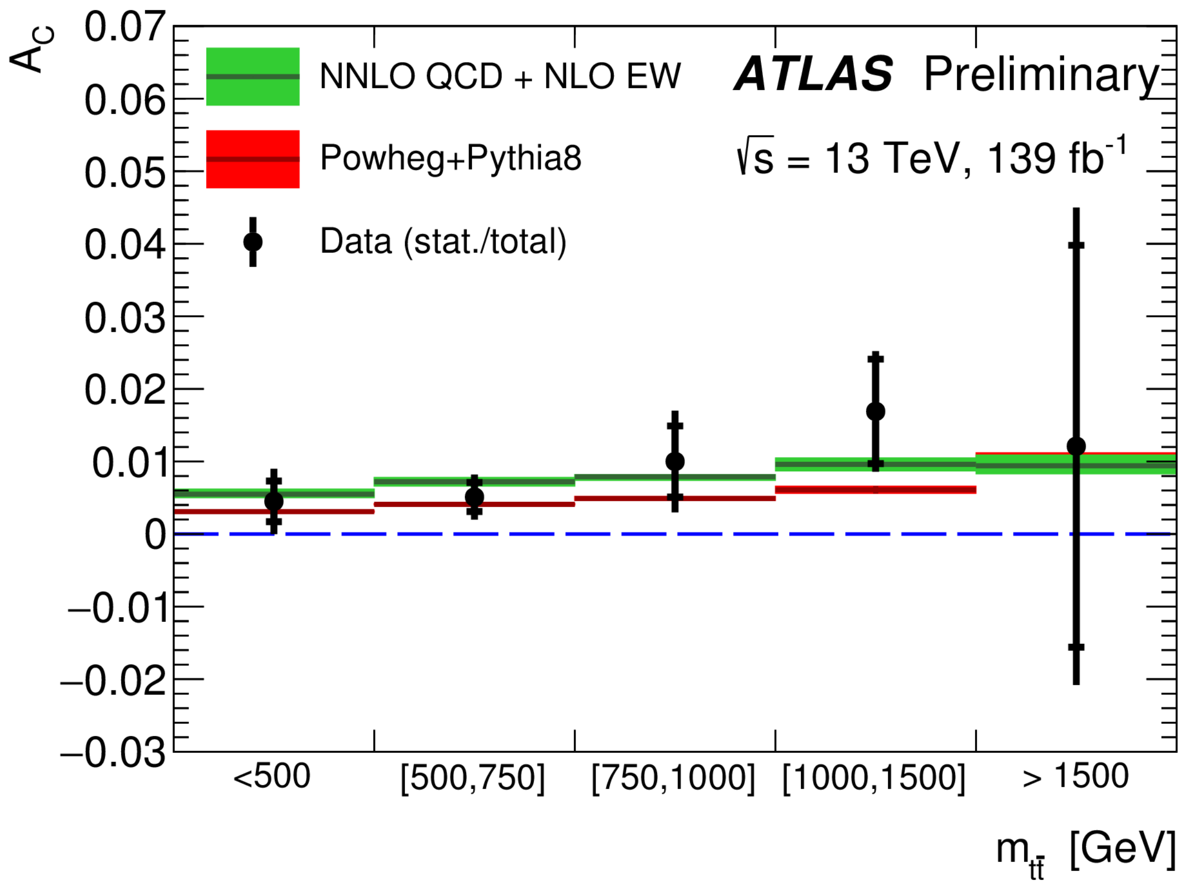
Differential results

Longitudinal boost of the $t\bar{t}$ system along the z axis = $\beta_z(t\bar{t})$

