New searches for charged lepton flavor violation with the ATLAS detector

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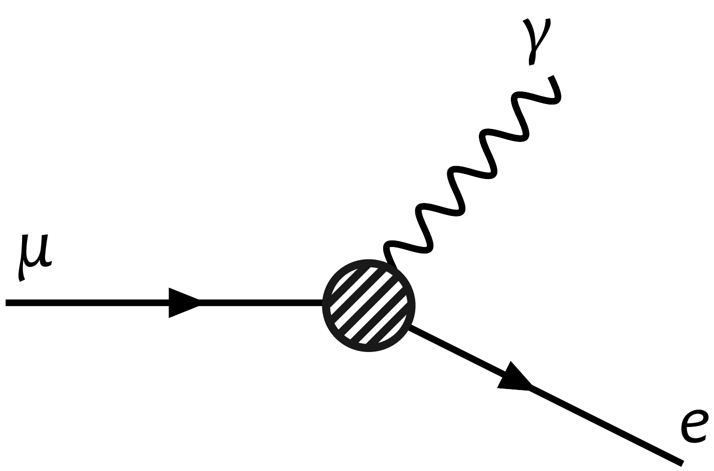
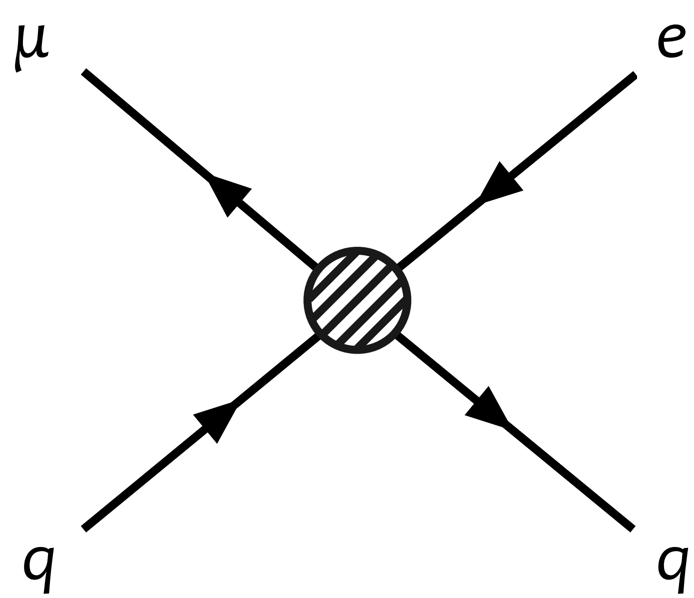
Experimental seminar

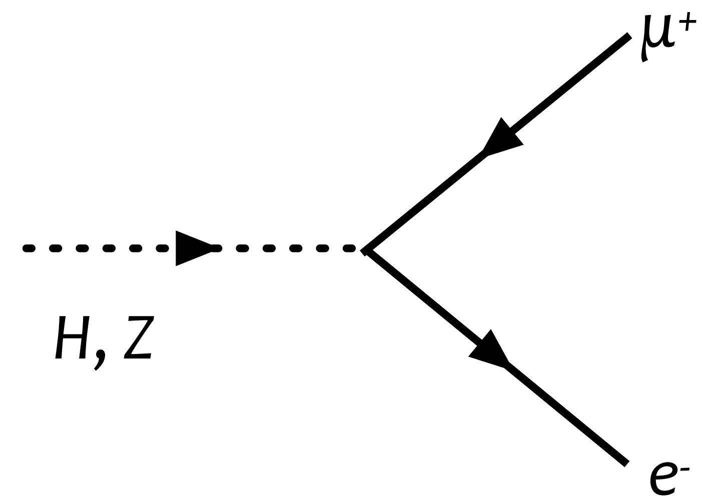
Outline

- Charged lepton flavour violation (cLFV), what is it?
- Experimental searches
  - Higgs boson
  - Heavy resonances
  - Top-quark
- Conclusions

cLFV, how it looks like







Why are we interested in this?

Isn't all this forbidden?

A closer look at the SM

"Canonical" SM

- massless ν,
- no ν-oscillations,
- $U(1)_e \times U(1)_\mu \times U(1)_\tau$

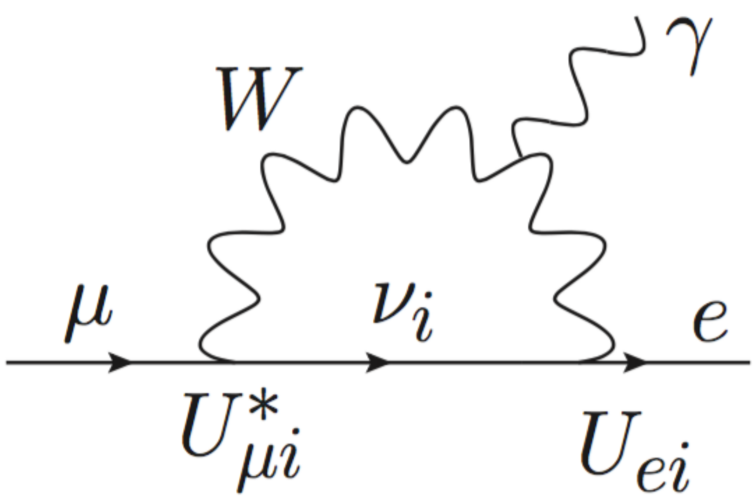
simply add ν_R →

SM + Dirac ν_R

- massive ν,
- ν mixing (PMNS matrix U),
- ~~$U(1)_e \times U(1)_\mu \times U(1)_\tau$~~

cLFV now allowed
but beyond experimental reach

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$

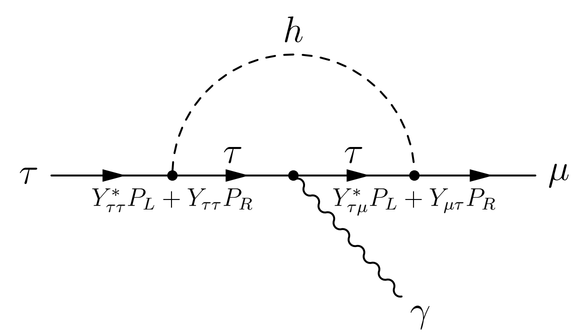


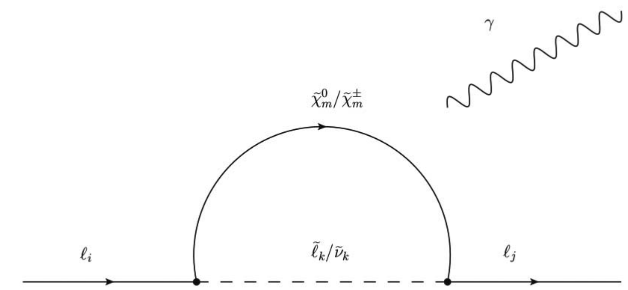
Observation of cLFV = probe for New Physics beyond simplest SM extension

Beyond the SM

Is this the full story?

- $m_\nu < 0.1$ eV → $Y_\nu < 5 \times 10^{-13}$ $\quad \Delta\mathcal{L}_Y = -(Y_\nu)_{ij}\bar{L}_i\phi^c\nu_{Rj}$
- Majorana mass term? $\quad \Delta\mathcal{L}_M \propto M\bar{\nu}^c_R\nu_R$
- See-saw? Heavy neutrino?
- … and many BSM models





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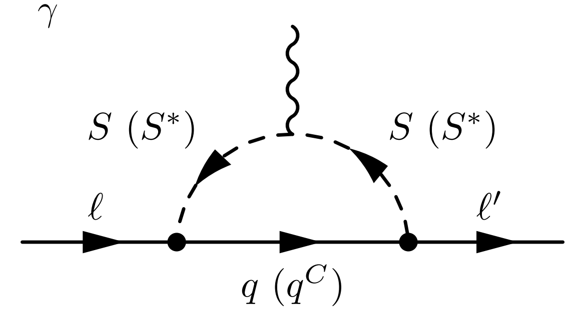
Many BSM models, e.g.:
2HDM,
SUSY,
Leptoquark models,
Z’, RS, …



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1. **Observation of cLFV = probe for New Physics**
2. **cLFV rates depend on the *unknown* mechanism underlying ν masses.**

Previous searches

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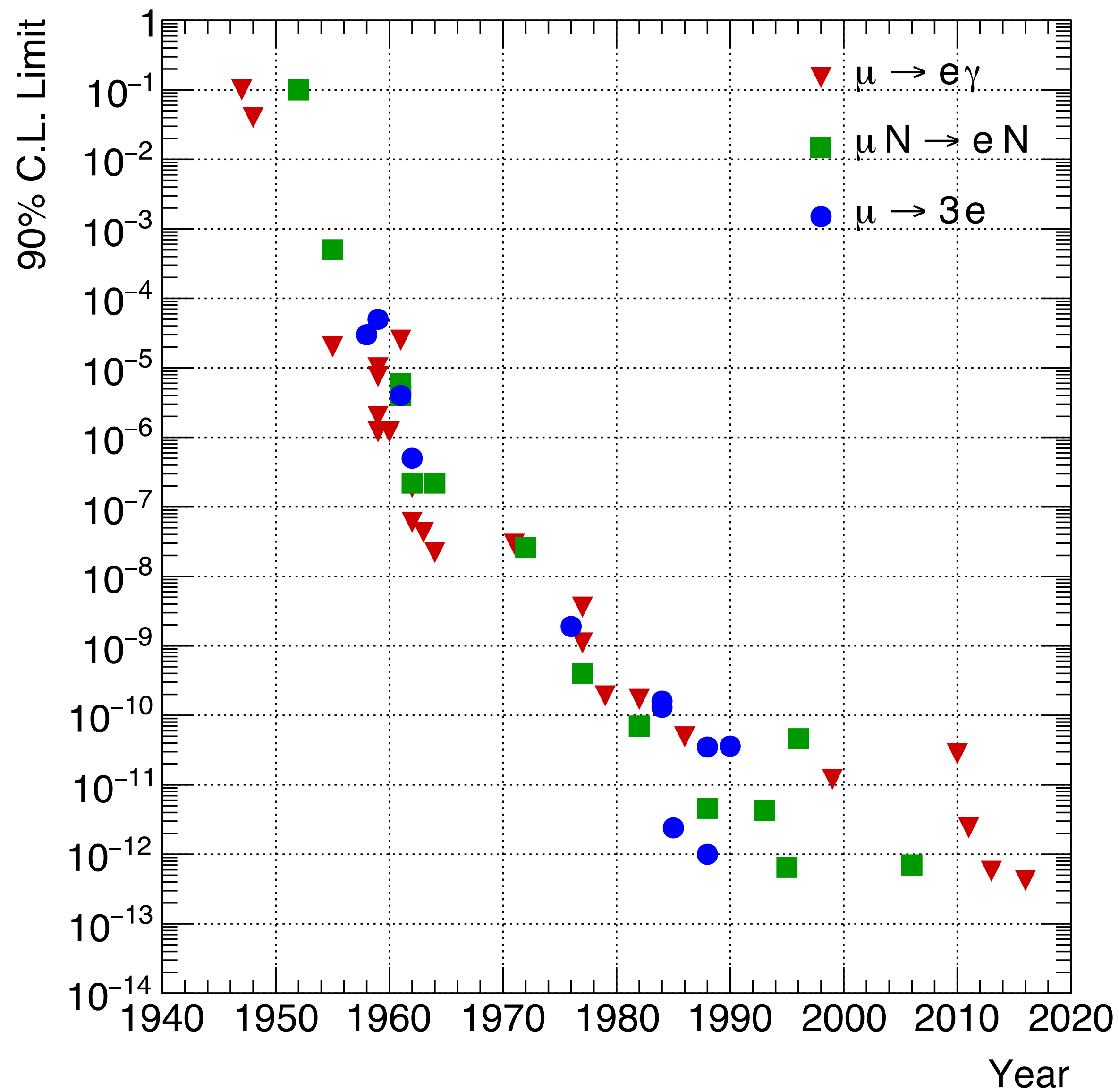

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Reaction	Present limit	C.L.	Experiment	Year
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ (a)	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$ (a)	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ (a)	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$ (a)	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998

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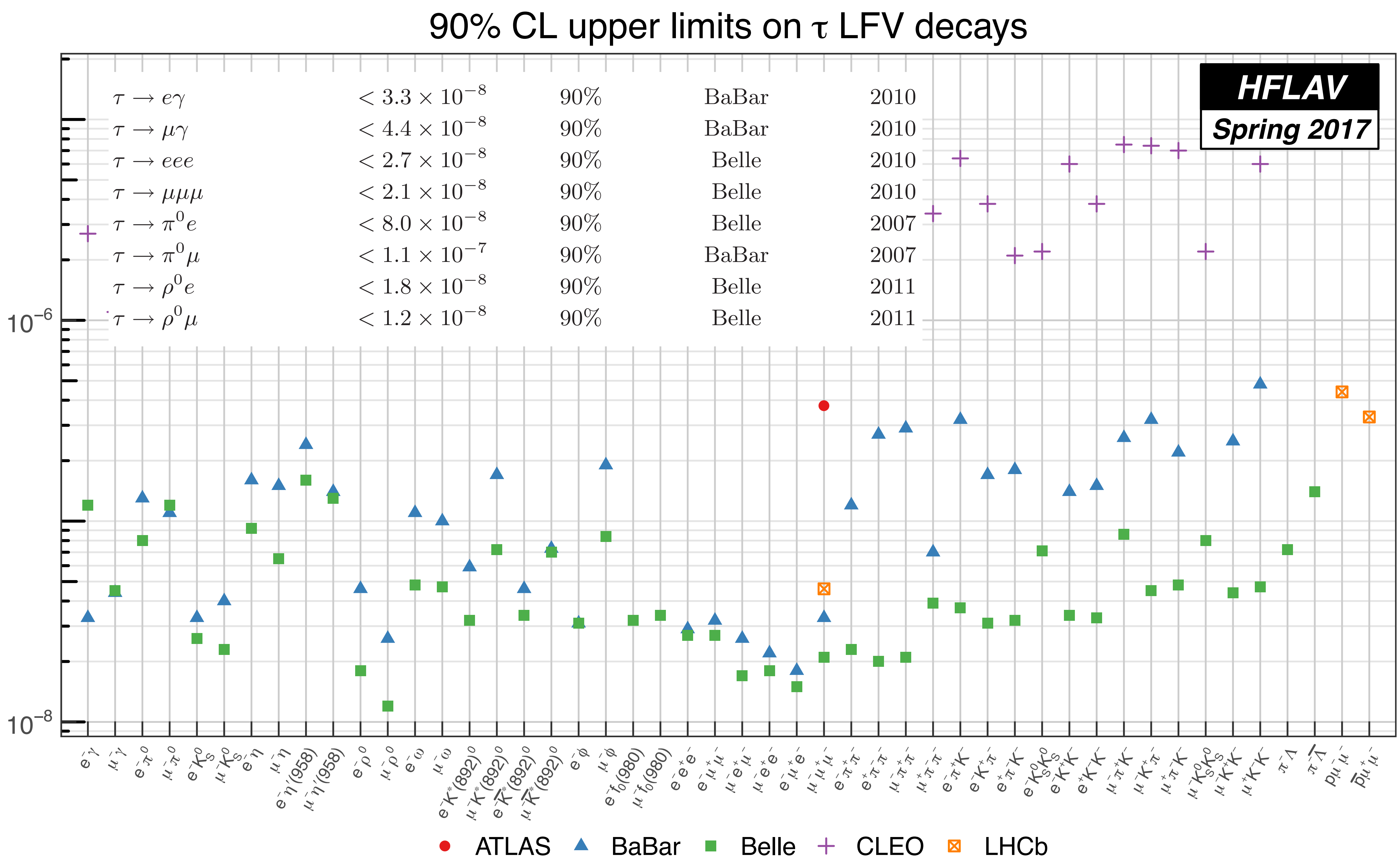
Previous searches



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Previous searches

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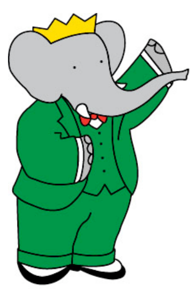

Reaction	Present limit	C.L.	Experiment	Year
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$	90%	KTeV	2008
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998
$K_L^0 \to \pi^0 \mu^+ e^-$	$< 7.6 \times 10^{-11}$	90%	KTeV	2008
$K^+ \to \pi^+ \mu^+ e^-$	$< 1.3 \times 10^{-11}$	90%	BNL E865	2005
$J/\psi \to \mu e$	$< 1.5 \times 10^{-7}$	90%	BESIII	2013
$J/\psi \to \tau e$	$< 8.3 \times 10^{-6}$	90%	BESII	2004
$J/\psi \to \tau \mu$	$< 2.0 \times 10^{-6}$	90%	BESII	2004
$B^0 \to \mu e$	$< 2.8 \times 10^{-9}$	90%	LHCb	2013
$B^0 \to \tau e$	$< 2.8 \times 10^{-5}$	90%	BaBar	2008
$B^0 \to \tau \mu$	$< 2.2 \times 10^{-5}$	90%	BaBar	2008
$B \to K \mu e^{(b)}$	$< 3.8 \times 10^{-8}$	90%	BaBar	2006
$B \to K^* \mu e^{(b)}$	$< 5.1 \times 10^{-7}$	90%	BaBar	2006
$B^+ \to K^+ \tau \mu$	$< 4.8 \times 10^{-5}$	90%	BaBar	2012
$B^+ \to K^+ \tau e$	$< 3.0 \times 10^{-5}$	90%	BaBar	2012
$B_s^0 \to \mu e$	$< 1.1 \times 10^{-8}$	90%	LHCb	2013
$\Upsilon(1s) \to \tau \mu$	$< 6.0 \times 10^{-6}$	95%	CLEO	2008
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995
$Z \to \tau \mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997

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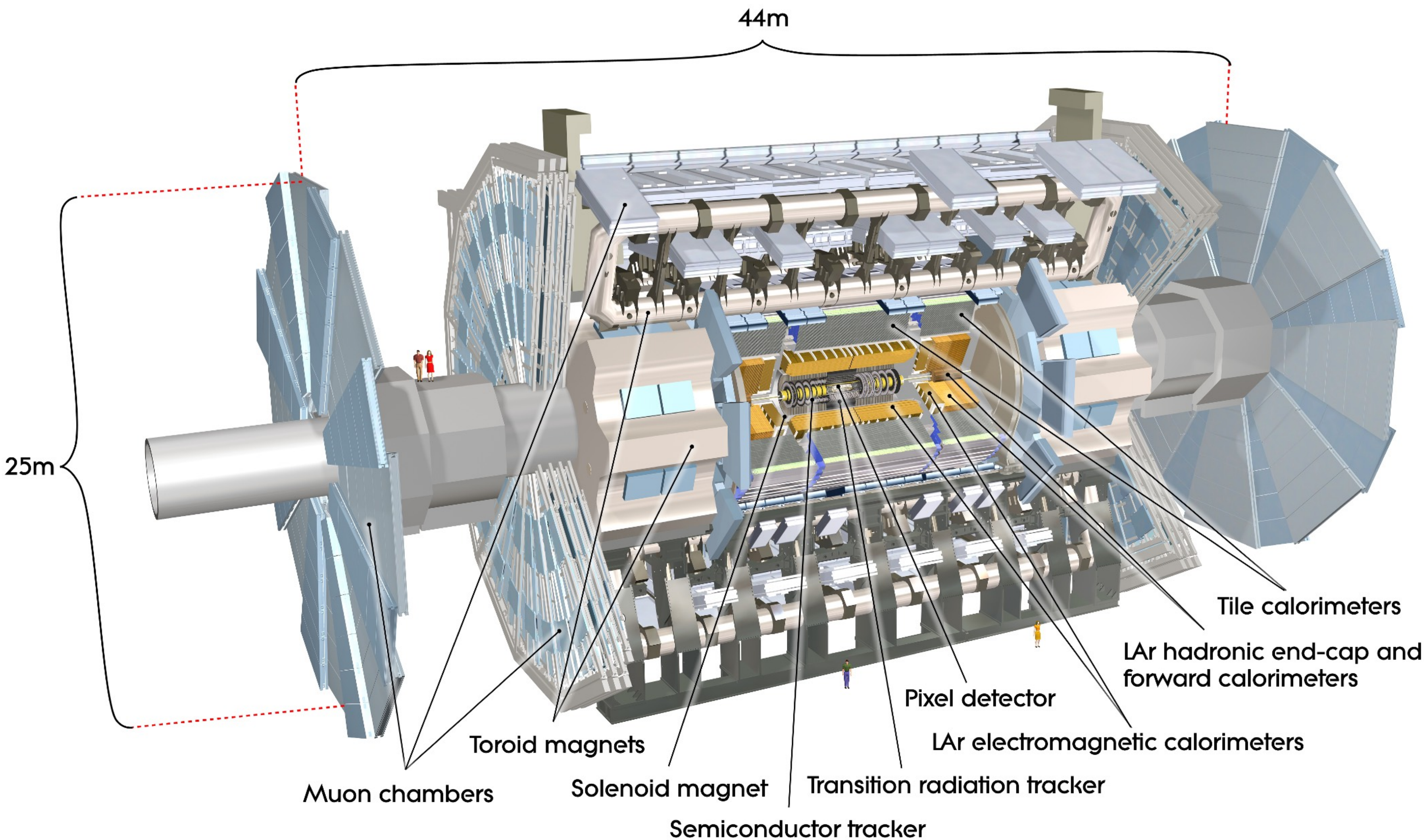
Higgs and top-quark sectors explored only at the LHC

The ATLAS detector



Selected cLFV searches by ATLAS

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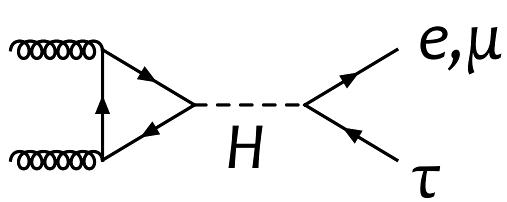
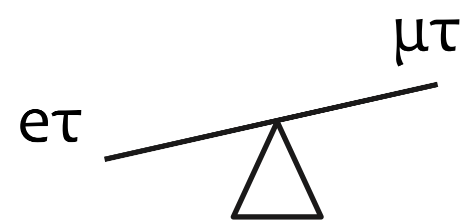
Higgs (2017, √s = 8 TeV, L = 20 fb^{-1}) *1508.03372, 1604.07730*

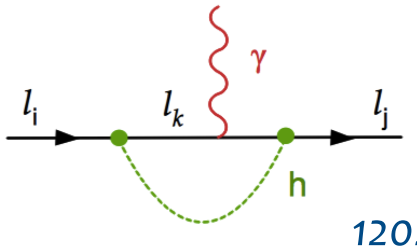
H → μτ

H → eτ

~~H → eμ ?~~







1202.5704

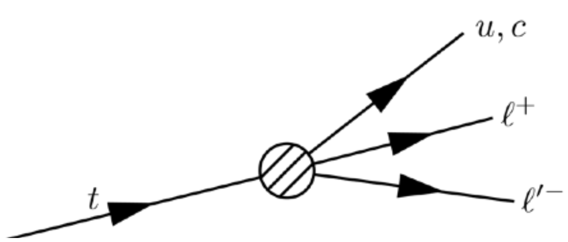
High mass resonances (Nov. '18, √s = 13 TeV, L=36 fb-1) *1807.06573*

X → eμ, eτ, μτ

X = Z', QBH, $\tilde{\nu}_{\tau}$ up to 6 TeV

Top quark decays (Sept. '18, √s = 13 TeV, L=80 fb^{-1}) *1809.09048*

t → ℓℓ'q



$H \to \ell\tau^{had}$ ($\ell = e, \mu$)

Two analyses, same strategy.

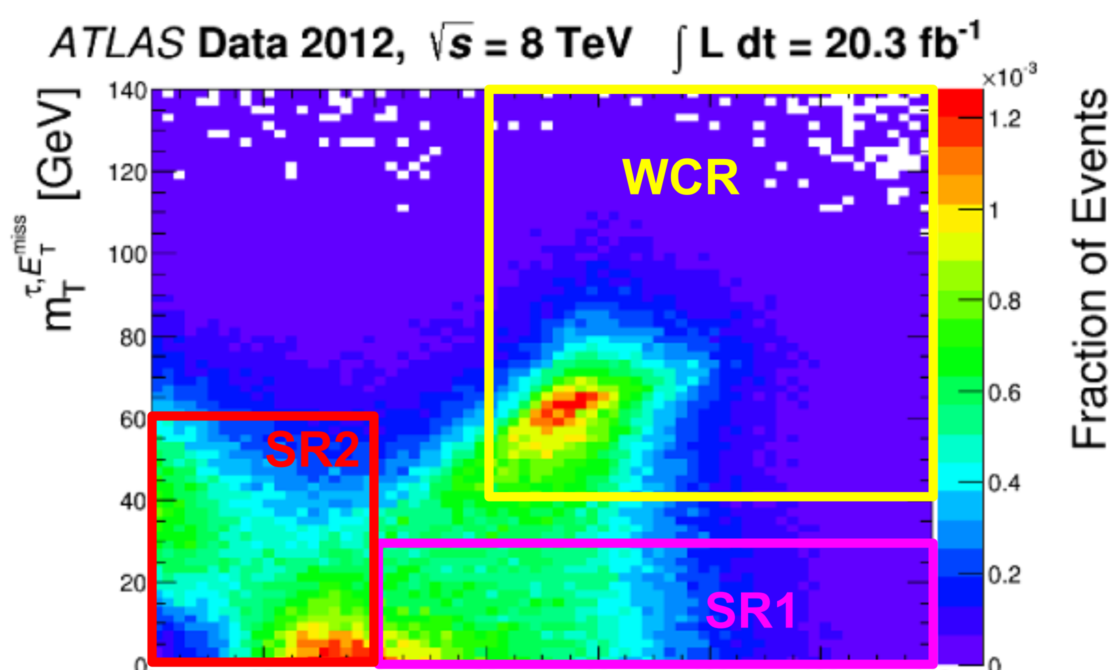
Selection:

= 1ℓ, $1\tau^{had}$, OS
$p_T^{\ell} > 26$ GeV, $p_T^{\tau} \geq 45$ GeV
$|\eta(\ell) - \eta(\tau)| < 2$
0 *b*-jets

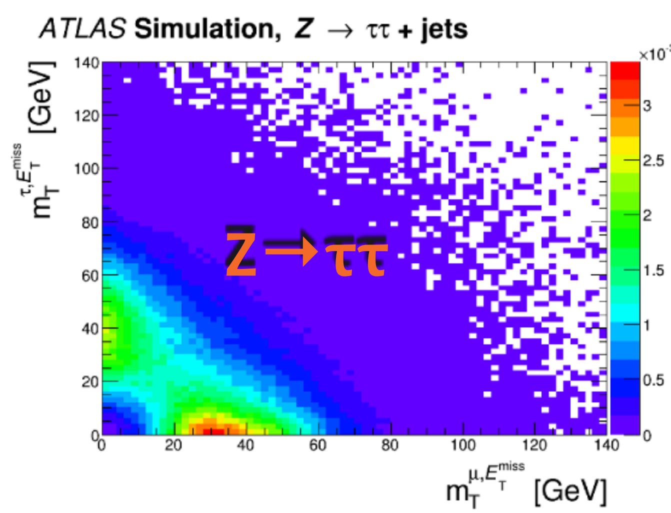
Backgrounds:

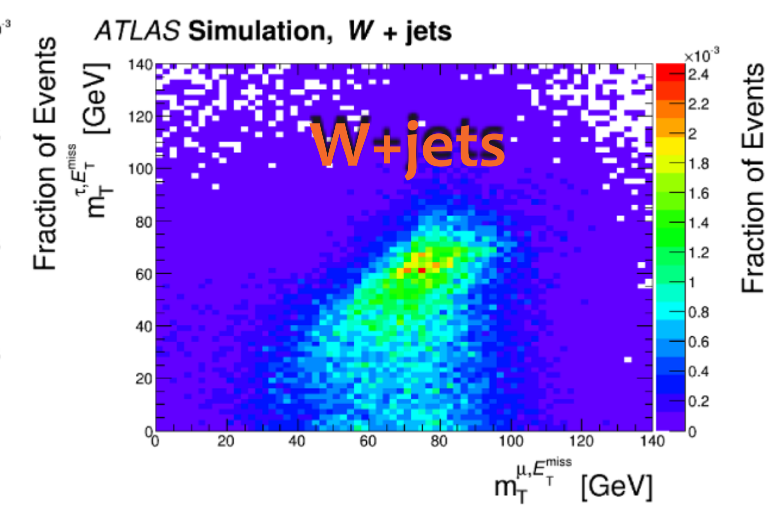
$Z \to \tau\tau$
W+jets with fake τ
multijet (fake τ, non-prompt μ)
$t\bar{t}$, *VV*, single top, $H \to \tau\tau$

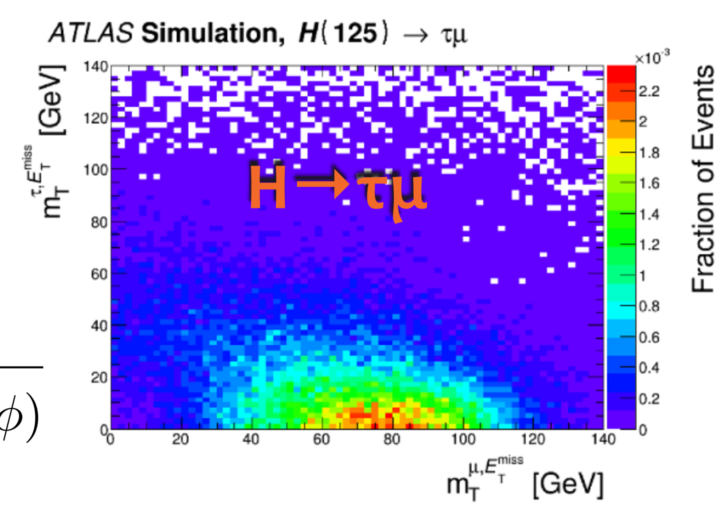
SR1: exclude *Z*+jets
SR2: exclude *W*+jets



$$m_T^{\mu,E_T^{miss}}\ [\mathrm{GeV}] = \sqrt{2 p_T^{\ell} E_T^{miss} (1 - \cos\Delta\phi)}$$







Background modeling

$$N_{\rm OS}^{\rm bkg} = r_{\rm QCD} \cdot N_{\rm SS}^{\rm data} + \sum_{\text{bkg-}i} N_{\rm OS-SS}^{\text{bkg-}i} \qquad N_{\rm OS-SS}^{\text{bkg}-i} = N_{\rm OS}^{\text{bkg}-i} - r_{\rm QCD} \cdot N_{\rm SS}^{\text{bkg}-i}$$

correction factor ~1

same sign $\tau\ell$ data events

“add ons”

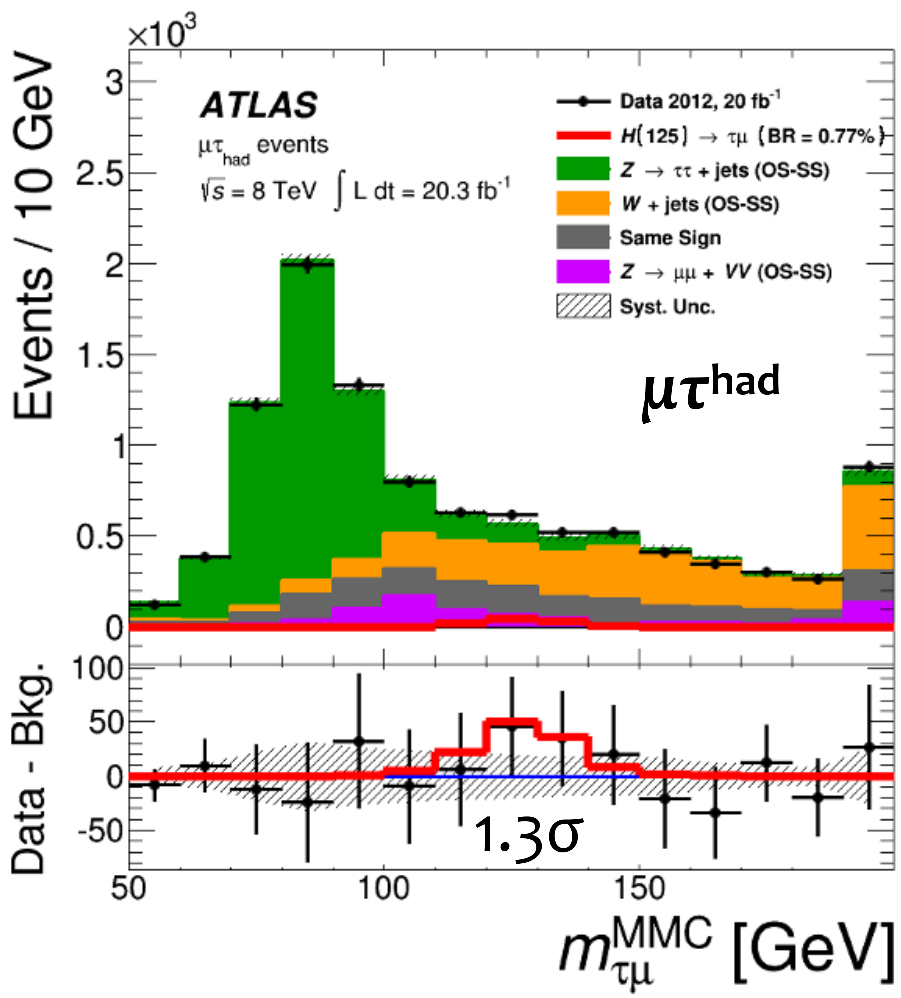
OS events for bkg. *i*

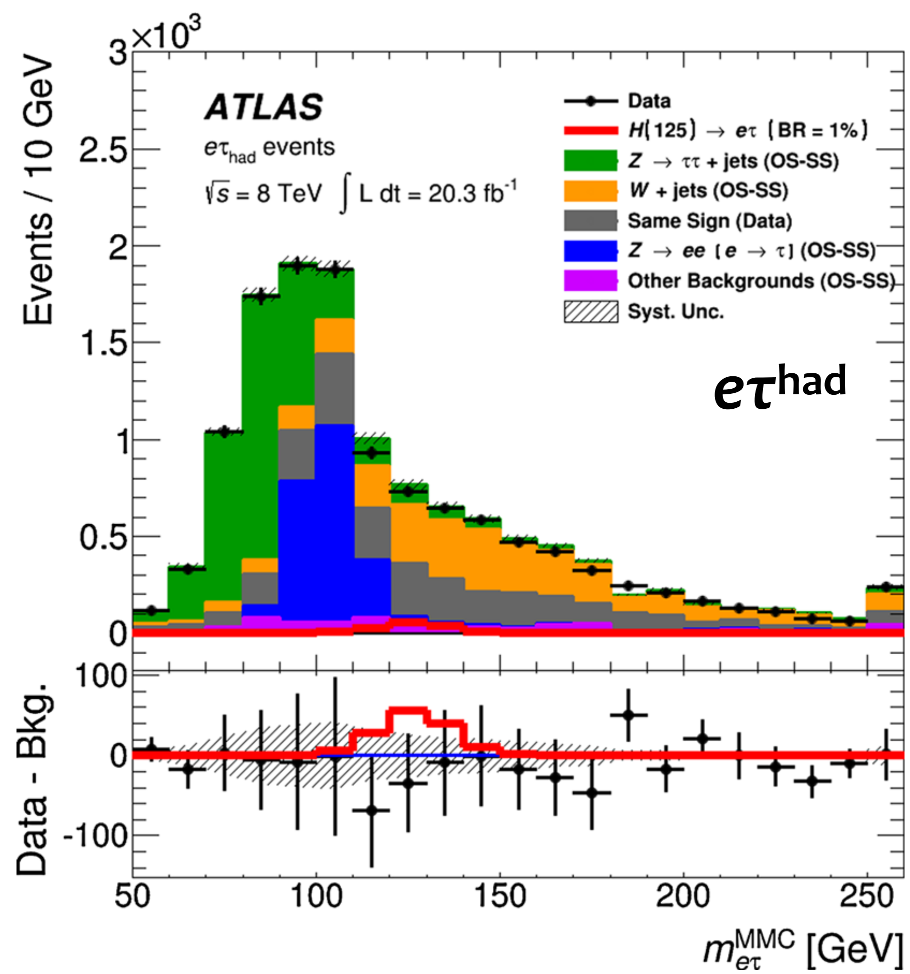
SS events for bkg. *i*

bkg = {Zττ, Zμμ, W+jets, top, VV, Hττ}

… per $m_{\tau\ell}$ bin

Results





$\mu\tau_{\rm had}$

Best fit Br = 0.77 ± 0.62 %

Exp. lim $1.24^{+0.50}_{-0.35}$ %

Obs lim Br < 1.85 %

$e\tau_{\rm had}$

Best fit Br = -0.47 ± 1.13 %

Exp lim $2.07^{+0.82}_{-0.58}$

Obs lim Br < 1.81 %

$H \rightarrow \ell\tau^{\mathrm{lep}}$ (ℓ=e, μ)

Selection:

= 1e, 1μ, OS

$p_T^{(\mathrm{leading})}$ > 35 GeV, $p_T^{(\mathrm{trailing})} \geq$ 12 GeV

0 b-jets, τ^{had} veto

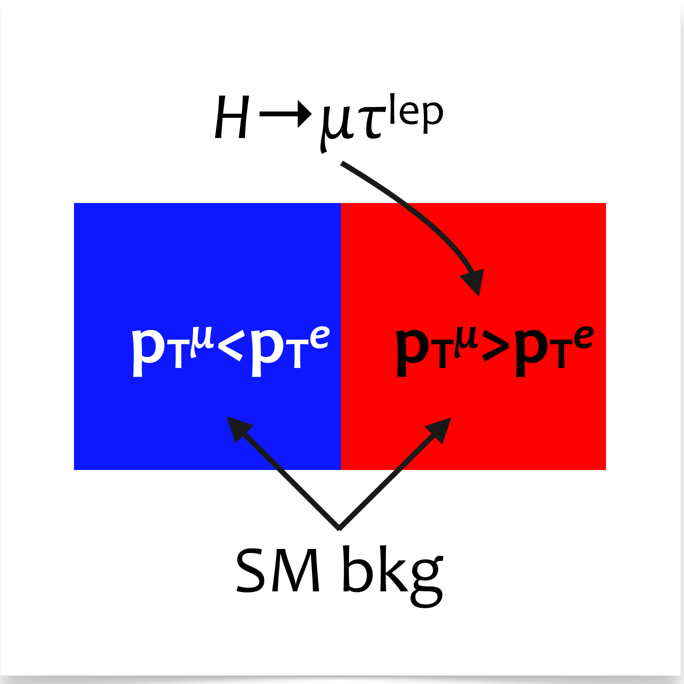
	N_{Jets}	$\Delta\Phi(\ell_2, E_T^{\mathrm{miss}})$	$\Delta\Phi(\ell_1,\ell_2)$	$\Delta\Phi(\ell_1, E_T^{\mathrm{miss}})$	$\Delta p_T(\ell_1,\ell_2)$
SR_{noJ}	0	≤ 0.7	≥ 2.3	≥ 2.5	≥ 7 GeV
SR_{Jets}	≥ 1	≤ 0.5	≥ 1.0	≥ 1.0	≥ 1 GeV

Data-driven background estimation:

- SM bkg symmetric under e<—>μ exchange
- $H \rightarrow \mu\tau \rightarrow \mu e\,(\nu\nu)$ breaks this symmetry, $p_T^{\mu} > p_T^{e}$
- split regions in ***μe*** ($p_T^{\mu} > p_T^{e}$) and ***eμ*** ($p_T^{\mu} < p_T^{e}$)
- extract μ fitting the discriminant using

$$L(b_i, \mu) = \prod_{i}^{N_{\mathrm{bins}}} \mathrm{Pois}(n_i \mid b_i) \times \mathrm{Pois}(m_i \mid b_i + \mu s_i)$$

- Correct for
  - Mis-reconstructed objects (fakes)
  - different efficiencies in ***μe*** vs ***eμ***
- for $H \rightarrow e\tau^{\mathrm{lep}}$ swap e, μ and repeat



Discriminant

$$m_{\text{coll}} = \sqrt{2 p_{\text{T}}^{\ell_1} (p_{\text{T}}^{\ell_2} + E_{\text{T}}^{\text{miss}})(\cosh \Delta\eta - \cos \Delta\phi)}$$