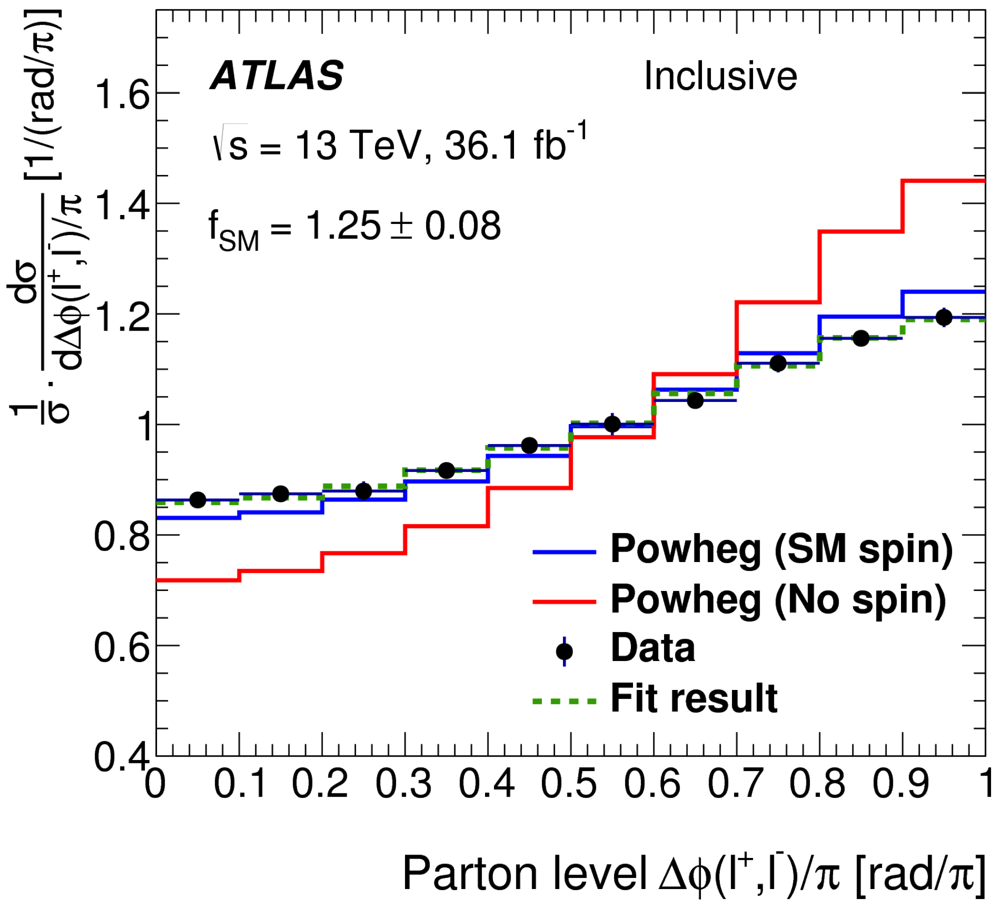
$m(t\bar{t})$

ATLAS-CONF-2019-026





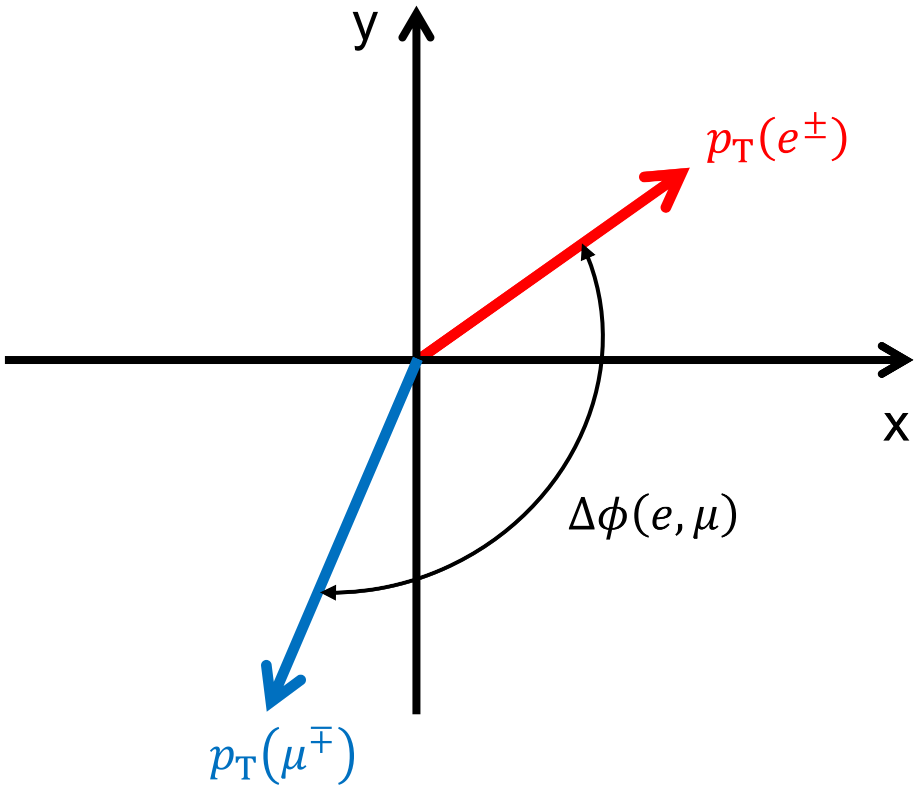
Spin correlations between top-quark and top-antiquark



„No spin“ hypothesis is clearly rejected.