Results

$\mu\tau^{lep}$

Best fit Br = 0.03 ± 0.87

Exp lim $1.73^{+0.74}_{-0.49}$ %

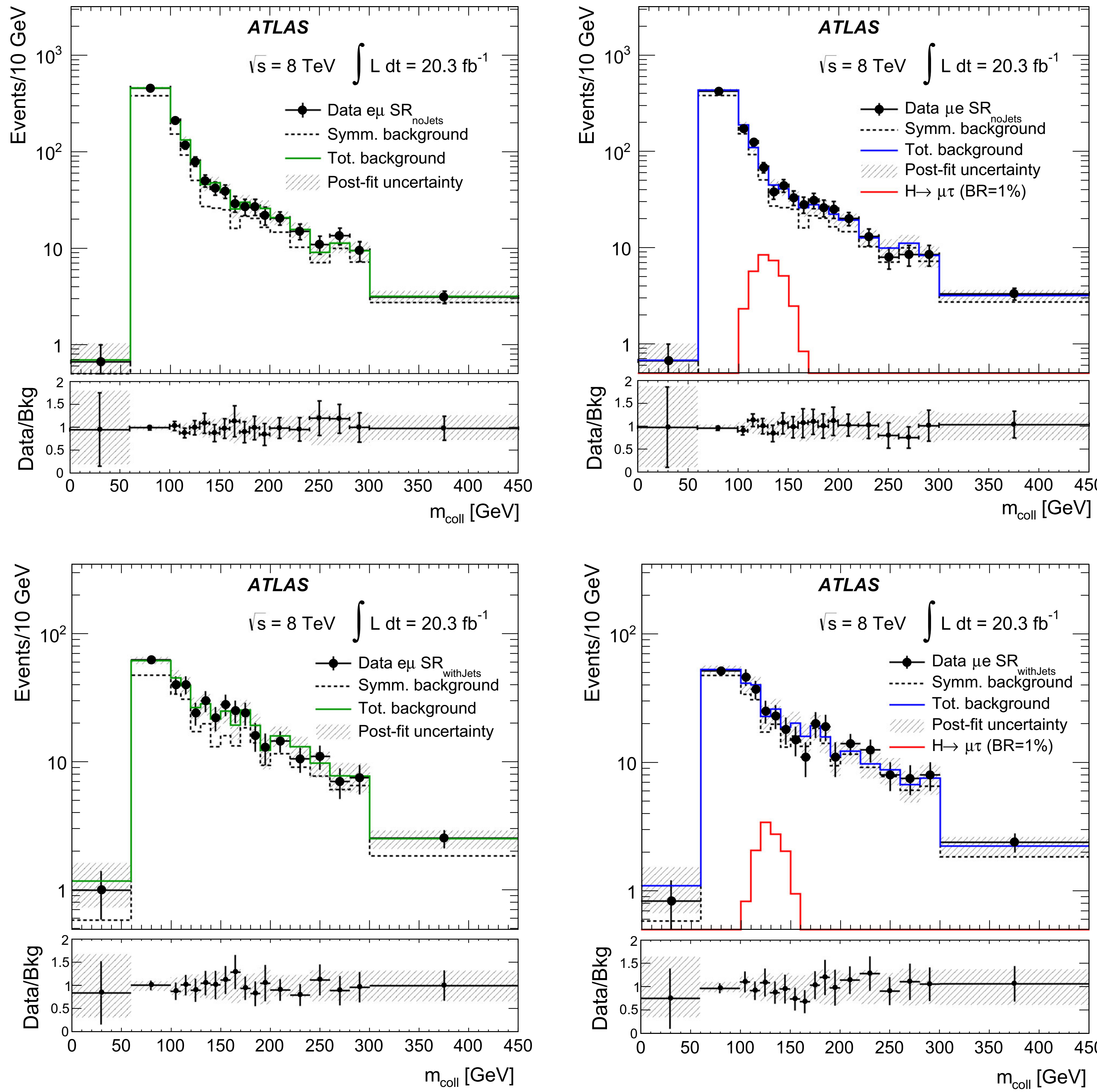
Obs lim 1.79 %

$e\tau^{lep}$

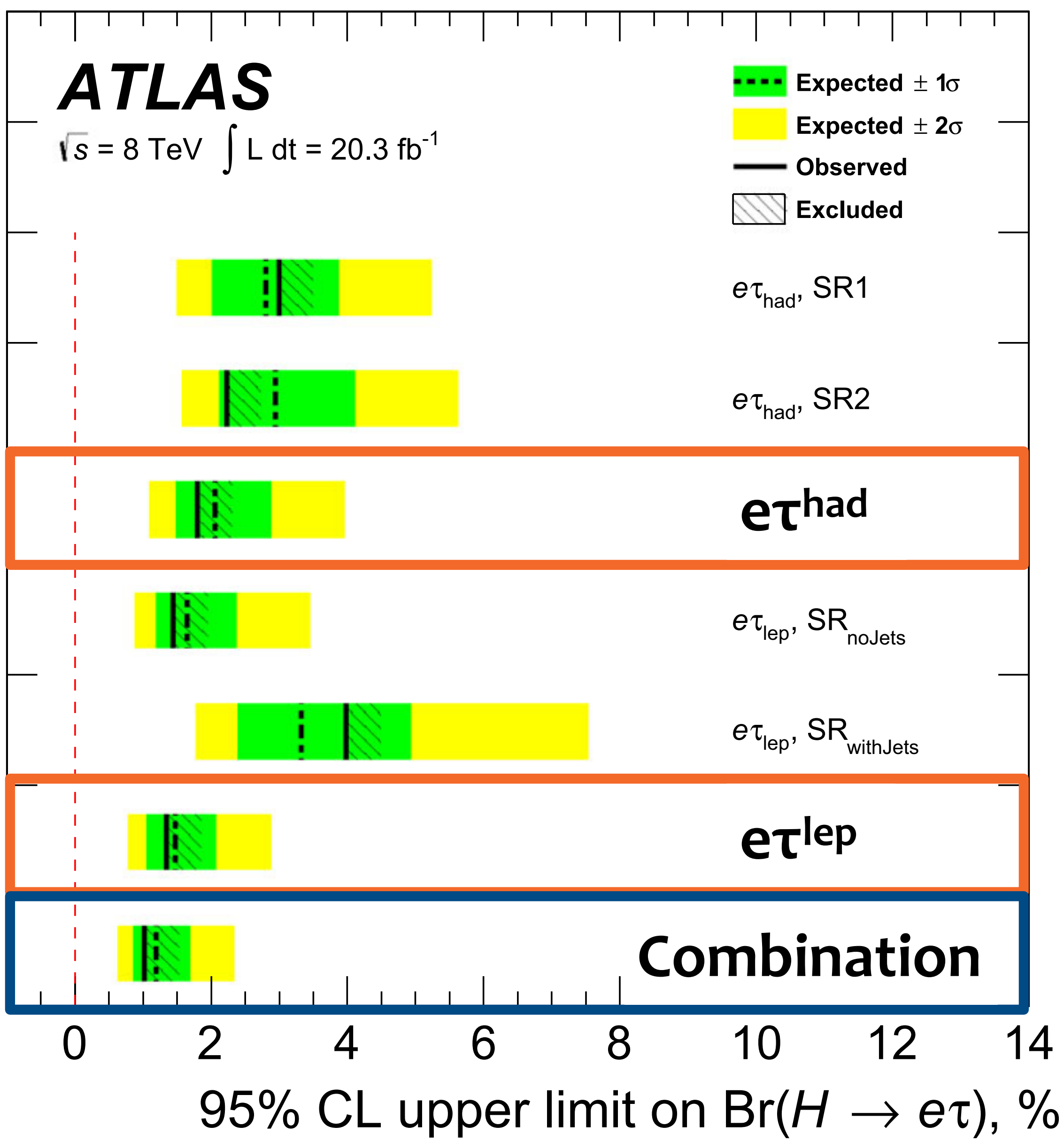
Best fit Br = -0.26 ± 0.81

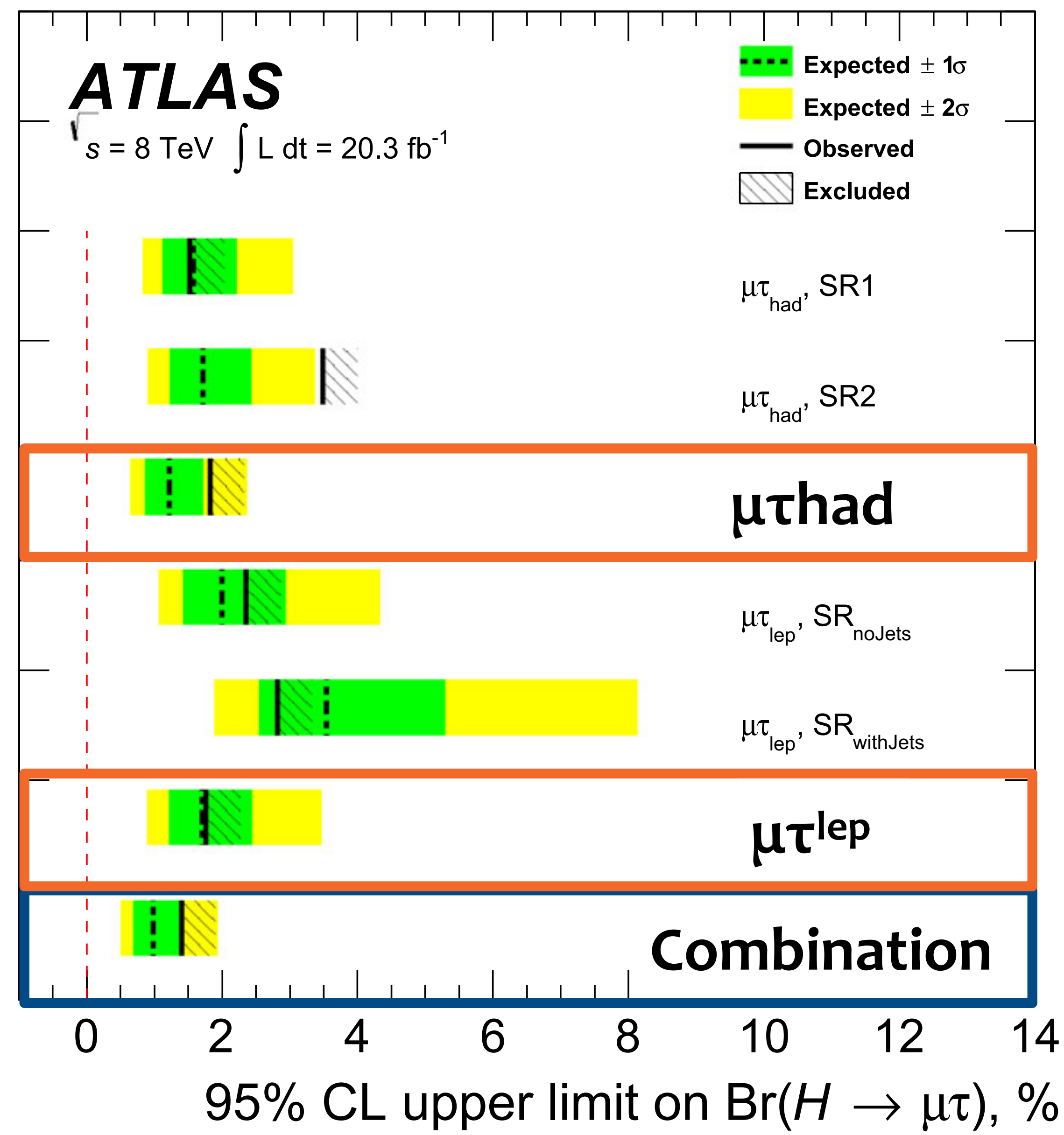
Exp lim $1.48^{+0.60}_{-0.42}$ %

Obs lim 1.36 %



$H\to\ell\tau$ combination





Br($H\to e\tau$) < 1.04 %

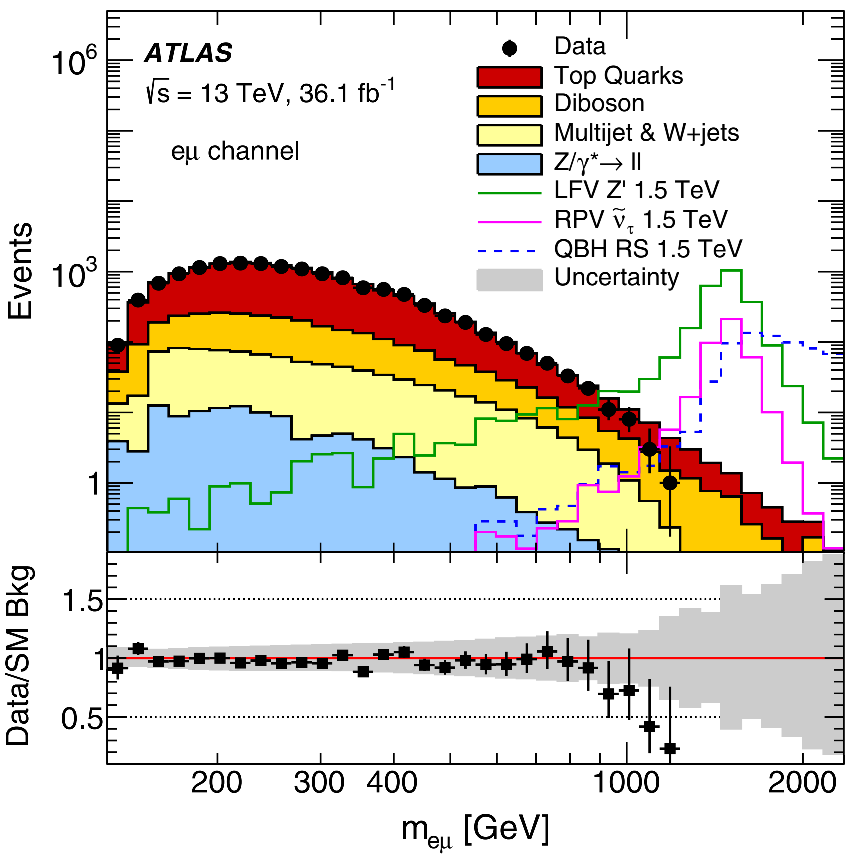
Br($H\to\mu\tau$) < 1.43 %

High-mass resonances

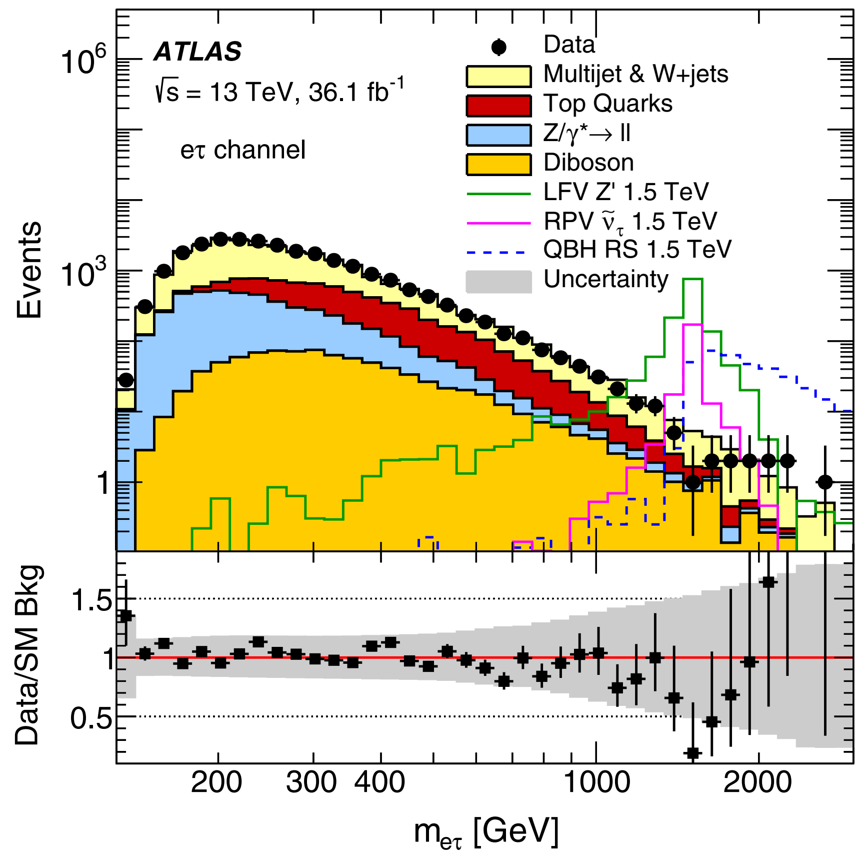
Three BSM models:

- *Z'* (same quark couplings as *Z*, one cLFV mode at a time)
- τ sneutrino coupled to 1st gen. quarks (RPV SUSY)
- Quantum black holes (*QBH*)

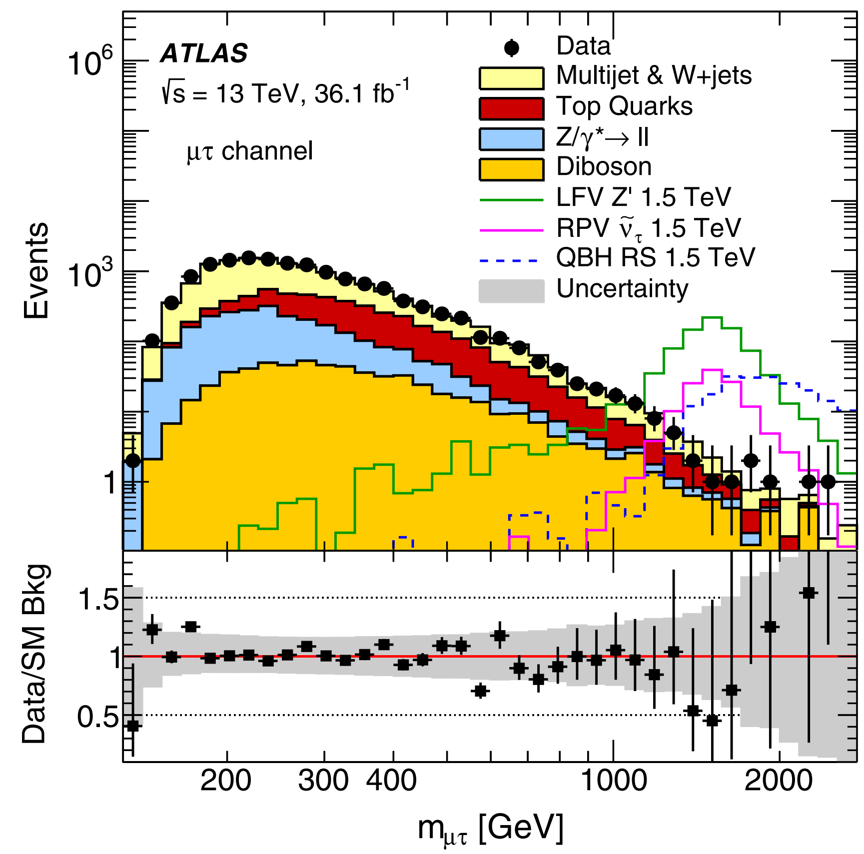
eμ



eτ

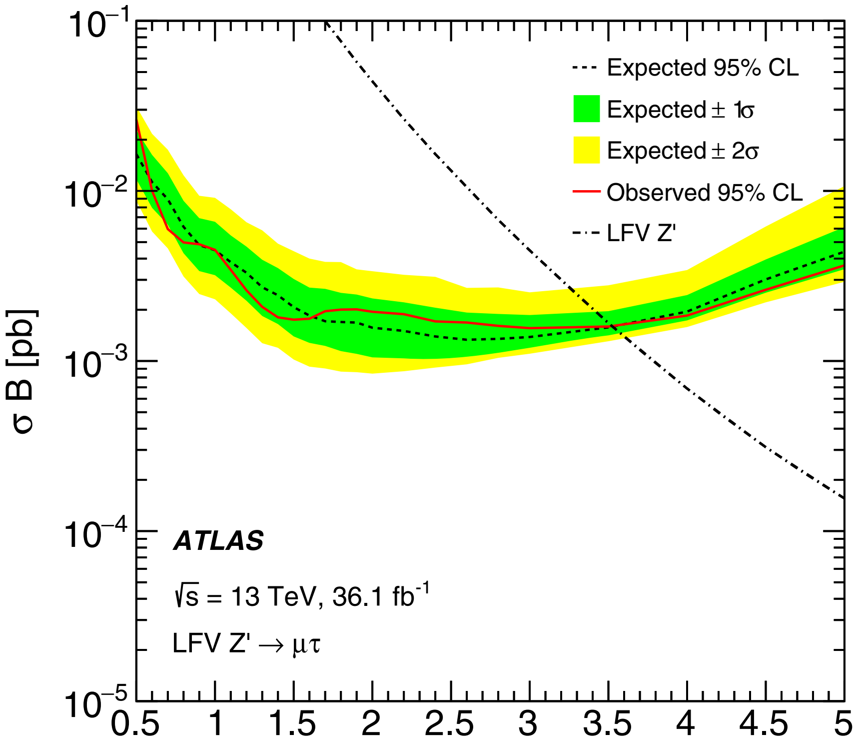


μτ

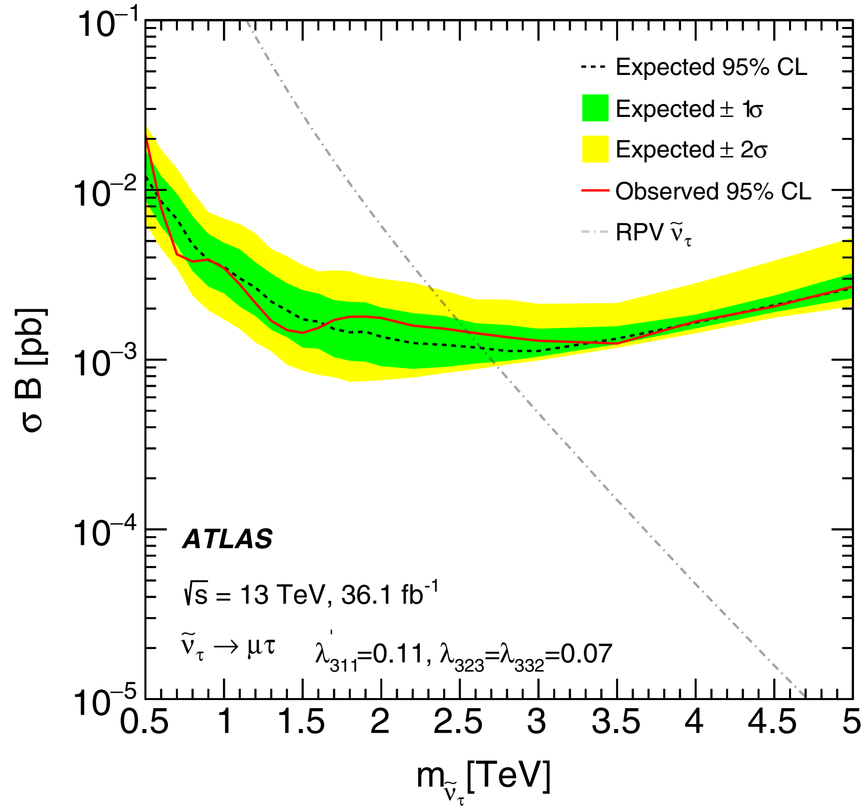


95% credibility level upper limits on cross sections

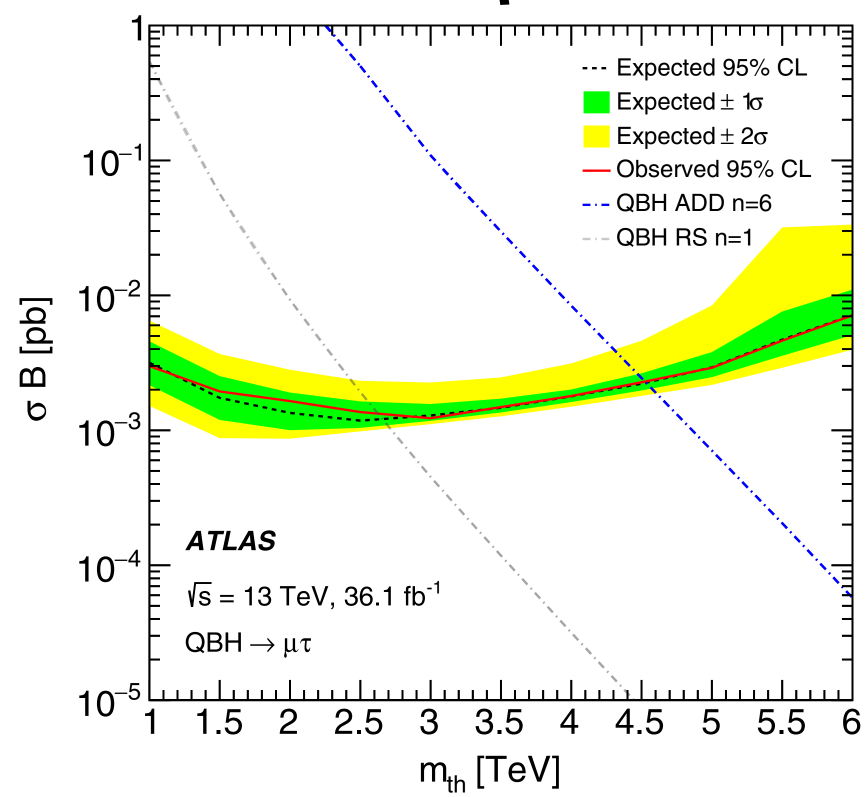
Z'