Difference in the azimuthal angle ϕ between electron and muon

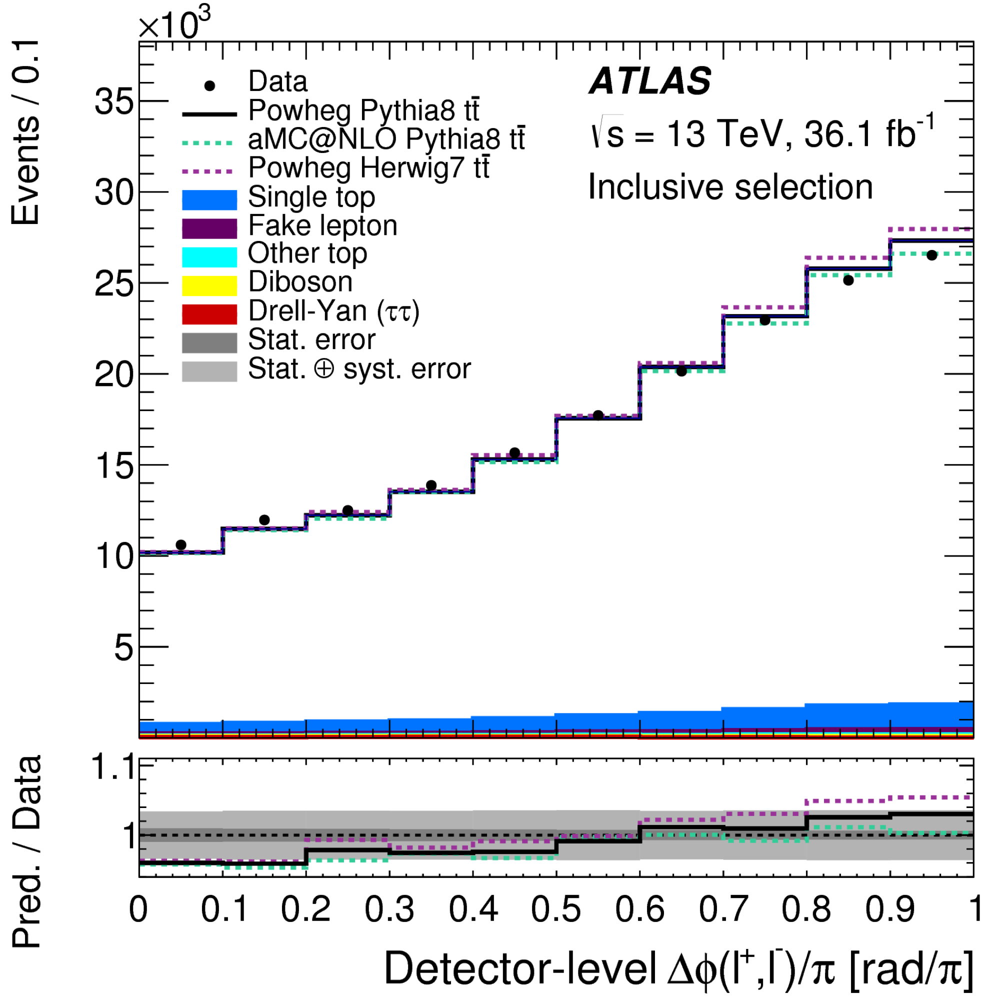
Transverse plane:



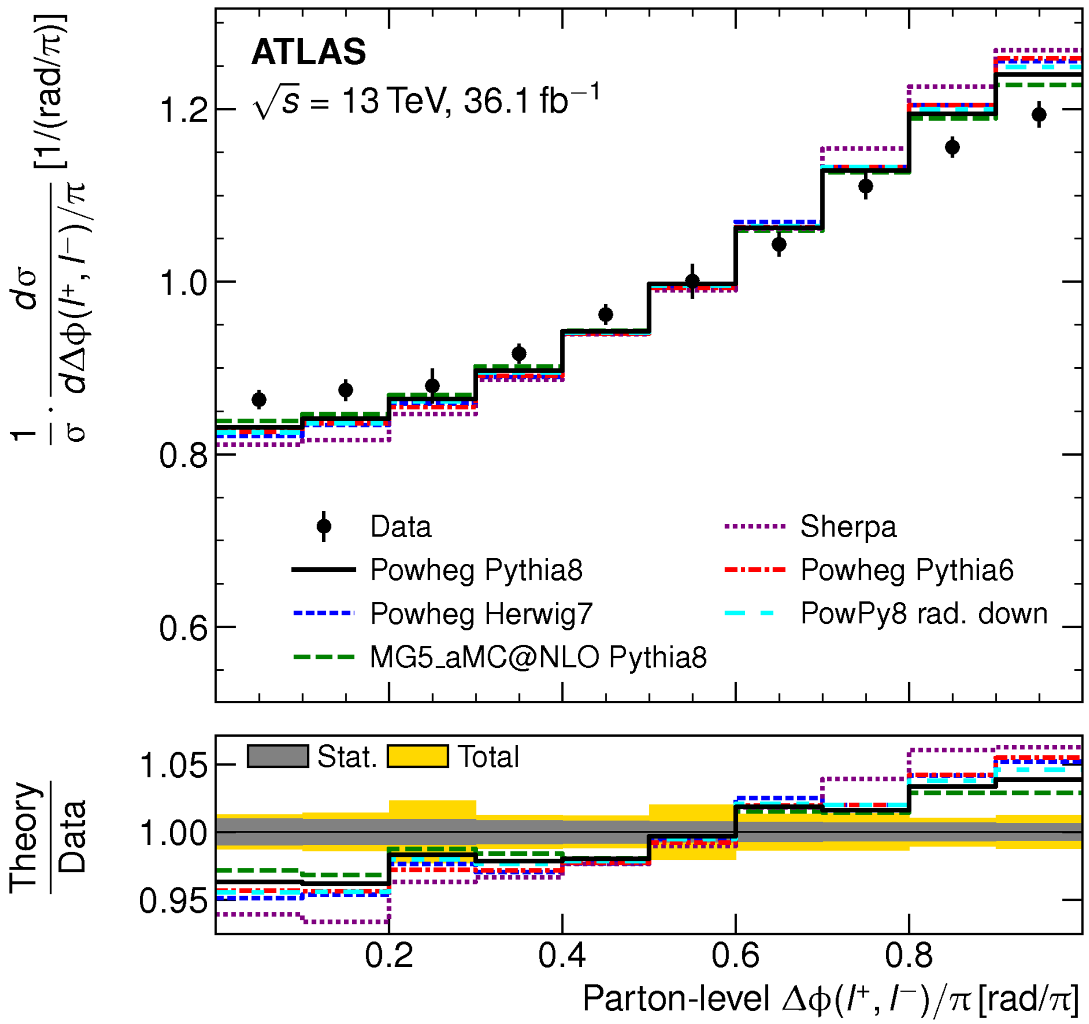
Normalised differential cross-section

BERGISCHE UNIVERSITÄT WUPPERTAL

Detector-level (reconstructed) distribution



Normalised differential cross-section

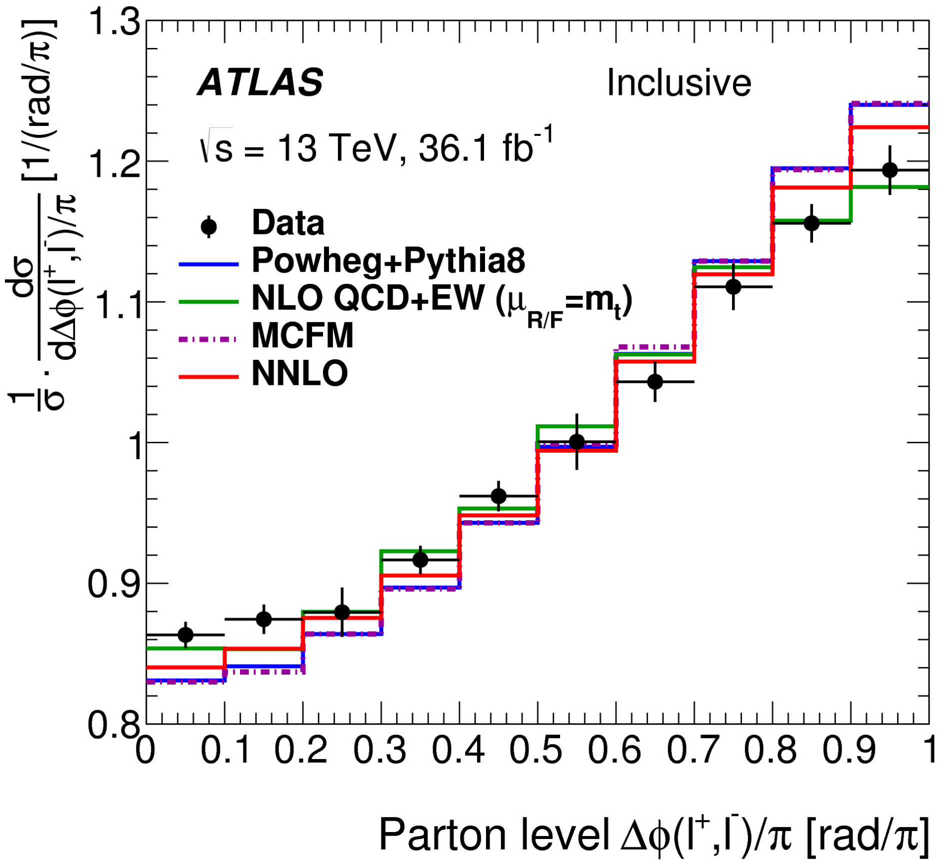


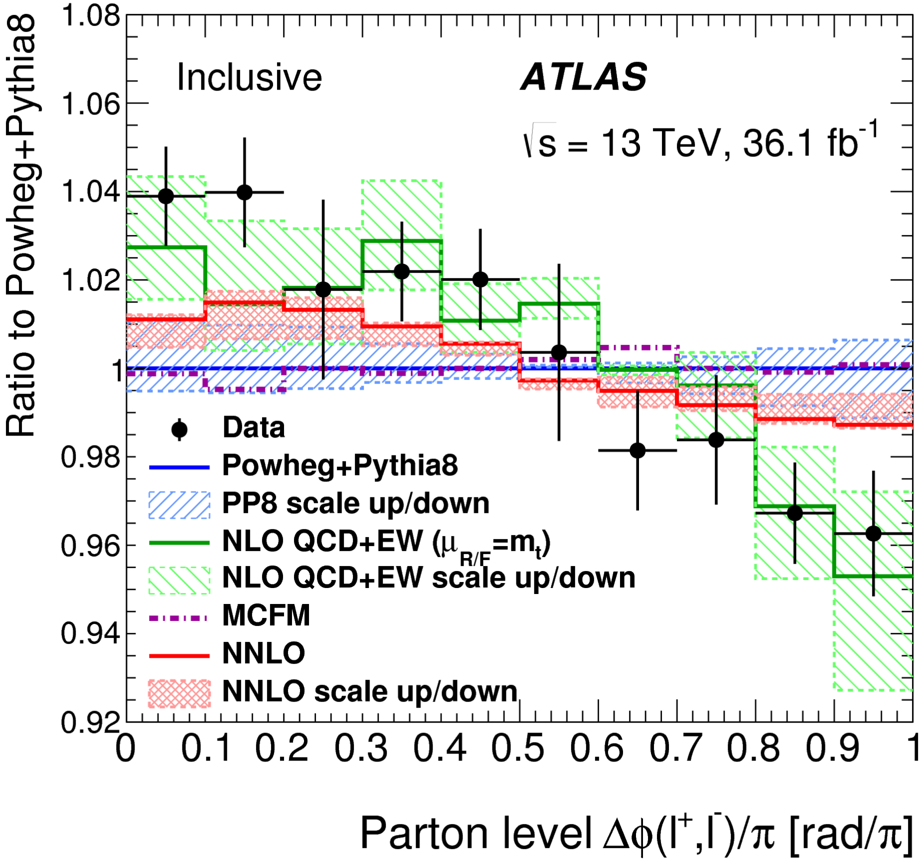
Uncertainties are too large to test the predictions.

Uncertainties shrink to the level of 1%.

Comparison to fixed-order calculations

BERGISCHE UNIVERSITÄT WUPPERTAL





Powheg+Pythia8 and NLO fixed-order MCFM) calculations do not describe the data.

NNLO result is closer to the data, but still no good description.

NLO calculation by Werner Bernreuther and Zongguo Si describes data well!

Main difference of B+S compared to MCFM and Powheg+Pythia: direct perturbative expansion of $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$

Other differences: choice of renormalisation and factorisation scales, electroweak corrections and PDFs.

Latest cross-checks

Fresh from Top2019: Talk by Alexander Mitov

Did expansion of normalized differential cross-section

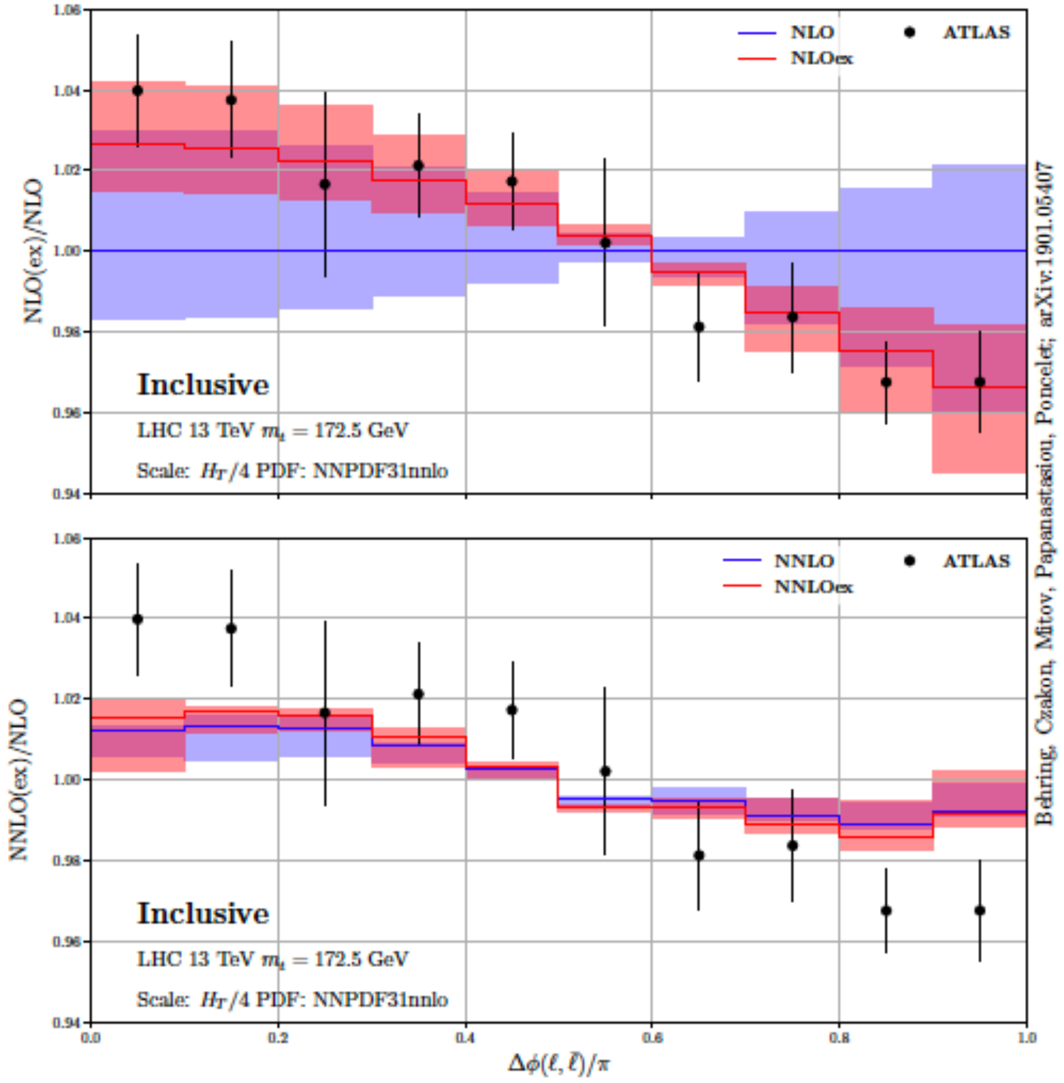
$$R^{\text{NNLO,exp}} = R^0 + \alpha_S R^1 + \alpha_S^2 R^2 \,,$$

$$R^0 = \frac{1}{\sigma^0}\frac{\mathrm{d}\sigma^0}{\mathrm{d}X} \,,$$

$$R^1 = \frac{1}{\sigma^0}\frac{\mathrm{d}\sigma^1}{\mathrm{d}X} - \frac{\sigma^1}{\sigma^0}\frac{1}{\sigma^0}\frac{\mathrm{d}\sigma^0}{\mathrm{d}X} \,,$$

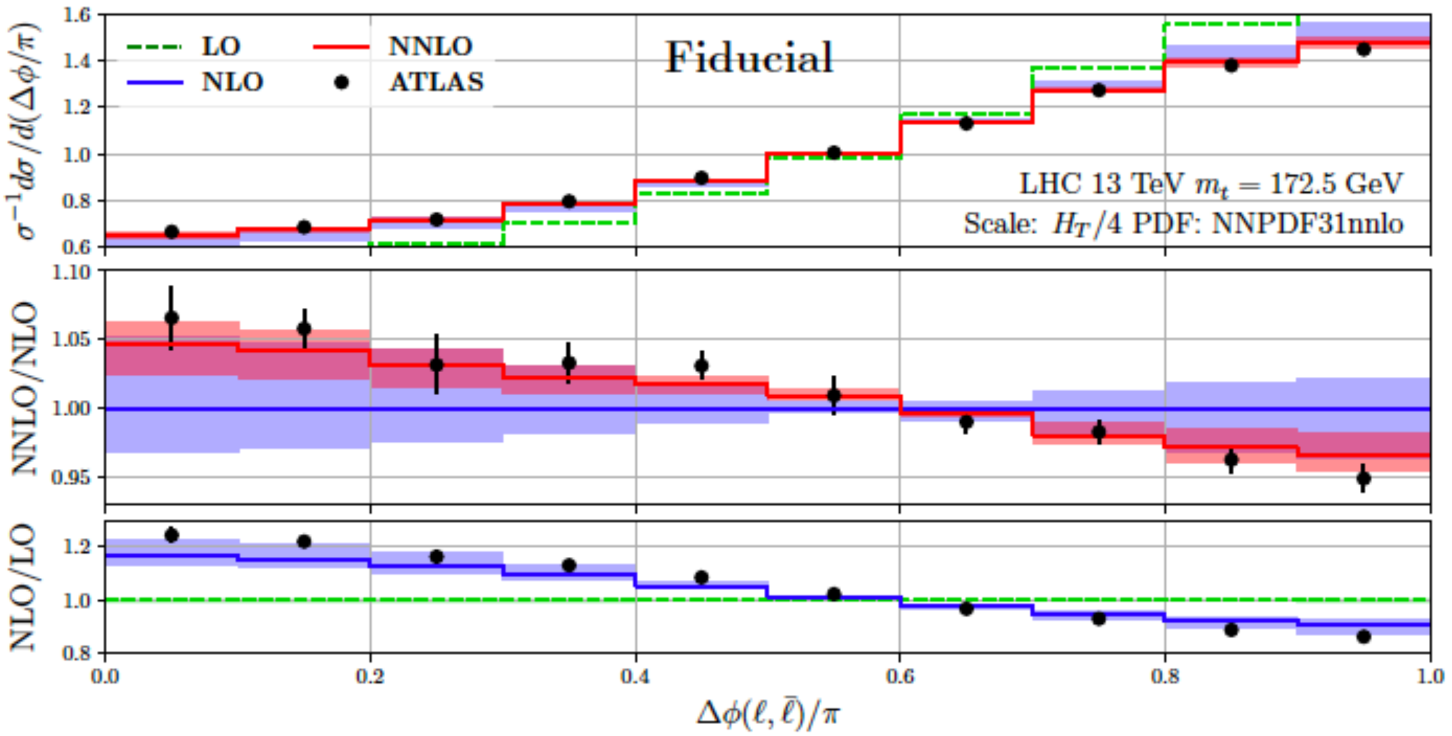
$$R^2 = \frac{1}{\sigma^0}\frac{\mathrm{d}\sigma^2}{\mathrm{d}X} - \frac{\sigma^1}{\sigma^0}\frac{1}{\sigma^0}\frac{\mathrm{d}\sigma^1}{\mathrm{d}X} + \left(\left(\frac{\sigma^1}{\sigma^0}\right)^2 - \frac{\sigma^2}{\sigma^0}\right)\frac{1}{\sigma^0}\frac{\mathrm{d}\sigma^0}{\mathrm{d}X}$$