$\tilde{\nu}_\tau$

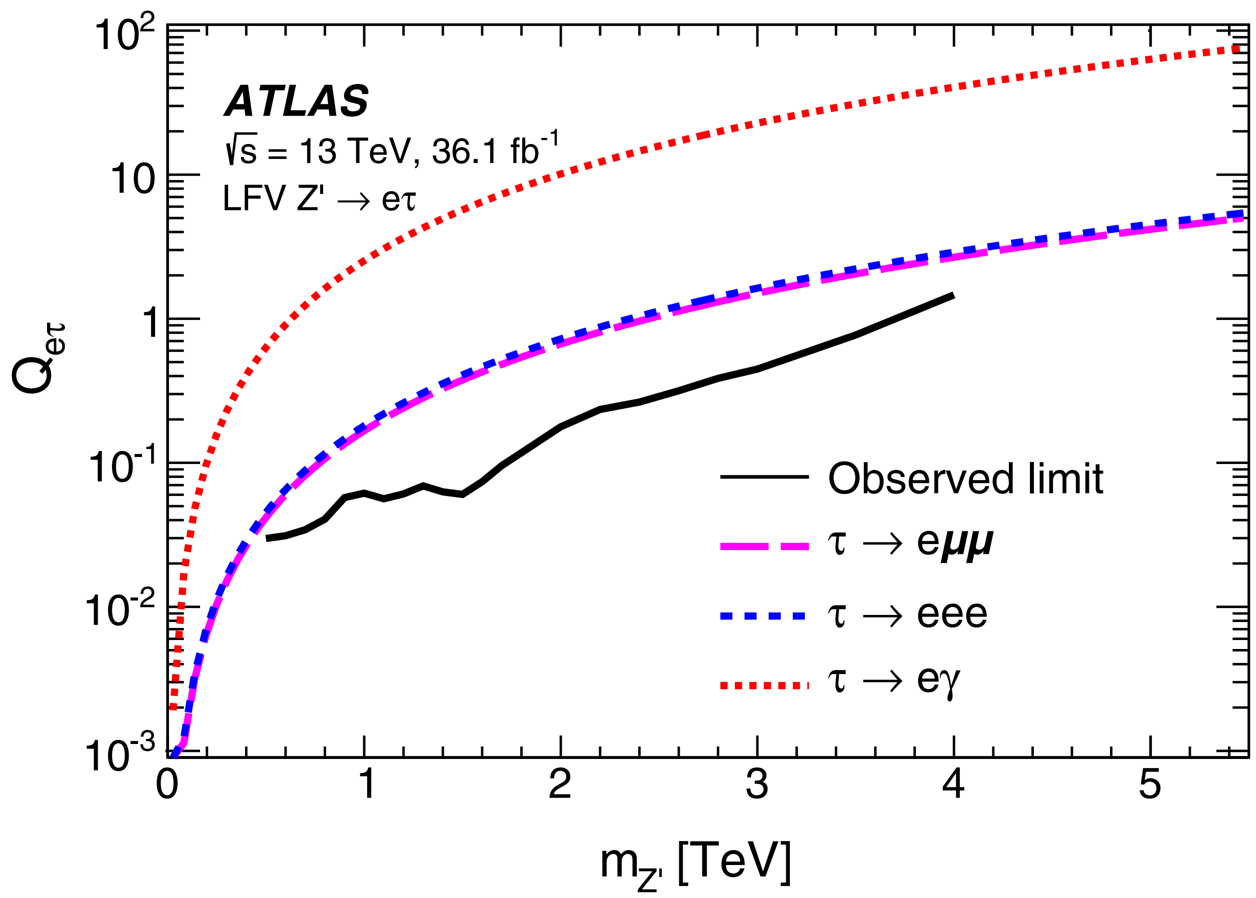


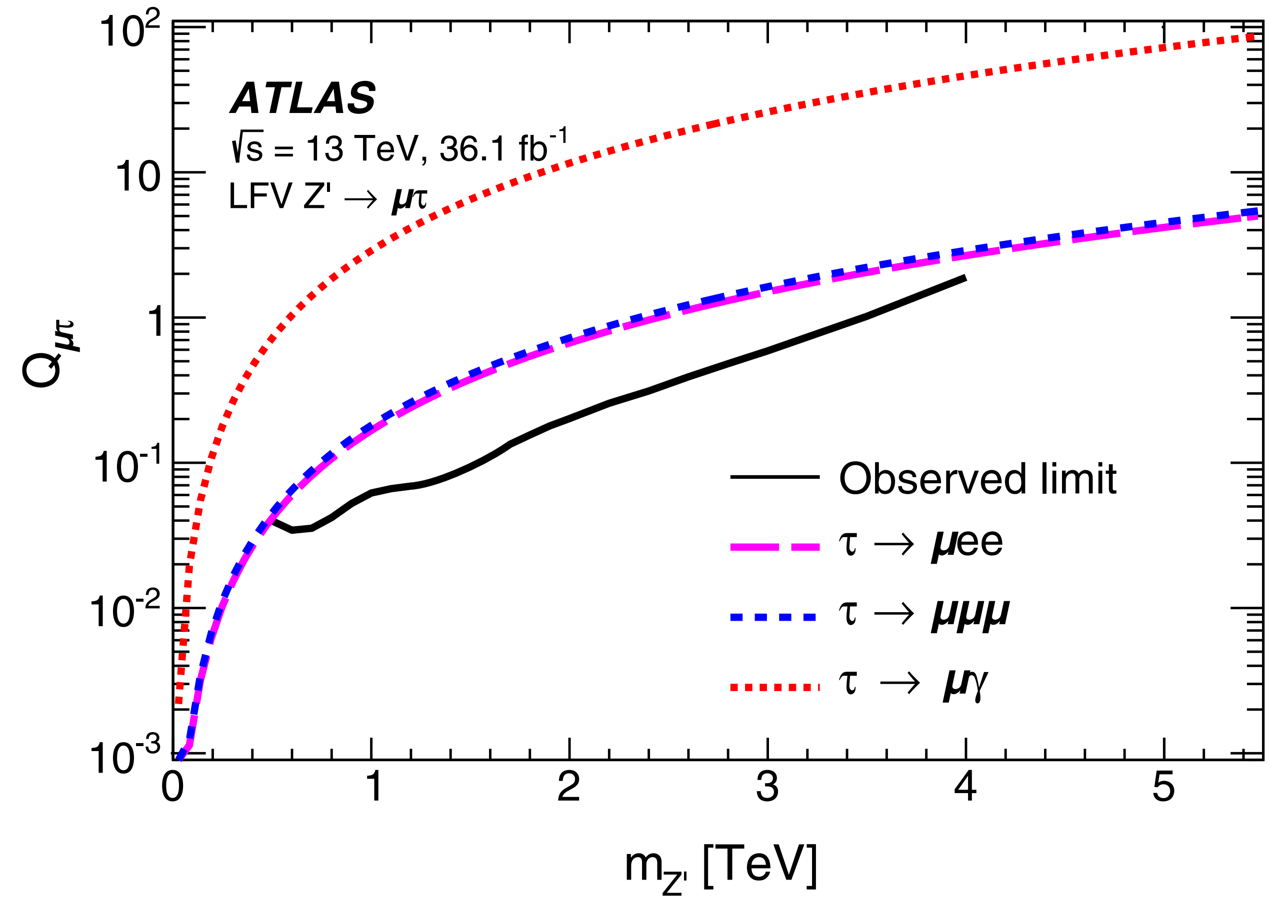
QBH



High-mass resonances

Stronger bounds on τ final states than those from low energy experiments





cLFV in top-quark decays

"the top could decay to a jet $+e\bar{\mu}$ with a branching ratio of order 10^{-3}. We estimate that the currently available LHC data (20 fb^{-1} at 8 TeV) could be sensitive to $BR(t \to e\bar{\mu} + \text{jet}) \sim 6 \times 10^{-5}$ ... "

Davidson *et al.*,
Eur. Phys. J. C75 (2015) no. 9, 450

"The dominant tree-level effects of LQ's to the rare LFV top decays $t \to \ell_i^+ \ell_j^- u_k$ can be summarized as ...
Currently no dedicated searches exist for such signatures, ... "

Doršner *et al.*,
Phys. Rept. 641 (2016) 1-68

...

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ATLAS EXPERIMENT

ATLAS CONF Note

ATLAS-CONF-2018-044

13th September 2018

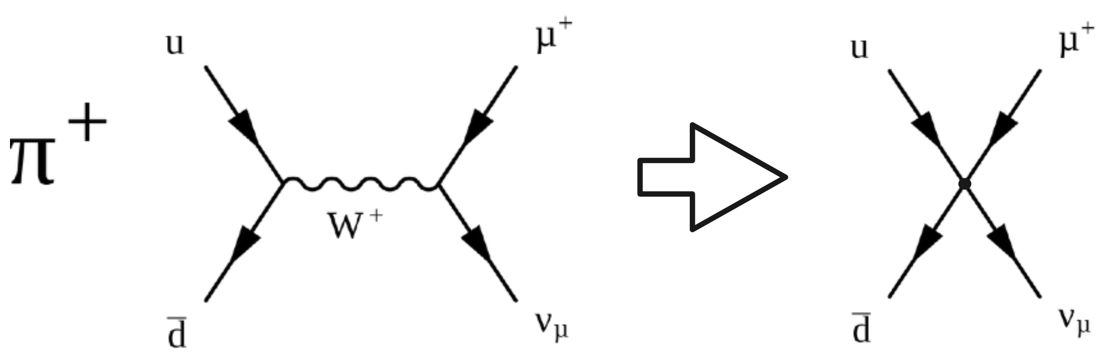
CERN

Search for charged lepton-flavour violation in top-quark decays at the LHC with the ATLAS detector

https://cds.cern.ch/record/2638305/

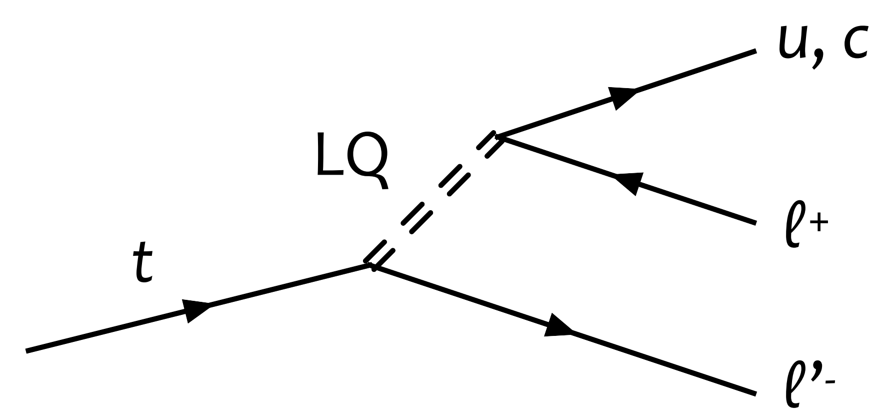
Search for t→ ℓℓ'q

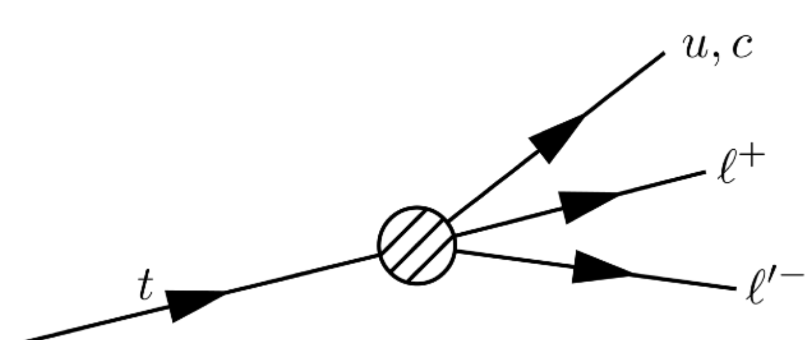
- t→ ℓℓ'q mediated by BSM particle
- No unexpected particle observed at the LHC
- Heavy new physics can be probed indirectly
- Remember the weak theory without the W boson:



$$\Delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}(\bar{u}\gamma^{\alpha}P_L d)(\bar{\mu}\gamma_{\alpha}P_L\nu)$$

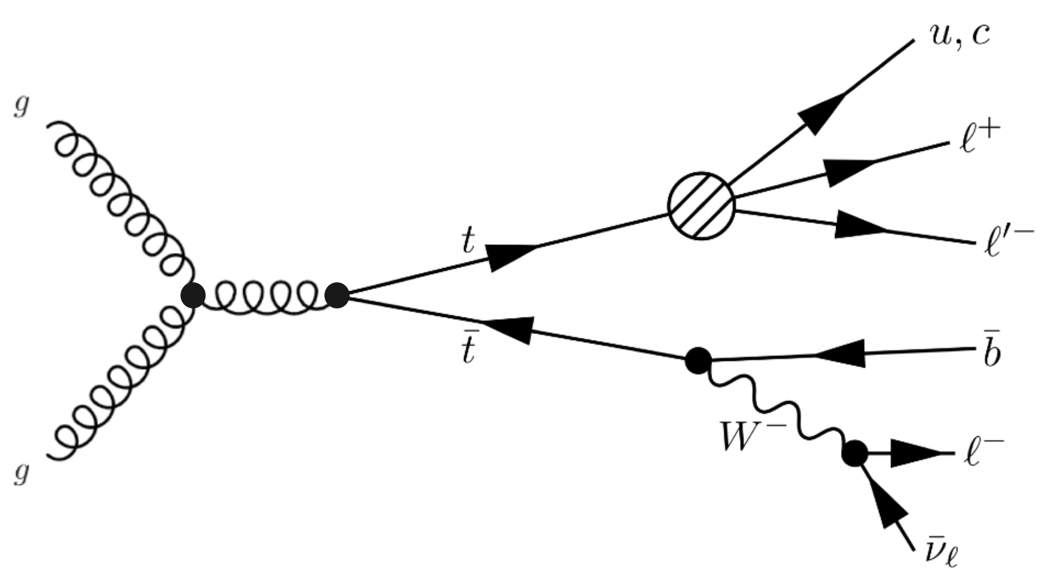
$$G_F \sim \frac{1}{M_W^2}$$





Model independent

Signal process



$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} \mathcal{O}_k^{(6)}$$

$$\mathcal{O}_{LL}^{AV} = (\bar{e}_i \gamma^\alpha P_L e_j)(\bar{u}_q \gamma_\alpha P_L t)$$

$$\mathcal{O}_{L}^{S+P} = (\bar{e}_i P_L e_j)(\bar{u}_q P_L t)$$

$$\mathcal{O}_{L}^{LQ} = (\bar{u}_q P_L e_j)(\bar{e}_i P_L t)$$

Signal process:

$pp \rightarrow t\bar{t} \rightarrow (\ell\ell' q)\ (W(\ell\nu))$ with $\ell = e, \mu, \boldsymbol{\tau}$

Br $(t \rightarrow e\mu q) \lesssim 3.7 \times 10^{-3}$

Final state probed:

= 3ℓ with $\boldsymbol{\ell = (e, \mu)}$, ≥ 2 jets, 1 *b*-jet, E_T^{miss}

How to generate events:

- FeynRules
- Madgraph5_aMC@NLO
- Pythia8 + EvtGen
- Geant4

Regions definition

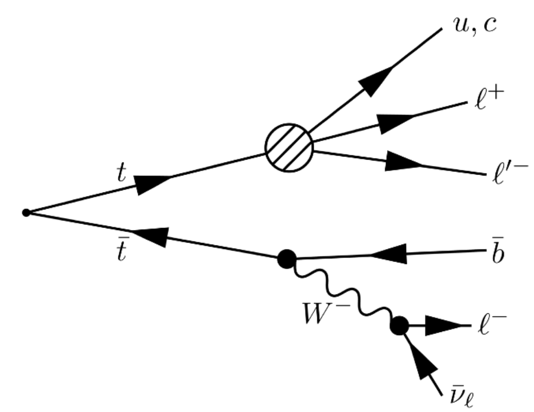
Event selection

=3 light leptons,

Z-veto (20 GeV wide), $m_{\ell\ell OS} > 15$ GeV

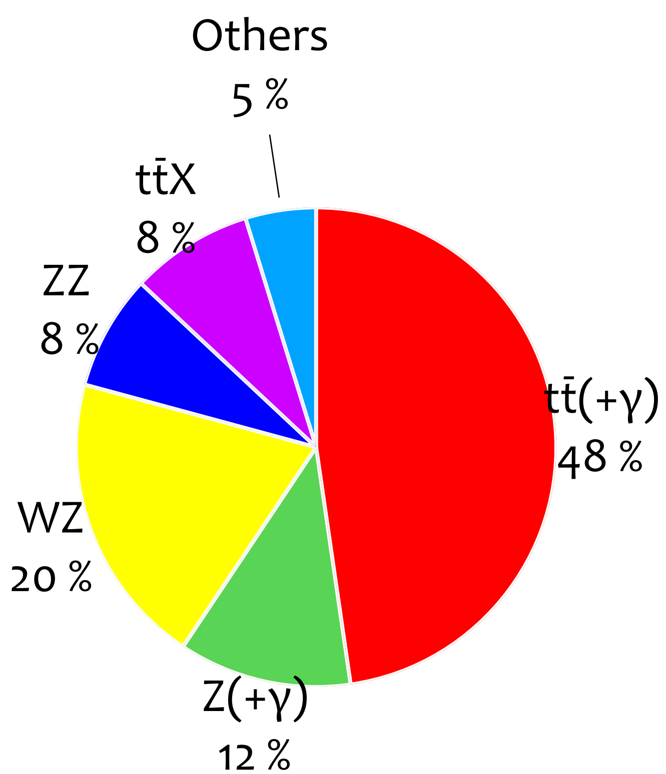
≥ 2 jets, ≤1 *b*-jet,

∑ lep. charges = ± 1.



Signal Region

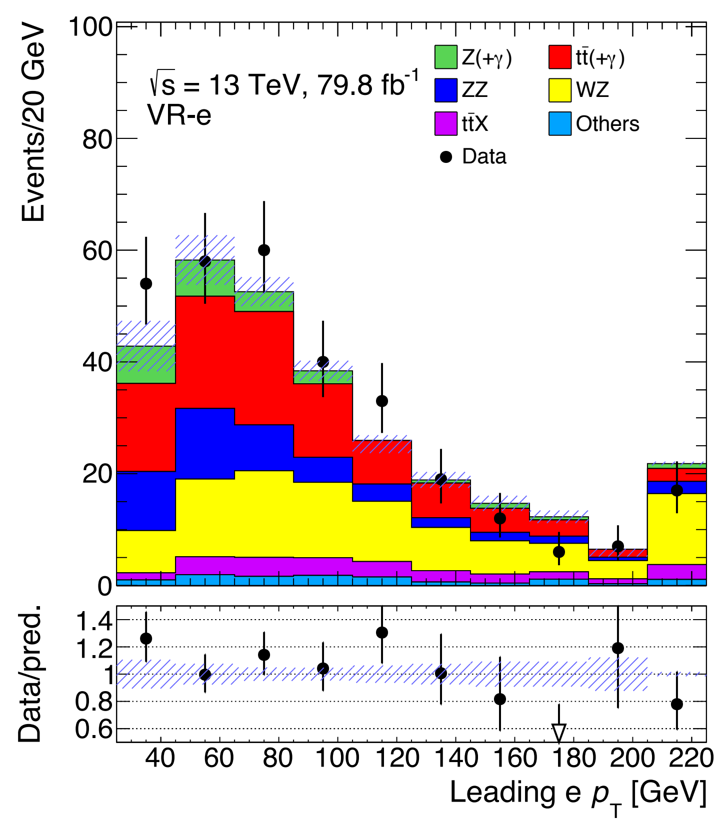
$N_e \geq 1$ & $N_\mu \geq 1$



tt̄X = tt̄Z, tt̄W, tt̄H

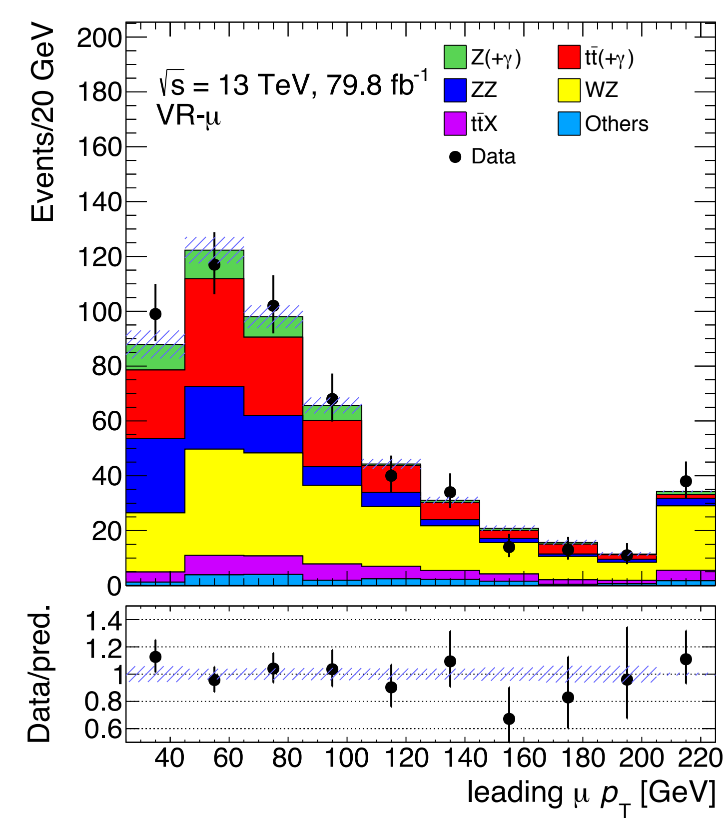
VR-e

$N_e = 3$



VR-μ

$N_\mu = 3$



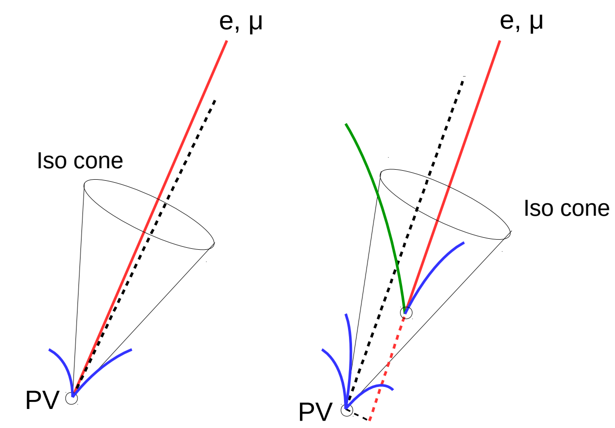
stat. only unc.

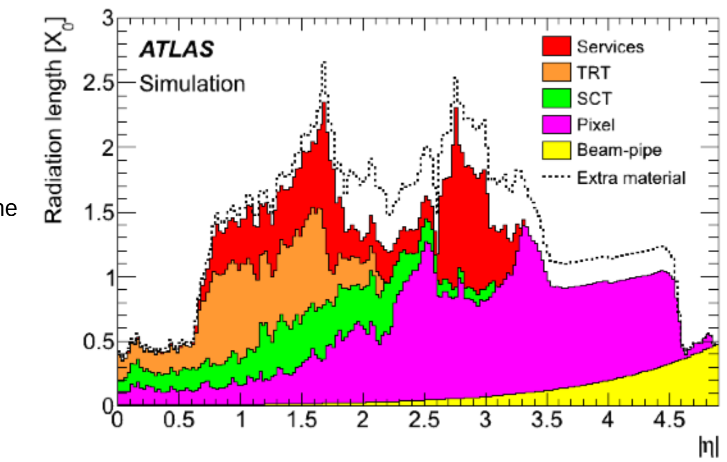
Major non-prompt lepton background in all regions.

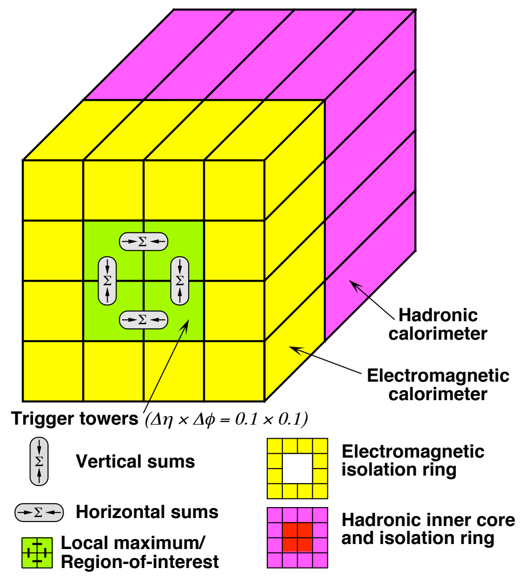
Non prompt lepton background

Non-prompt lepton origin:

- hadron decays (mostly *c*- and *b*-hadrons)
- γ-conversion in the detector material







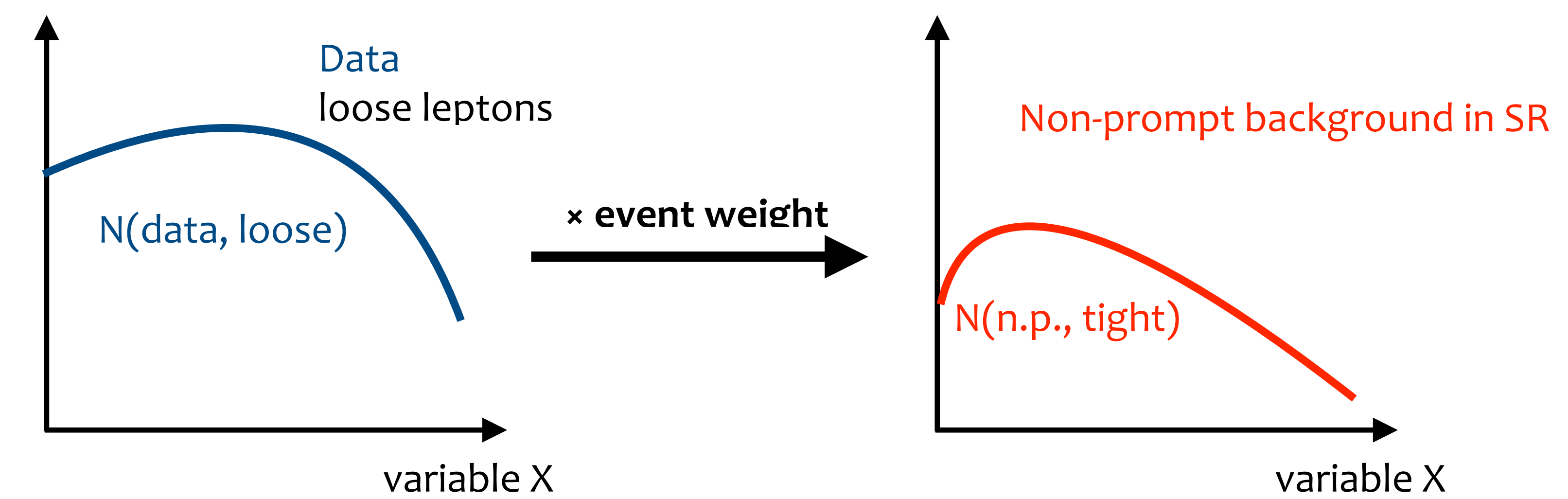
Background suppression?

- by isolation requirements at track or calorimeter level
- ... but "tight isolation" already applied

Modelling

- background dependent on details of particles' interaction
- MC simulation not completely reliable
- data driven estimate preferable

Goal:



Lepton jargon:
tight = isolated
loose = no isolation req.

How?

$$\begin{pmatrix} N_{TT} \\ N_{T\bar{T}} \\ N_{\bar{T}T} \\ N_{\bar{T}\bar{T}} \end{pmatrix} = \begin{pmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{pmatrix} \begin{pmatrix} N^{TT}_{RR}/rr \\ N^{TT}_{RF}/rf \\ N^{TT}_{FR}/fr \\ N^{TT}_{FF}/ff \end{pmatrix}$$

Number of events with 1 tight leptons and 1 not-tight

r (f) = **matrix method efficiencies,**
probability of a loose prompt (n.p.) lepton of being tight

Number of events with 2 tight leptons, one **prompt** one **n.p.**

Inverting the matrix: $N_F = N_{RF} + N_{FR} + N_{FF}$

Inverting the matrix for each event → event weight

The MM efficiencies

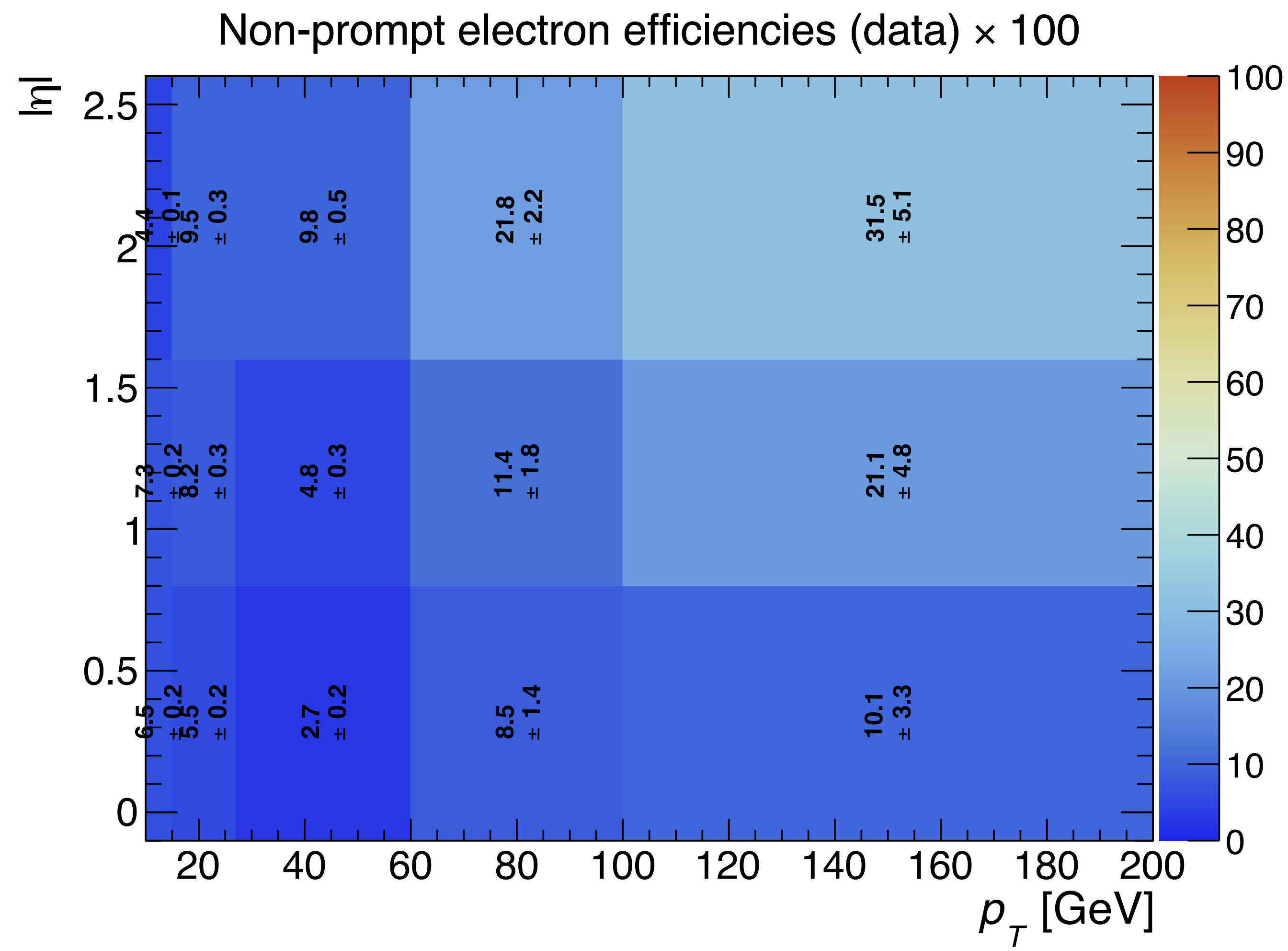
- **2ℓ regions, tag&probe**
  probe = trailing lepton

- **Opposite-Sign, “prompt enriched”**

$$r = \frac{N_T}{N_L}$$

- **Same-Sign, “n.p. enriched”**

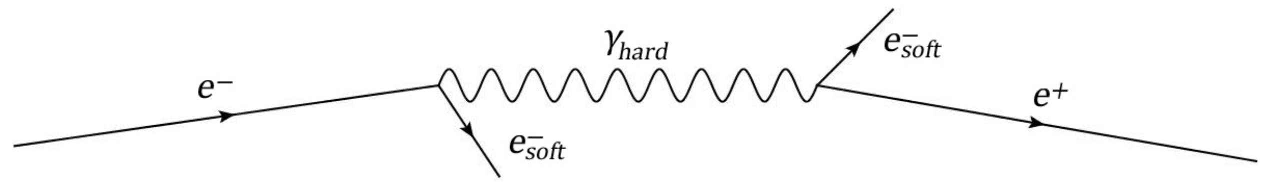
$$f = \frac{N_T - N_T^{CF} - N_T^{MCprompt}}{N_L - N_L^{CF} - N_L^{MCprompt}}$$



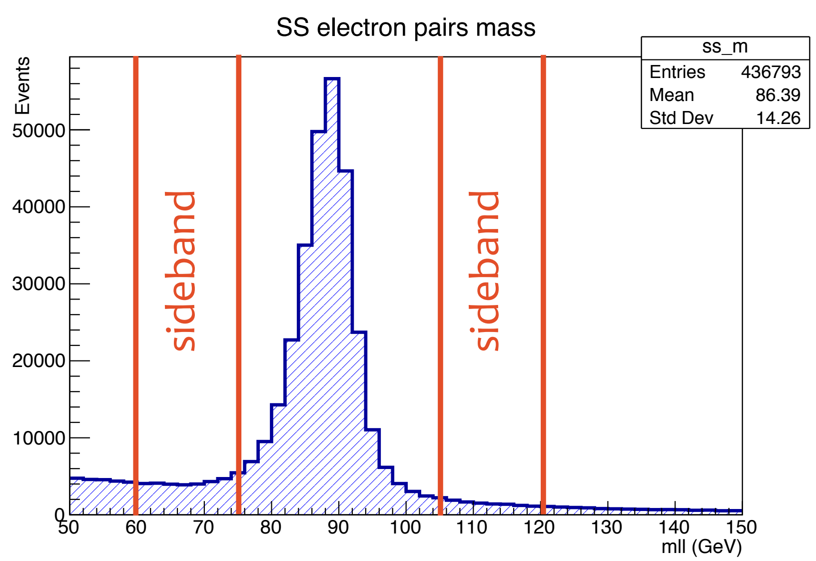
Prompt lepton contamination,
estimated from simulation

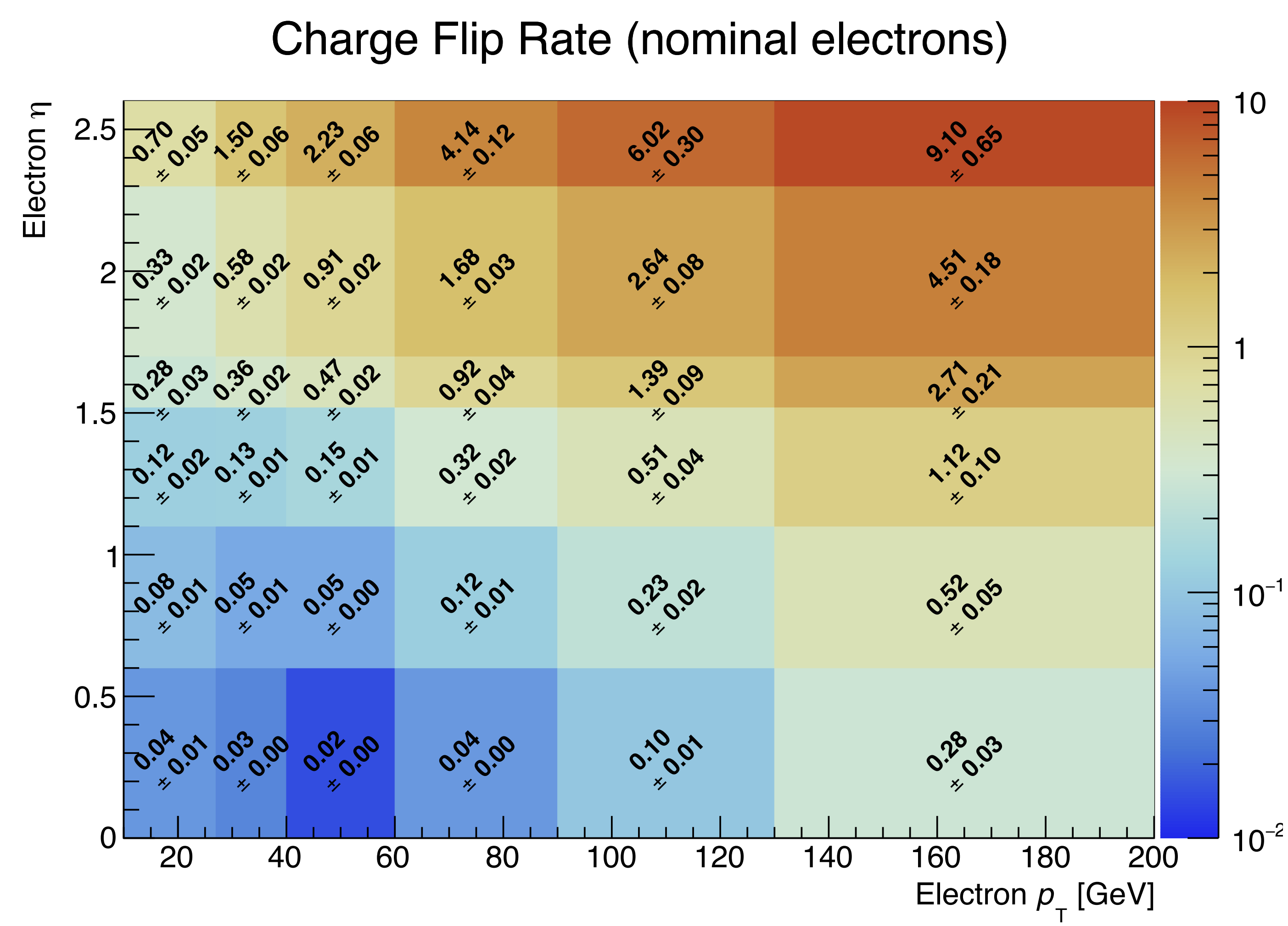
Electron charge flip (CF) **cont.**
via reweighing of OS events

The charge flip rates



- Z-boson peak in SS and OS di-electron invariant mass





- Fit charge flip rates ϵ

$$L = \prod_{ij} \frac{((\epsilon_i + \epsilon_j)N_{ij})^{N_{ij}^{ss}}}{N_{ij}^{ss}} e^{(\epsilon_i + \epsilon_j)N_{ij}}$$

The matrix method application

Complication:

events are selected by trigger requiring isolation
cannot ask for three loose leptons!

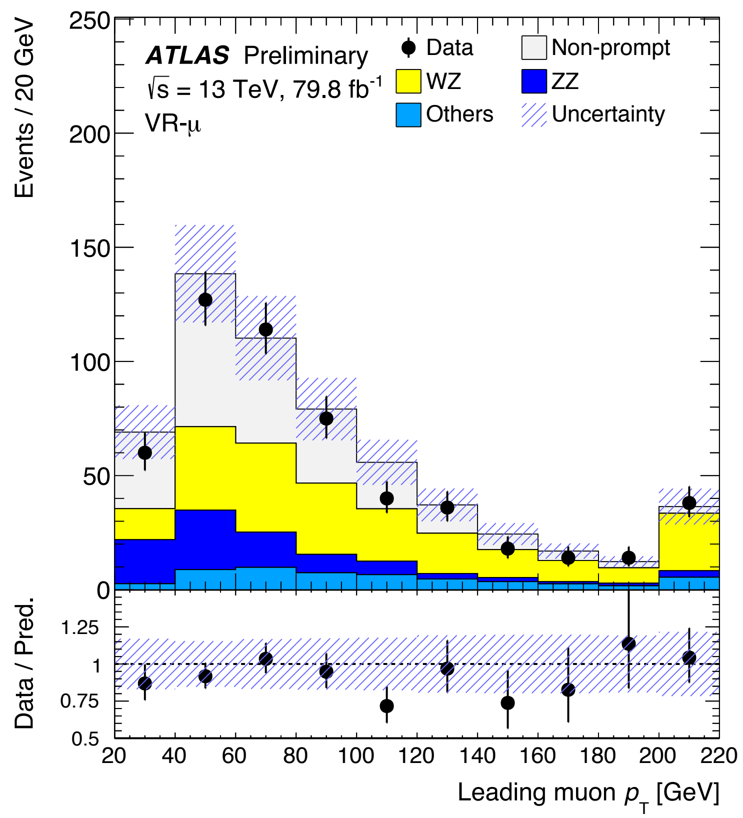
Solution:

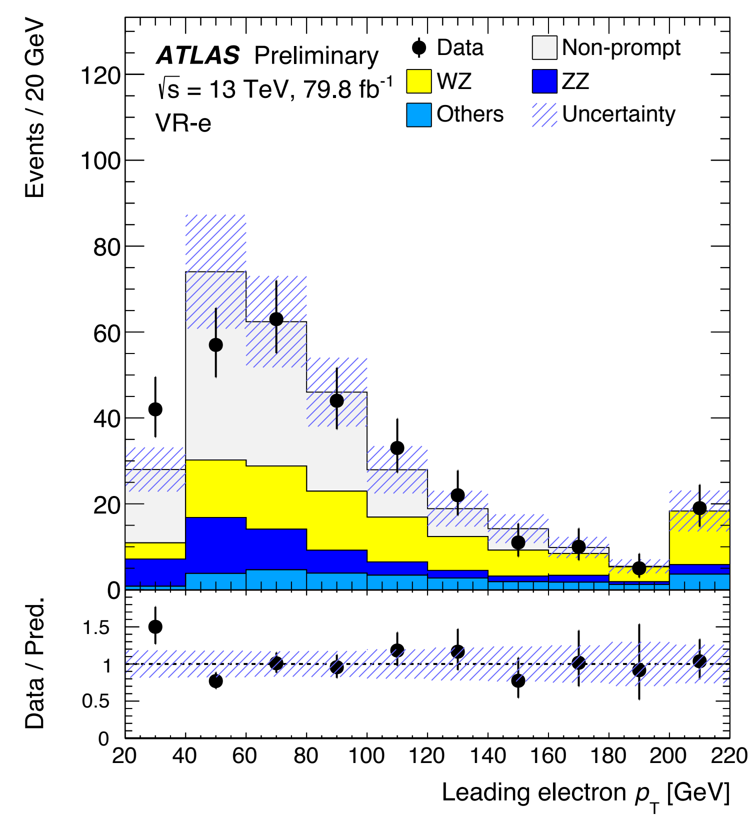
- consider only the 2nd and 3rd leading leptons
- …assumed not to be matched to a trigger requiring isolation (true in 88% of $t\bar{t}$ in SR)

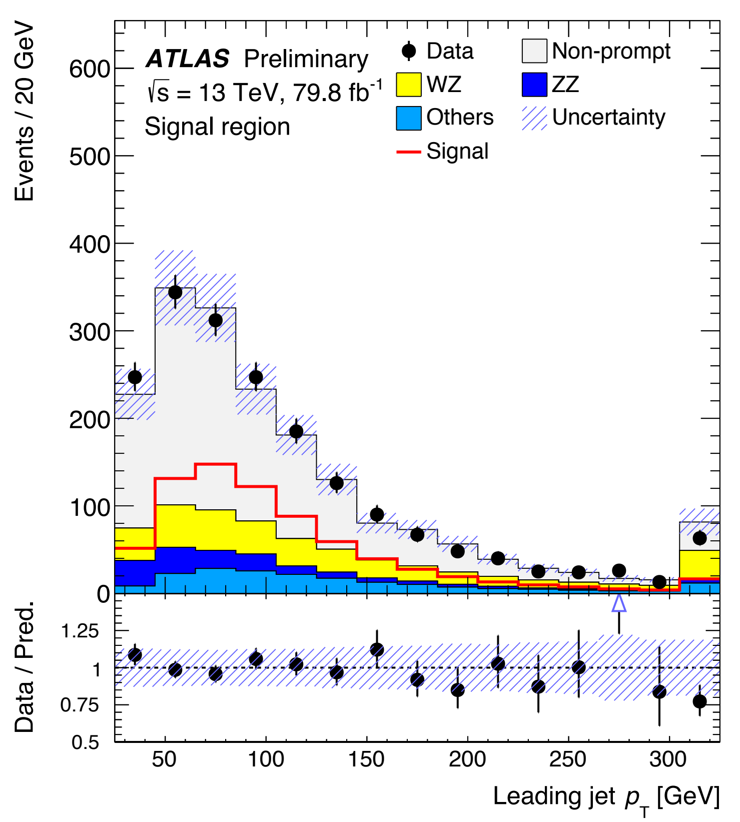
That's why matrix for 2ℓ only is shown, although there are 3 leptons!