- Confirms that expansion of $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ describes the data at NLO!
- But no effect at NNLO!



Fiducial cross-sections

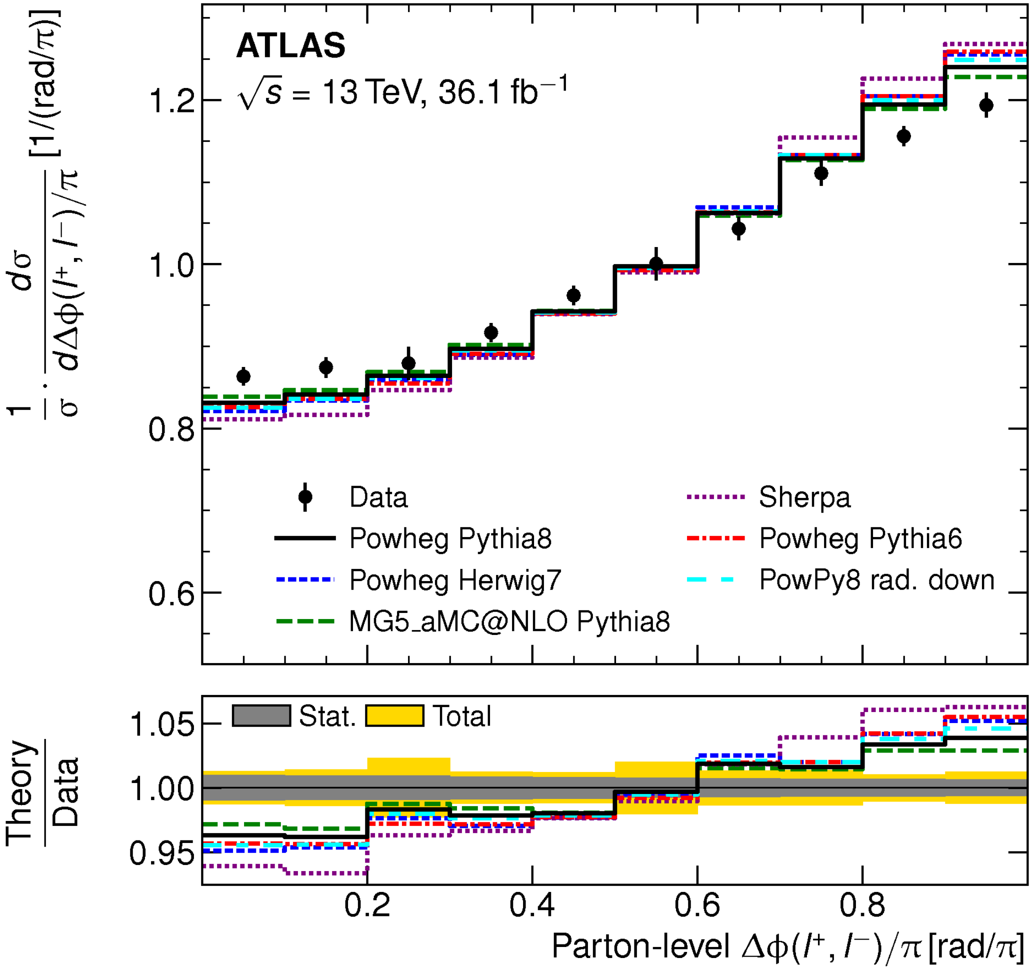
At the fiducial level NNLO describes the data well.