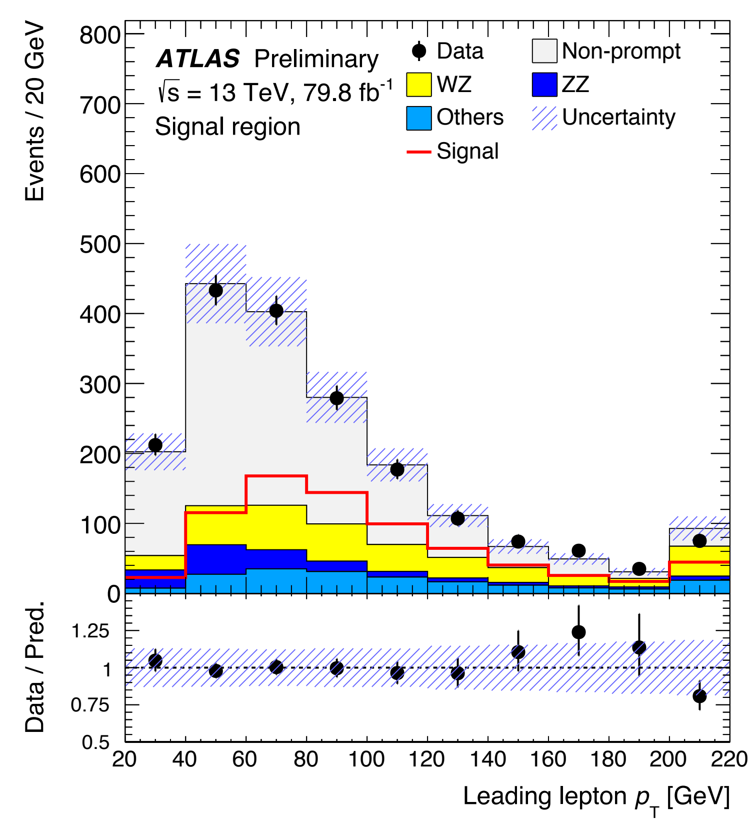
$$\begin{pmatrix} N_{TT} \\ N_{T\bar{T}} \\ N_{\bar{T}T} \\ N_{\bar{T}\bar{T}} \end{pmatrix} = \begin{pmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{pmatrix} \begin{pmatrix} N_{RR}^{TT}/rr \\ N_{RF}^{TT}/rf \\ N_{FR}^{TT}/fr \\ N_{FF}^{TT}/ff \end{pmatrix}$$

Modelling





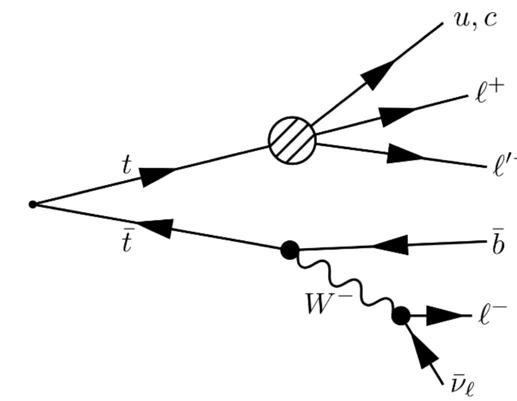


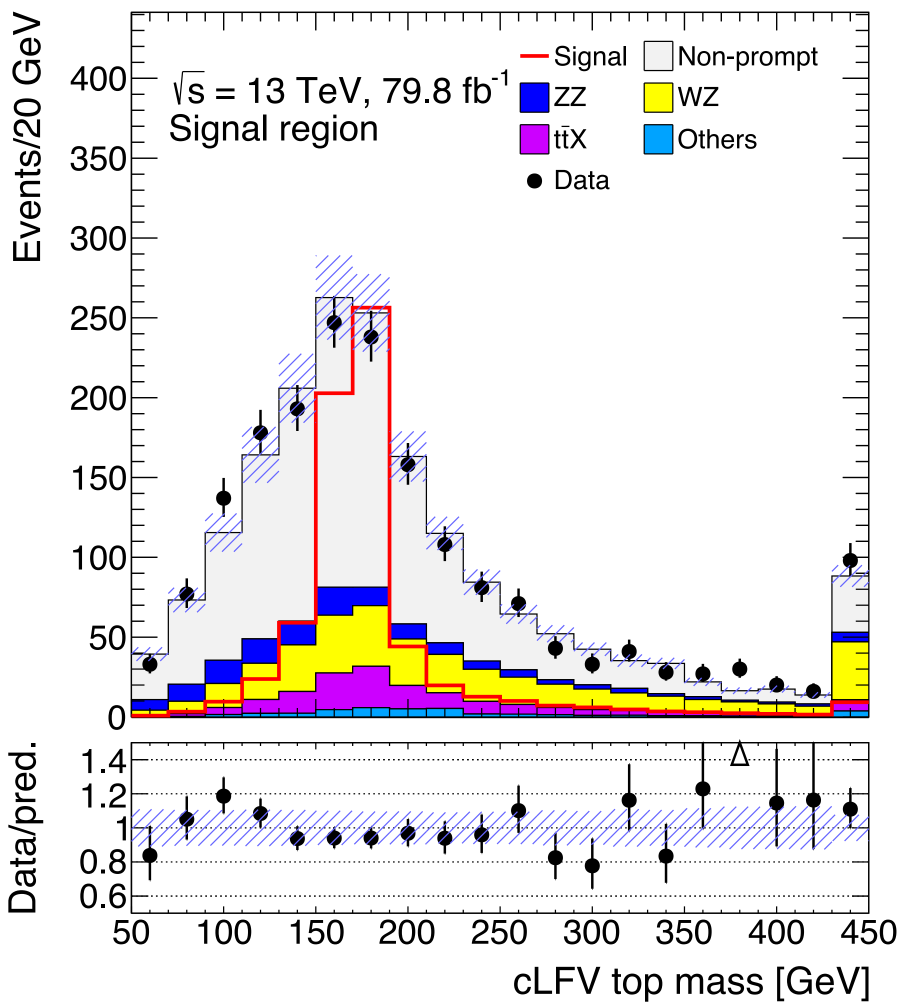


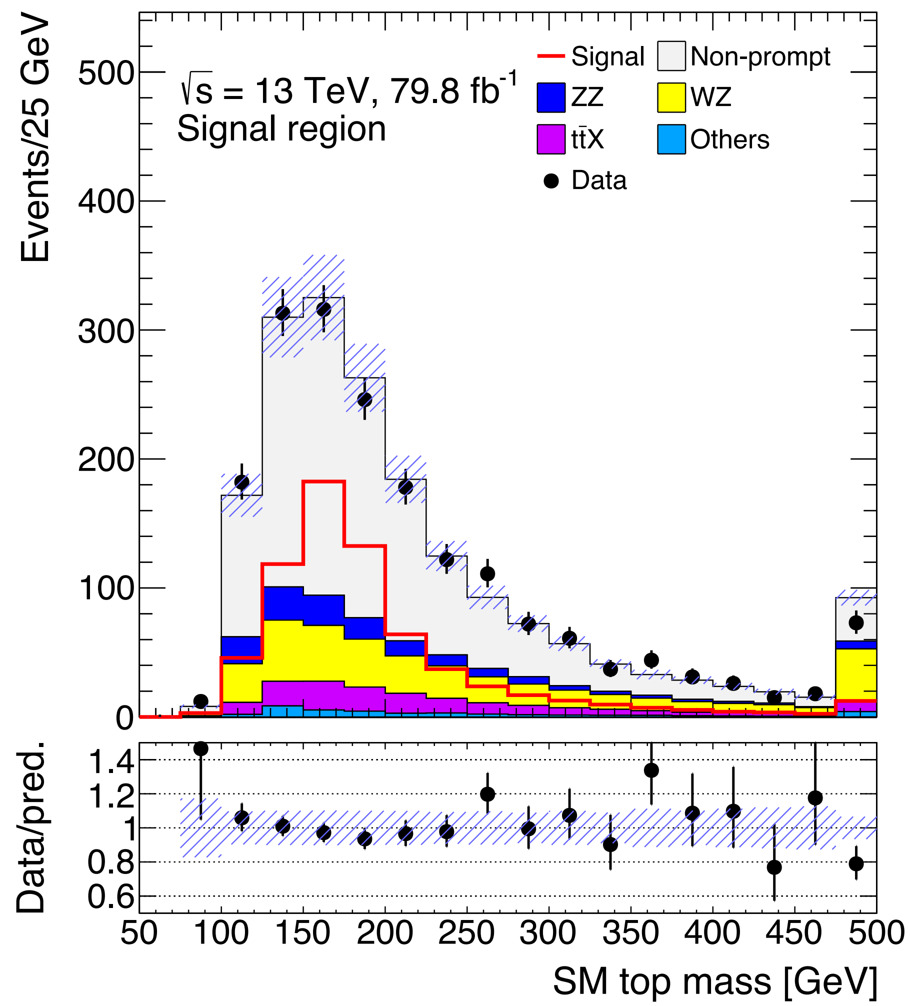
All syst. included
$Br(t \to \ell\ell' q) = 3 \times 10^{-4}$

Kinematic reconstruction

- the jet with highest b-tagging probability assigned to SM top
- cLFV top = OSDF lepton pair + jet with min(√s - m_t)
- SM top = reserved jet + remaining lepton + neutrino





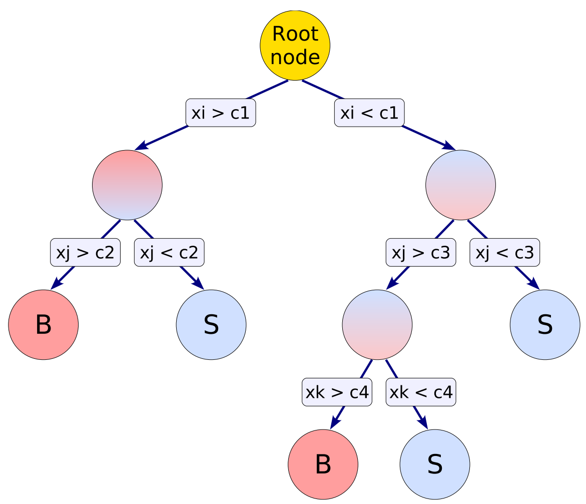


Stat. + 10% syst on Non-prompt
Br(t→ℓℓ'q) = 3 × 10^{-4}

MVA discriminant

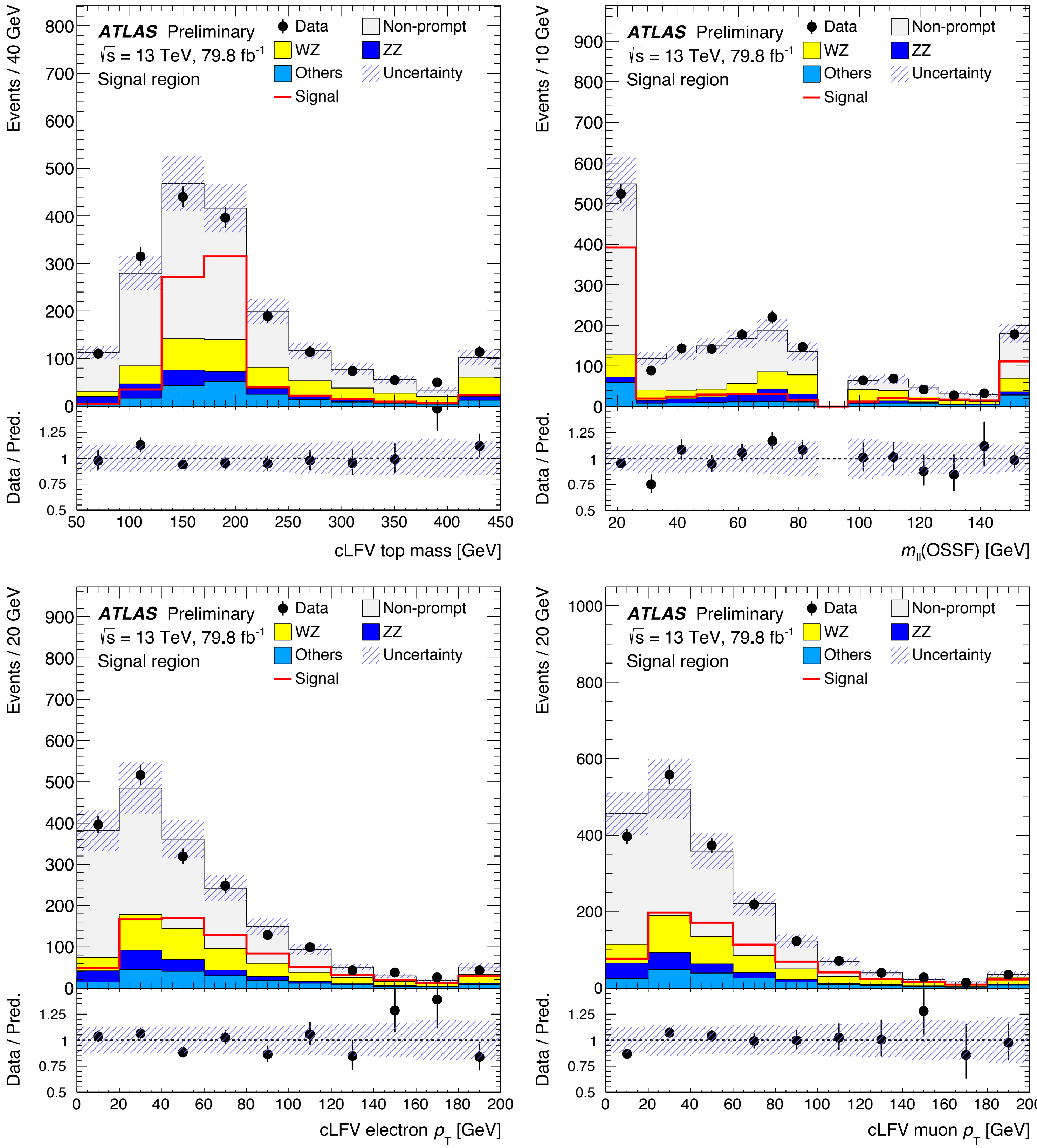
BDT trained on MC

1000 trees, tree depth 3



13 input variables

Variable	Separation (%)
OSSF lepton pair invariant mass	11
cLFV top mass	10
p_T of the electron associated to the cLFV decay	9.1
p_T of the muon associated to the cLFV decay	8.5
p_T of the lepton associated to the SM decay	8.3
Scalar mass of all jets and leptons in the event	7.6
Same-sign electron pair invariant mass	6.9
Missing transverse momentum	6.8
Number of b-jets	6.7
W transverse mass associated to the SM top lepton	6.6
ΔR between the cLFV electron and the cLFV light jet	6.5
SM top mass	6.4
ΔR between the cLFV muon and the cLFV light jet	6.3
BDT discriminant	44



All syst. included, Br($t \rightarrow \ell\ell' q$) = 3 × 10^{-4}

Systematics

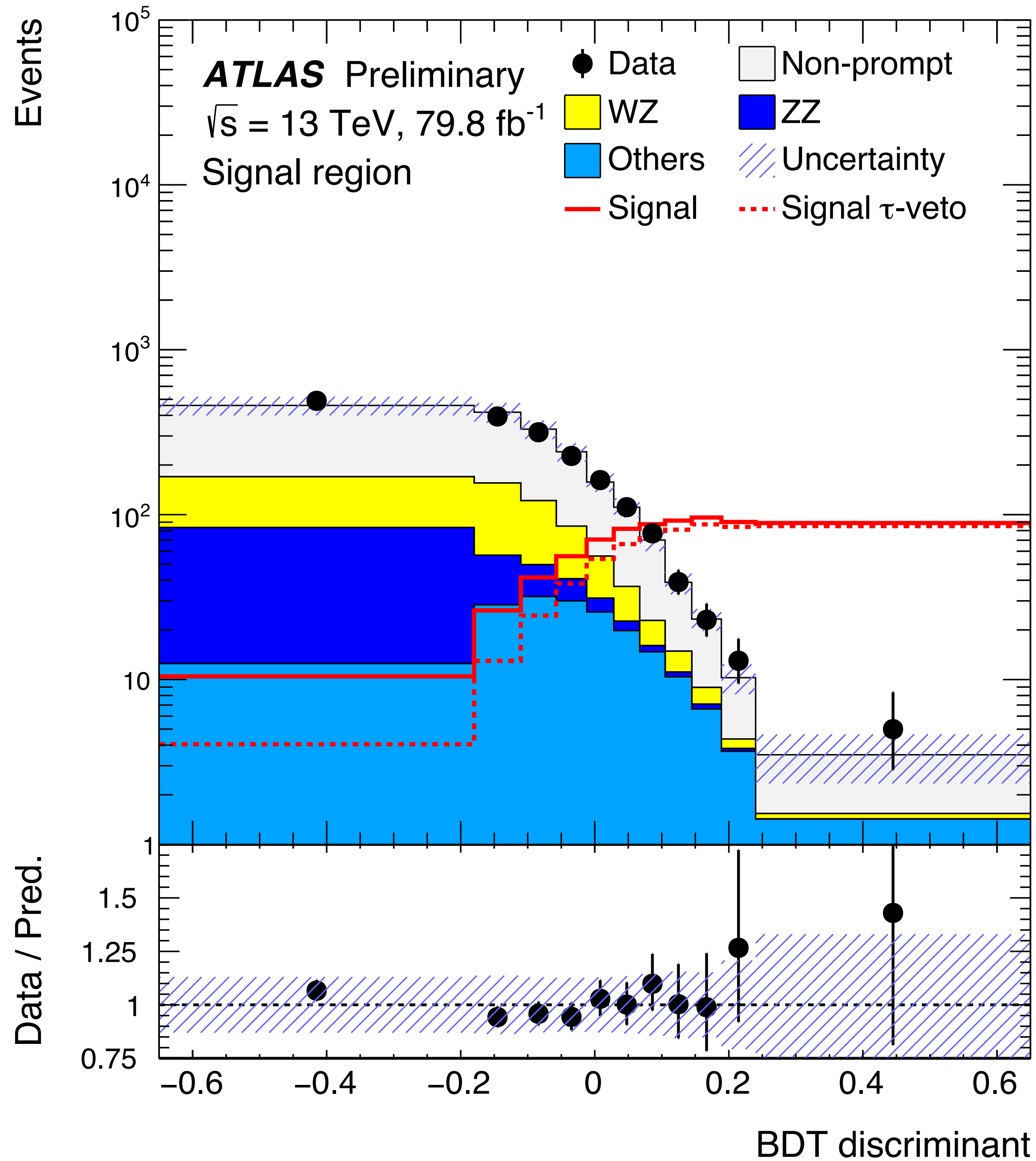
- Non-prompt background:

	Δnorm	components
non-closure	10 %	N
stat. unc. efficiencies	8.1 %	S+N
trigger matching assumption	6.5 %	S+N
stat. uncertainty	1.3 %	S+N
variation of 2ℓ-SS regions	3.2 %	S+N
prompt containation in 2ℓ-SS	2.6 %	S+N
efficiencies parametrisation	1 %	S+N
charge flip contamination	0.3 %	S+N
Total	15 %	

- Prompt background (MC)
  - cross section uncertainty,
  - μ_R, μ_F variations (~15% for WZ, ZZ),
  - VV modelling (35% WZ, 33% ZZ),
  - instrumental (2.2% variation of total background).

- Signal sample uncertainties
  - PDF + scale variations acceptance (±4.3%),
  - instrumental

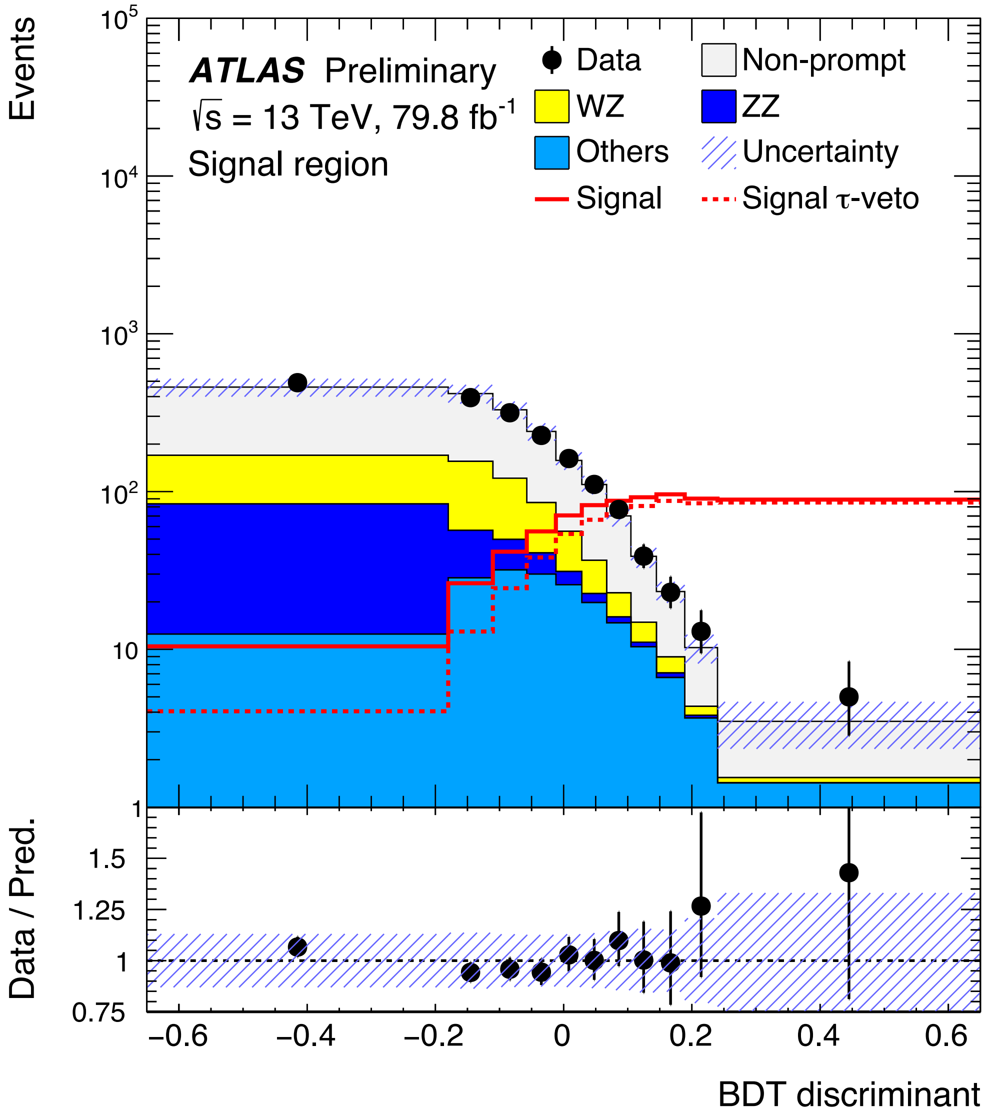
Results



$Br(t \rightarrow \ell\ell' q) = 3\times10^{-4}$

Non-prompt leptons	WZ	ZZ	$t\bar{t}V$	Other prompt SM	Expected events	Data
1190(180)	350(140)	140(52)	108(10)	76(10)	1860(230)	1857

Upper limits



Upper limit for t→ℓℓ’q:

$$\mathcal{B}(t \to \ell\ell' q) < 1.36^{+0.61}_{-0.37} \times 10^{-5} \quad \text{(expected)}.$$

$$\mathcal{B}(t \to \ell\ell' q) < 1.86 \times 10^{-5} \quad \text{(observed)}.$$

Upper limit for t→eμq (τ-veto in cLFV vertex):

$$\mathcal{B}(t \to e\mu q) < 4.8^{+2.1}_{-1.4} \times 10^{-6} \quad \text{(expected)}.$$

$$\mathcal{B}(t \to e\mu q) < 6.6 \times 10^{-6} \quad \text{(observed)}.$$

…to be compared to the indirect limit:

$Br(t \to e\mu q) < 3.7 \times 10^{-3}$.

Summary

- Four cLFV searches by ATLAS:
  - $H \to \mu\tau$
  - $H \to e\tau$
  - Heavy resonances
  - first direct search in the top sector

- Background estimation technique

…and now?

Conclusions - the big picture

Open questions:

- Nothing up to the Planck scale?
- Chasing models still worth?
- Where to look?

Some facts:

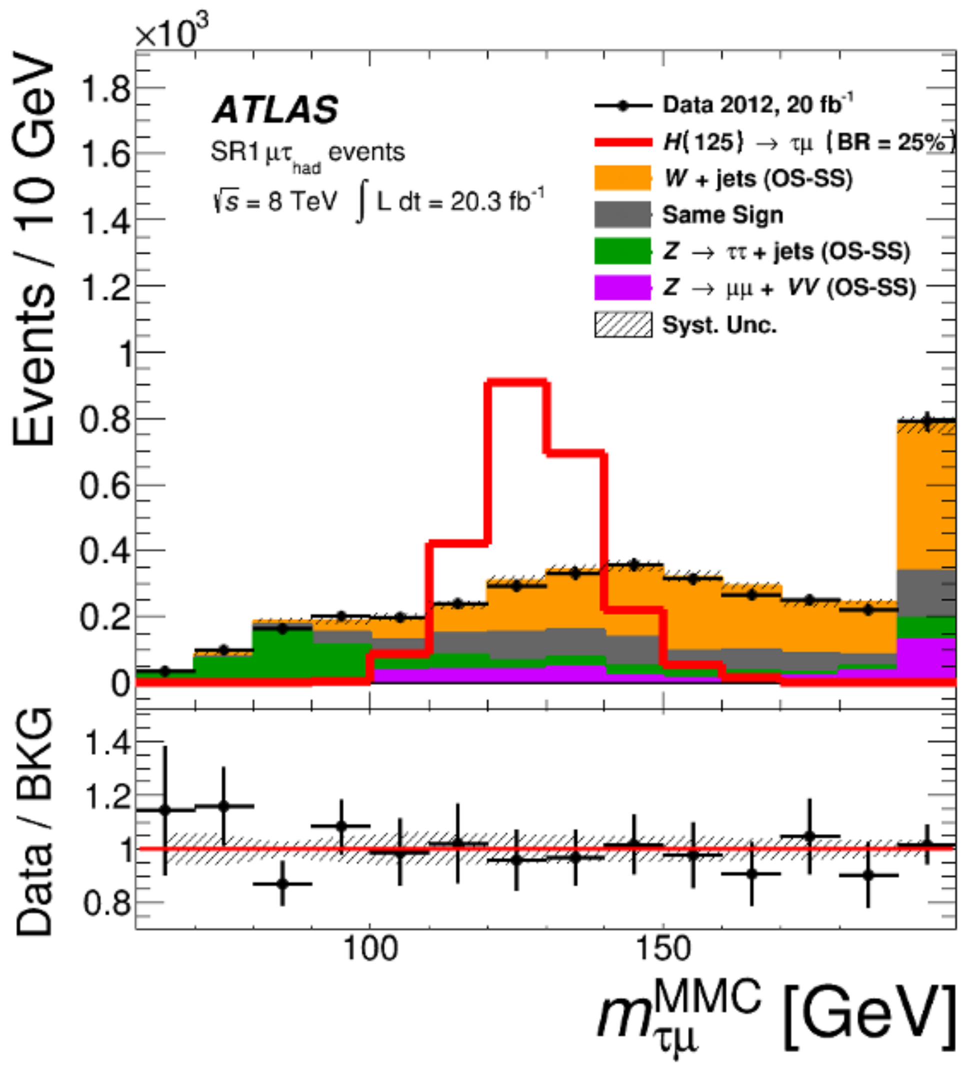
- BSM physics exists
- 140 fb^{-1} data sitting there
- “Nothing beats data” (T. Plehn, TOP2018)

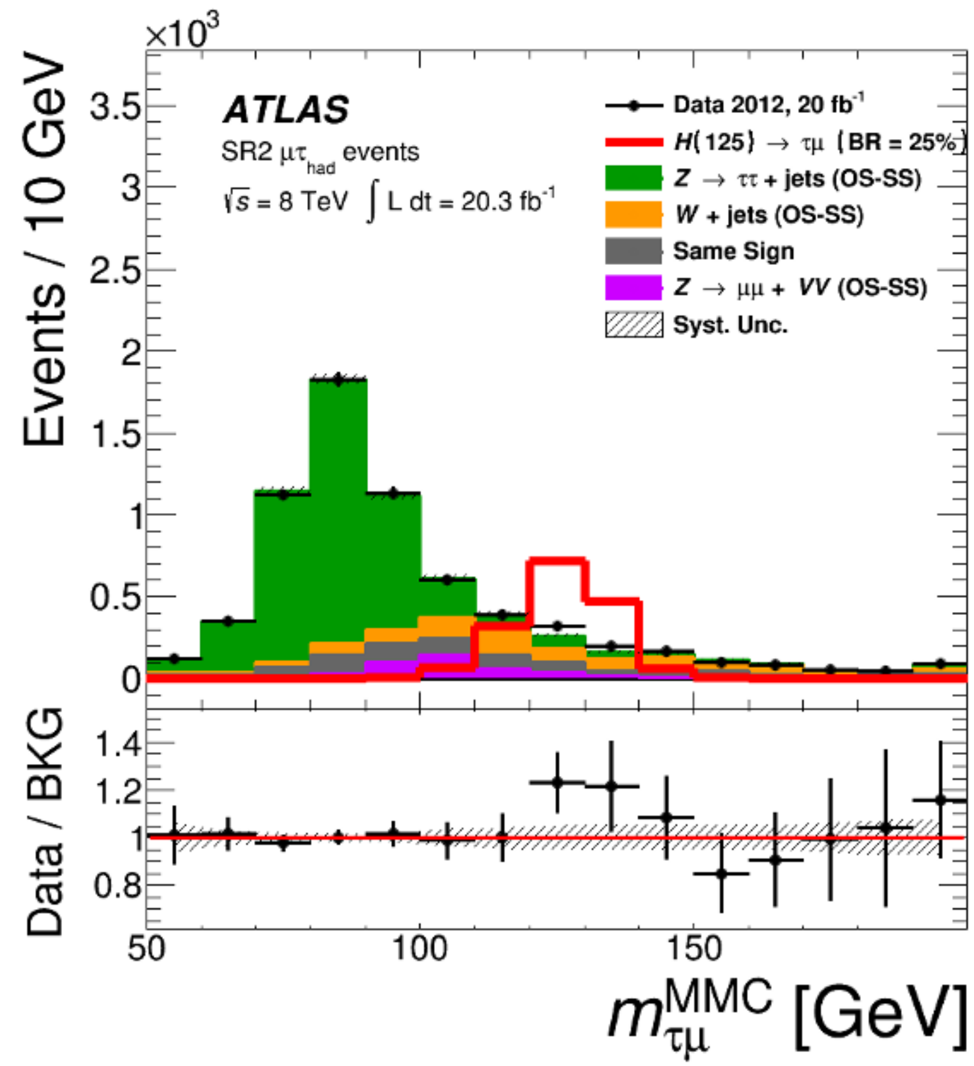
Strategy:

- Constrain EFT operators to bound heavy BSM physics
- Precision measurements for weakly coupled BSM physics

BACKUP

$H \to \mu\tau$





2.2σ local significance

CMS results

CMS $\sqrt{s}$ = 8 TeV, 19.7 fb^{-1}

- Br($h \to \mu\tau$) < 1.51%
  Expected 0.75 ± 0.38%
  Significance +2.4σ

1502.07400

ATLAS $\sqrt{s}$ = 8 TeV, 20 fb^{-1}

- Br($H \to \mu\tau$) < 1.43 %
- Br($H \to e\tau$) < 1.04 %

CMS $\sqrt{s}$ = 13 TeV, 35.9 fb^{-1}, BDT for μτ

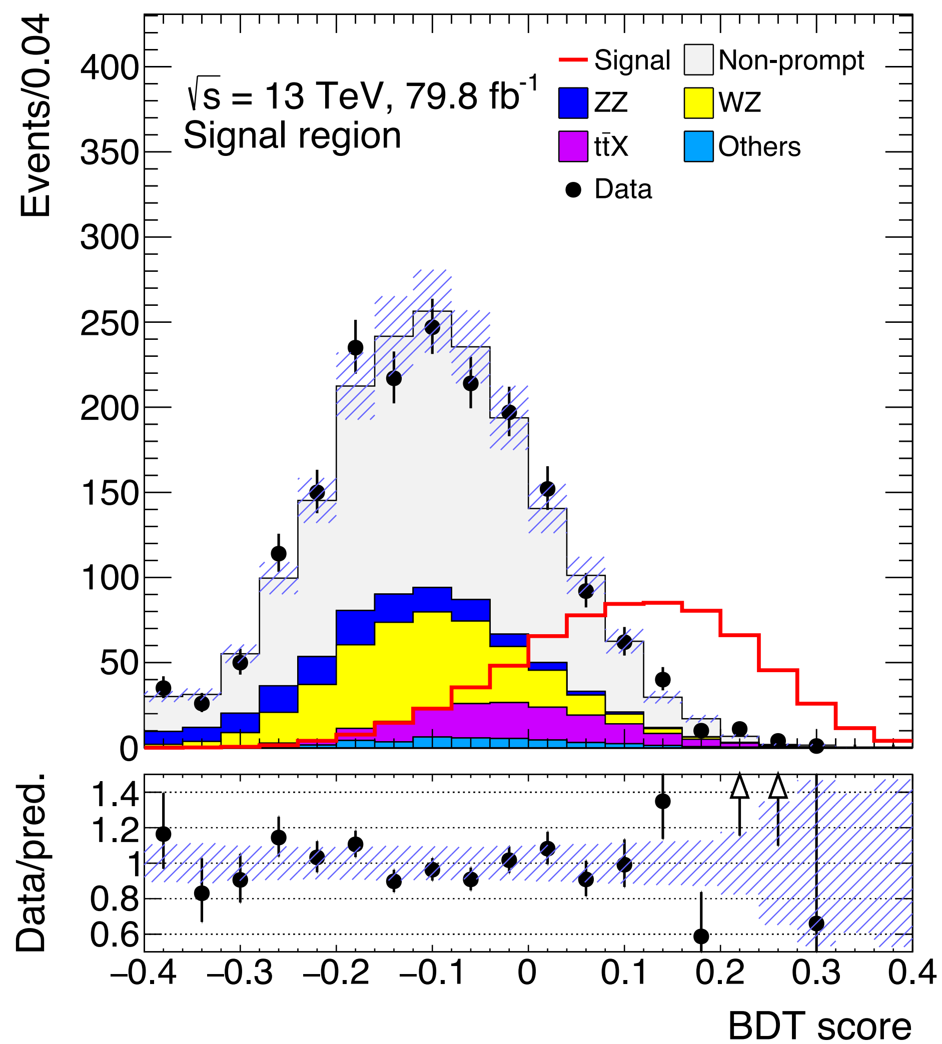
- Br($h \to \mu\tau$) < 0.25% (0.25%)
- Br($h \to e\tau$) < 0.61% (0.37%)

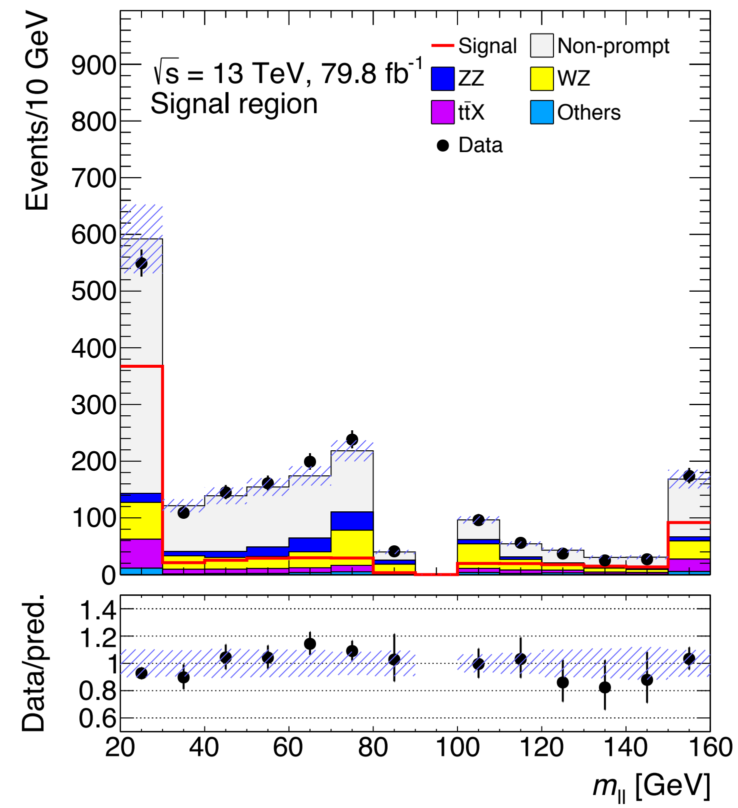
1712.07173

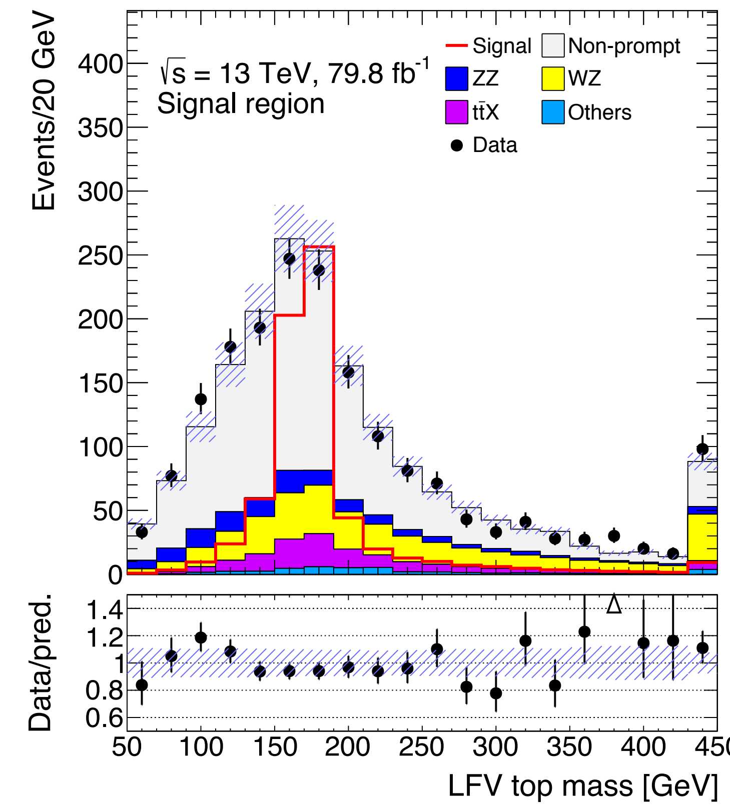
$$L(\mu, b_{ij}, n_{ij}^{\mathrm{np}}, m_{ij}^{\mathrm{np}}) = \prod_{i}^{N_{m_{\mathrm{coll}}}} \prod_{j}^{N_{p_{\mathrm{T}}^{\ell_2}}} \mathrm{Pois}(n_{ij} \mid A_j b_{ij} + n_{ij}^{\mathrm{np}})$$
$$\times \mathrm{Pois}(m_{ij} \mid b_{ij} + m_{ij}^{\mathrm{np}} + \mu s_{ij})$$
$$\times \mathrm{Gaus}(n_{ij}^{\mathrm{np}} | N_{ij}^{\mathrm{np}}, \sigma_{N_{ij}^{\mathrm{np}}})$$
$$\times \mathrm{Gaus}(m_{ij}^{\mathrm{np}} | M_{ij}^{\mathrm{np}}, \sigma_{M_{ij}^{\mathrm{np}}}).$$

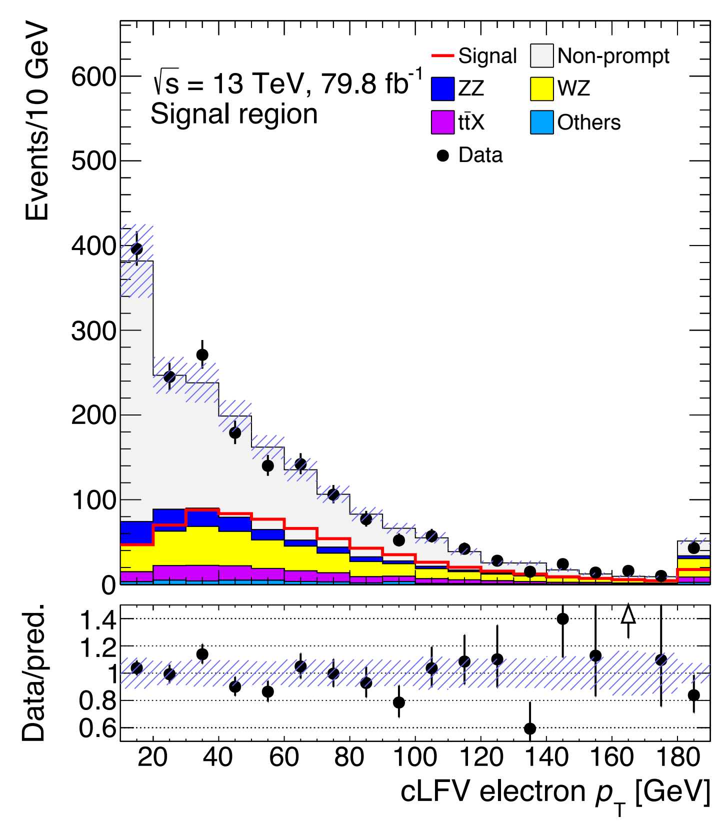
Signal reconstruction and discrimination