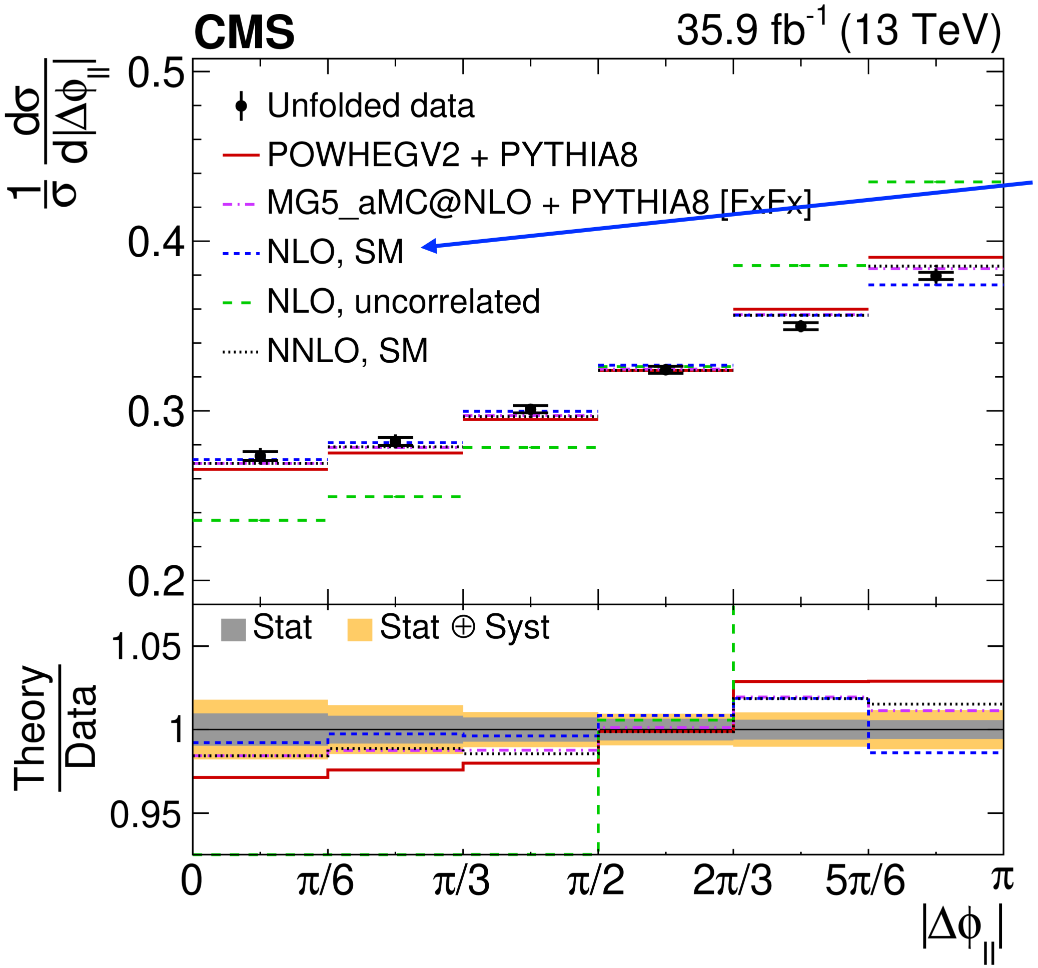


Behring, Czakon, Mitov, Papanastasiou, Poncelet arXiv:1901.05407

Points to the Monte-Carlo-based acceptance corrections as the cause of the difference.

Comparison ATLAS and CMS





Bernreuther + Si

The MG5_aMC@NLO+Pythia8 [FxFx] setup of CMS agrees with the data within the 1 s.d. band.

- In $\Delta\phi(e,\mu)$ both experiments observe a slope with respect to the Powheg prediction.
- In ATLAS the slope is slightly larger $(1.03 - 0.97)/\pi$ versus $(1.025 - 0.975)/\pi$.

Summary and Conclusions

BERGISCHE UNIVERSITÄT WUPPERTAL

- The top-quark plays an important role in the SM, mainly through loop corrections.
- The LHC is a copious source of top quarks. Run 2 provides us with millions of reconstructed top-quark events.
- The SM is challenged by direct and indirect searches, as well as by precision measurements.