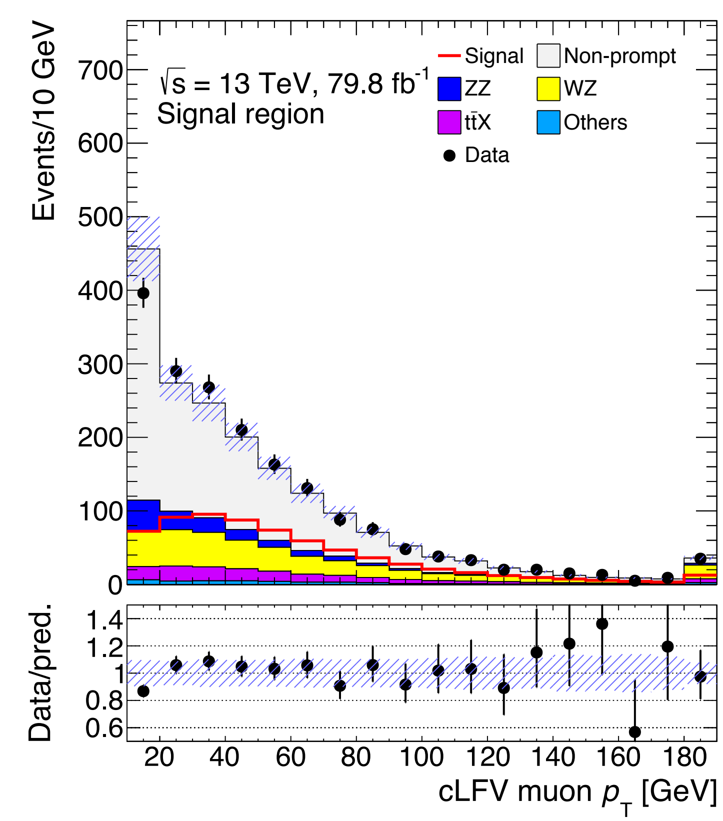
- The four most discriminating variables are shown.
- Not all syst. included!
- The signal is normalised to $Br(t \to \ell\ell' q) = 3 \times 10^{-4}$



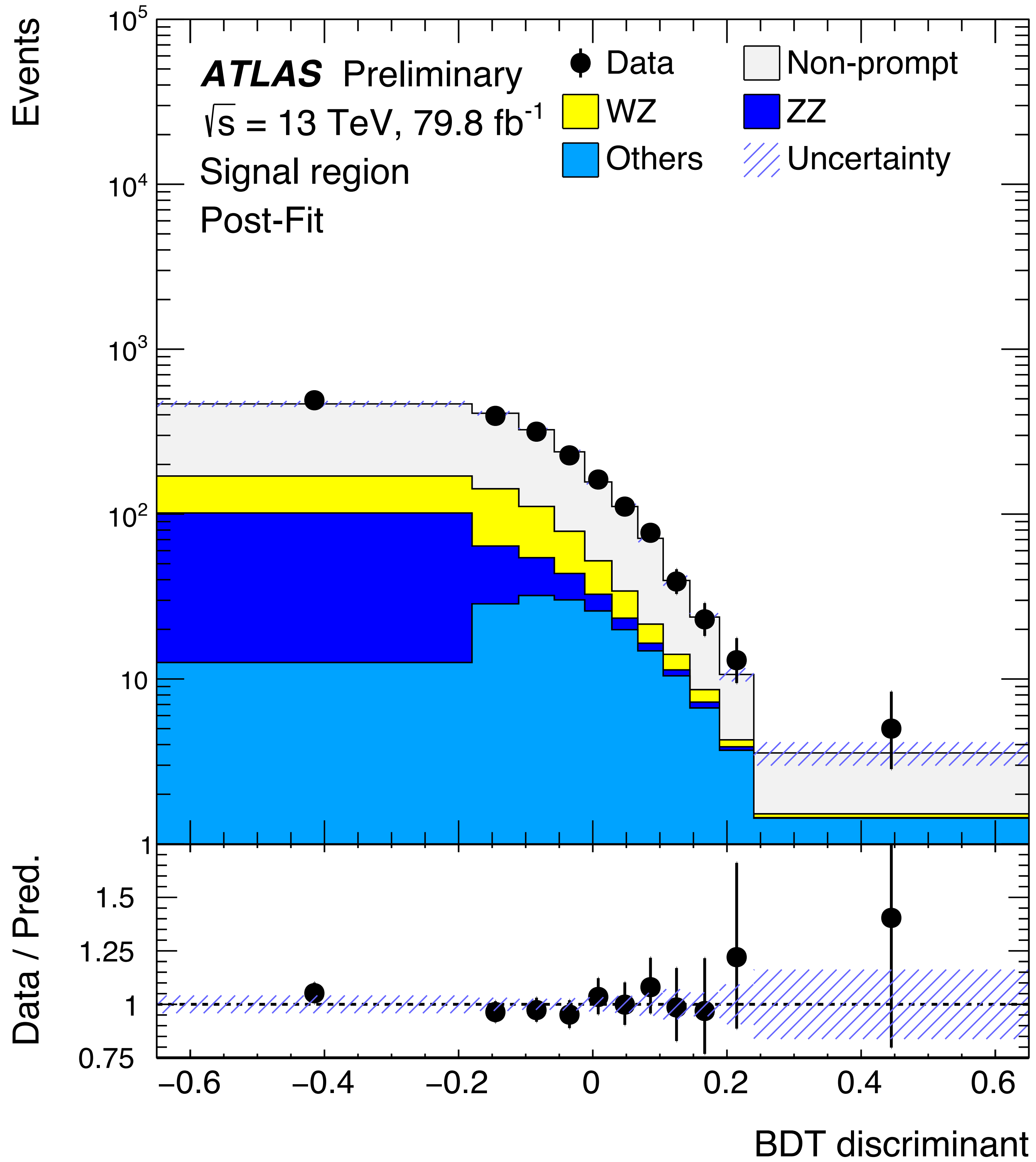






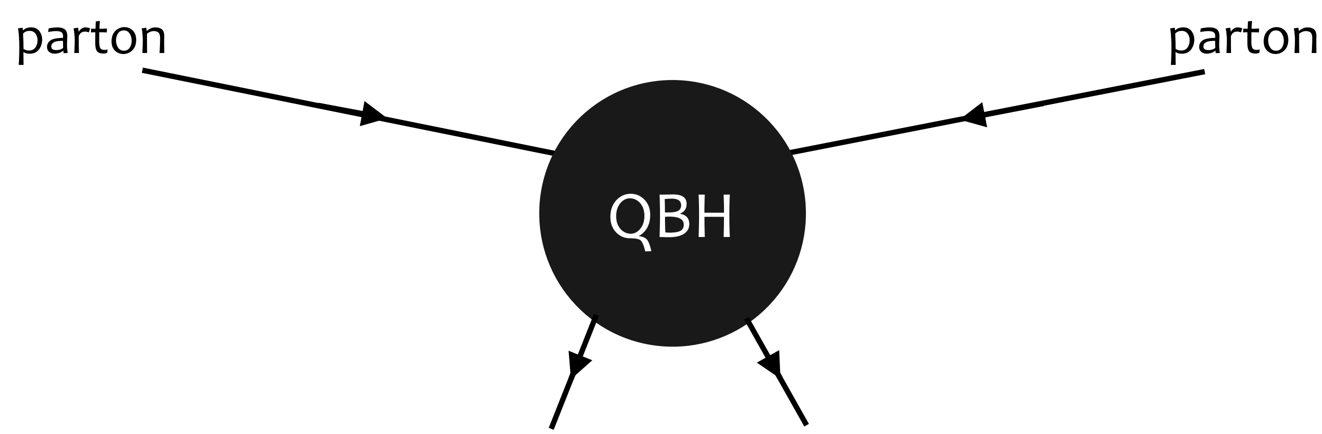


B-only fit



ATLAS Preliminary
√s = 13 TeV, 79.8 fb-1
Signal region
Post-Fit
Data
Non-prompt
WZ
ZZ
Others
Uncertainty
Events
Data / Pred.
BDT discriminant

Quantum black hole



- QBH forms if partons satisfy the hoop conjecture

$$r \lesssim R_{\mathrm{H}} \equiv 2\,\ell_{\mathrm{p}}\,\frac{E}{m_{\mathrm{p}}}$$

$m_{\mathrm{p}}, \ell_{\mathrm{p}}$ = Planck mass and length
E = total energy in center-of-mass frame
r = system radius

1311.5698

- Color, charge, angular momentum conserved
- Small number of final state particles (=2 most probable)
- Gravity coupling equally to all quarks, leptons and gauge bosons (?)

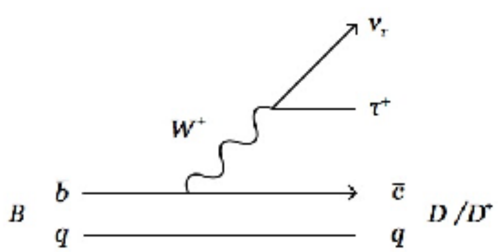
0912.0826

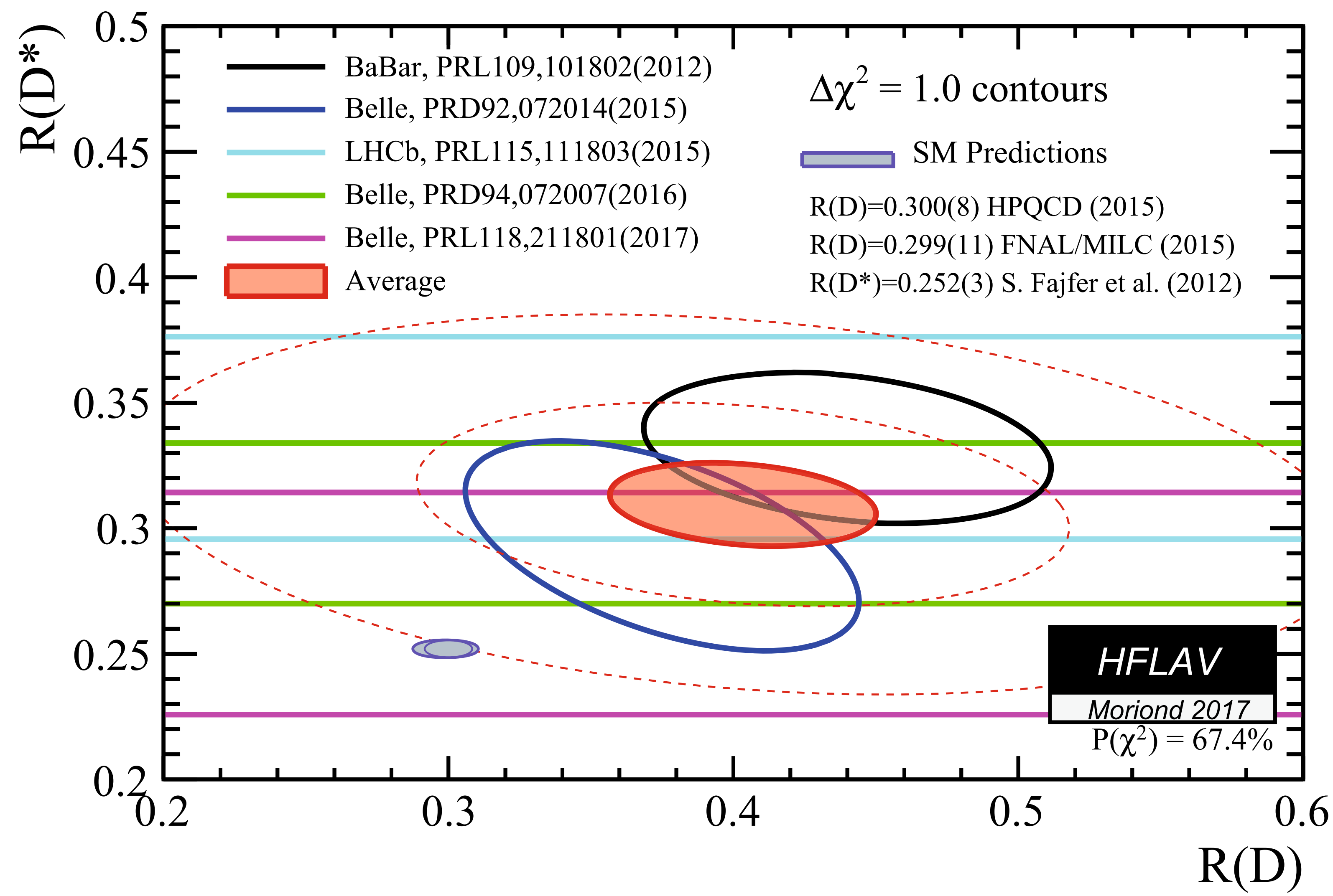
LFU & LFV - R_{D^*}, R_D

b → cτν

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)},$$

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$





A notable example is the semileptonic lepton flavor universality (LFU) ratio $R_D \equiv \Gamma(B \to D\tau\bar{\nu})/\Gamma(B \to D\ell\bar{\nu})$ comparing the τ and light lepton couplings with large precision. It has been shown that scalar [137,142–148] as well as vector LQs [131,145,146,149] may significantly alter this LFU ratio. The world averages of R_D and the analogous observable defined for the $B \to D^*\ell\bar{\nu}$ transition R_{D^*} calculated in the winter 2016 HFAG edition [150] agree with the SM at the 4σ level, as shown in Eqs. (40) and (41).

It has been suggested in Ref. [147] that a minimal extension of the SM with S_1 scalar LQ of mass of the order of 1 TeV can provide an explanation of $R_{D^{(*)}}$ in addition to observables R_K and muon $(g-2)$

Doršner *et al.*,
Phys. Rept. 641 (2016) 1-68

LFU & LFV - R_{K^*}, R_K

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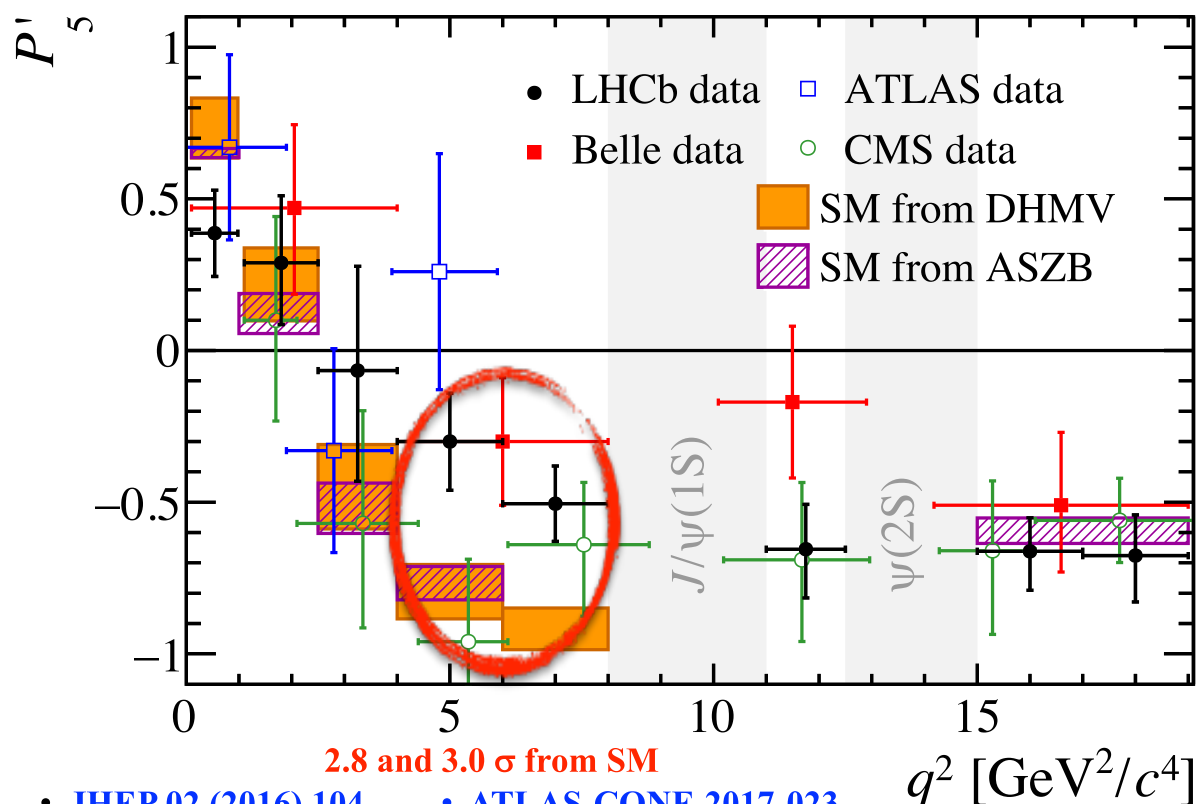
Angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$

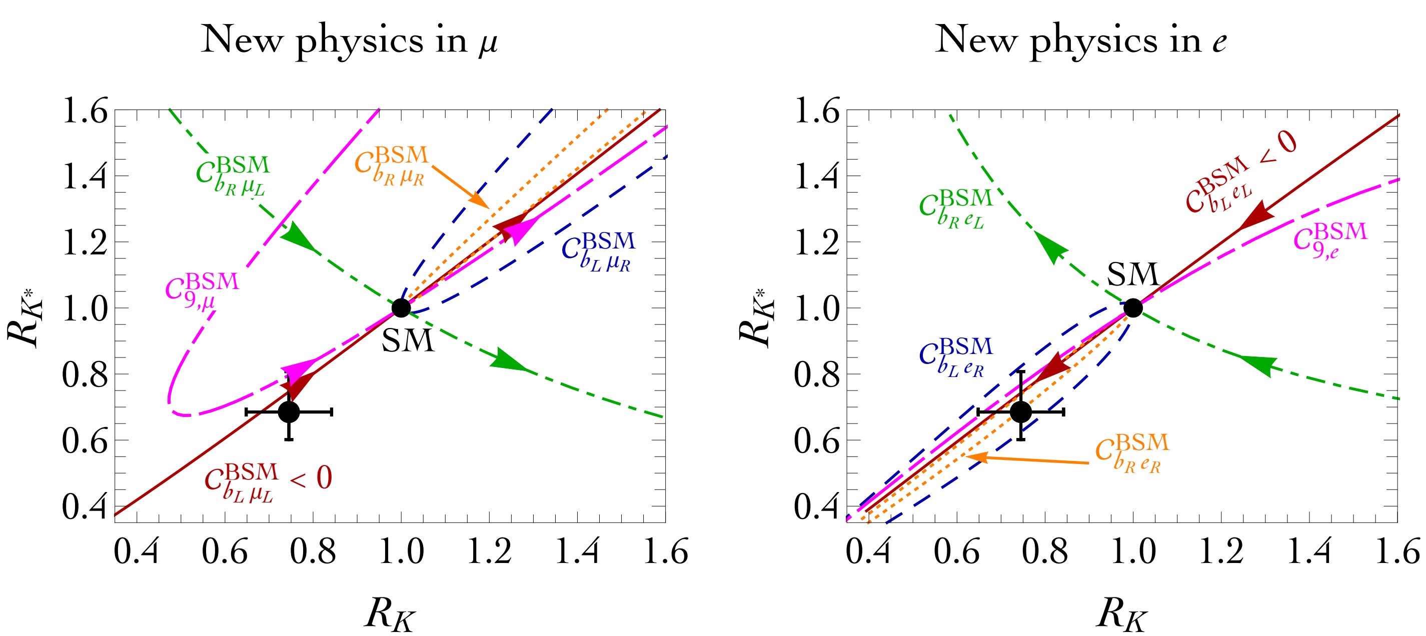


- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

R_{K^*} is 2.5σ off in each bin

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]



1704.05438

"Flavour anomalies after the R_{K^*} measurement"

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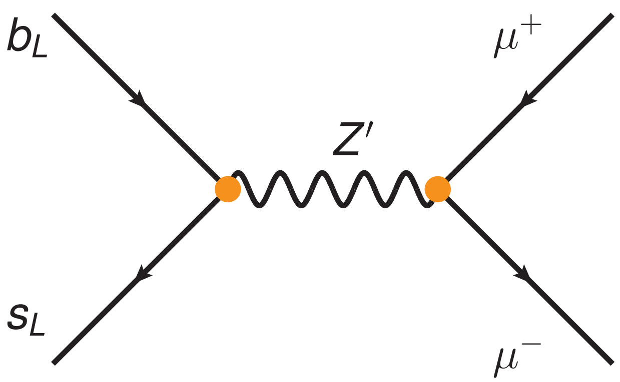
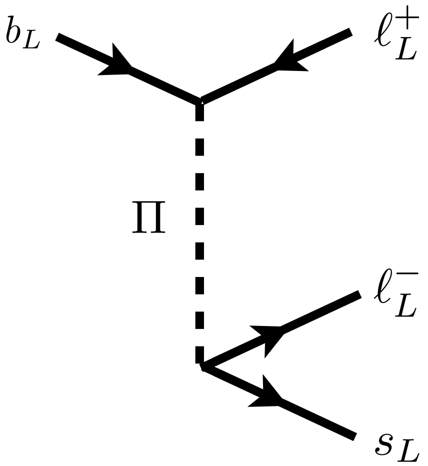
Simplified Models

[About 100 papers…]





M. Nardecchia
https://bit.ly/2Ag0A4I

"Only two options on the market"

$$\frac{\Delta_{bs}\Delta_{\mu\mu}}{m_{Z'}^2} \approx \frac{1}{(30\mathrm{TeV})^2}$$

$$\frac{\lambda_{b\mu}\lambda_{s\mu}}{m_{\Pi}^2} \approx \frac{1}{(30\ \mathrm{TeV})^2}$$

	Spin	Quantum Number	Clean observables new physics in e	Clean observables new physics in μ	All observables
S_3	0	$(\bar{3}, 3, 1/3)$	✓	✓	✓
R_2	0	$(3, 2, 7/6)$	✓		
$\tilde{R}_2$	0	$(3, 2, 1/6)$			
$\tilde{S}_1$	0	$(\bar{3}, 1, 4/3)$	✓		
U_3	1	$(3, 3, 2/3)$	✓	✓	✓
V_2	1	$(\bar{3}, 2, 5/6)$	✓		
U_1	1	$(\bar{3}, 1, 2/3)$	✓	✓	✓

Table 3: *Which lepto-quarks can reproduce which $b \to s\ell^+\ell^-$ anomalies.*

Something recent accounting for all these flavour anomalies: 1808.00942