NP searches in ττ, μμ, τν tails (Z' & W' searches) at ATLAS & CMS

Y. Takahashi (Zurich)
On behalf of ATLAS & CMS Collaboration

In this talk

- I will *not* just review recent Z', W' searches, but try to put them in the context of B-physics anomalies (including theorist's plot as well)

- "Target analysis" depends on if we aim for
  - Combined explanation of R(K[*]) and R(D[*])
  - Independent explanation

→ I split my talk into 2 parts

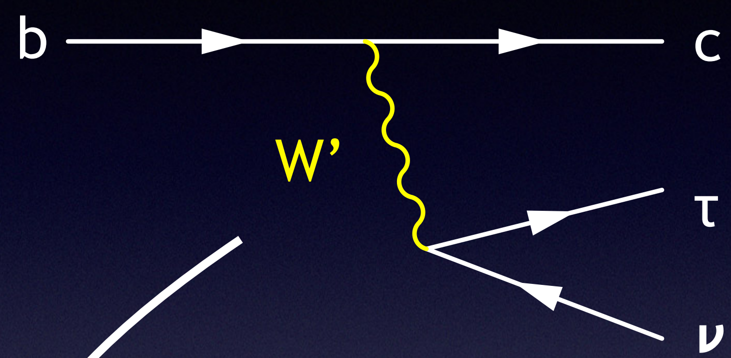
Combined explanation: Target signature ($Z' \to \tau\tau$)

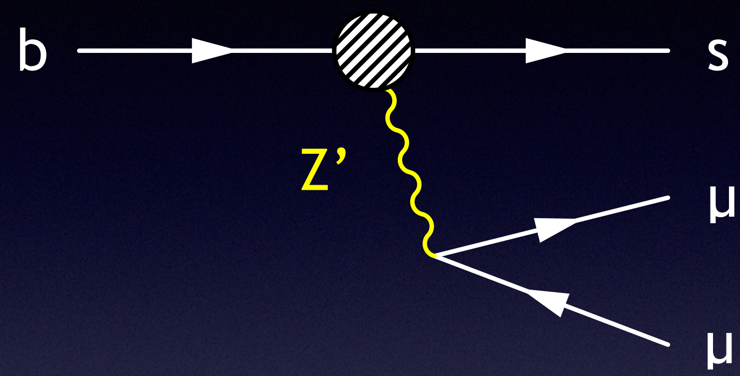
Extra $SU(2)_L$ doublet seems to be a good solution

Note: you need some trick, to achieve $M^{NP}(b \to s\mu\mu) << M^{NP}(b \to c\tau\nu)$

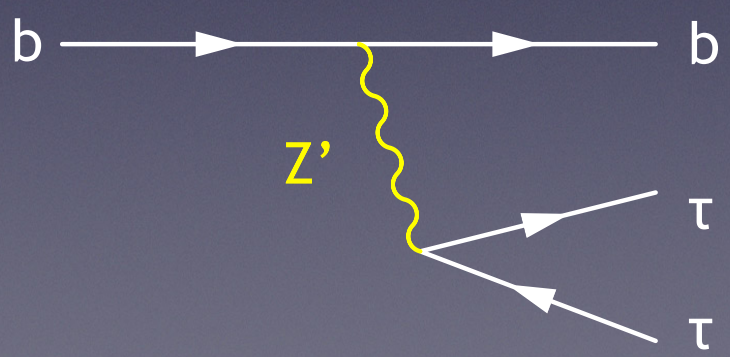
Combined explanation: Target signature (Z’ → ττ)

Extra $SU(2)_L$ doublet seems to be a good solution





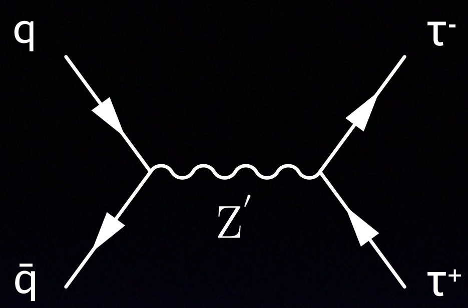
Note: you need some trick, to achieve $M^{NP}(b \to s\mu\mu) << M^{NP}(b \to c\tau\nu)$



If you assume CKM like coupling,
we should expect huge enhancement
due to no CKM suppression ($1/|V_{cb}|^2$ ~ 600)
→ We should look at (bb →) Z’ → ττ

Z’ → ττ search (ATLAS, 35.9/fb)

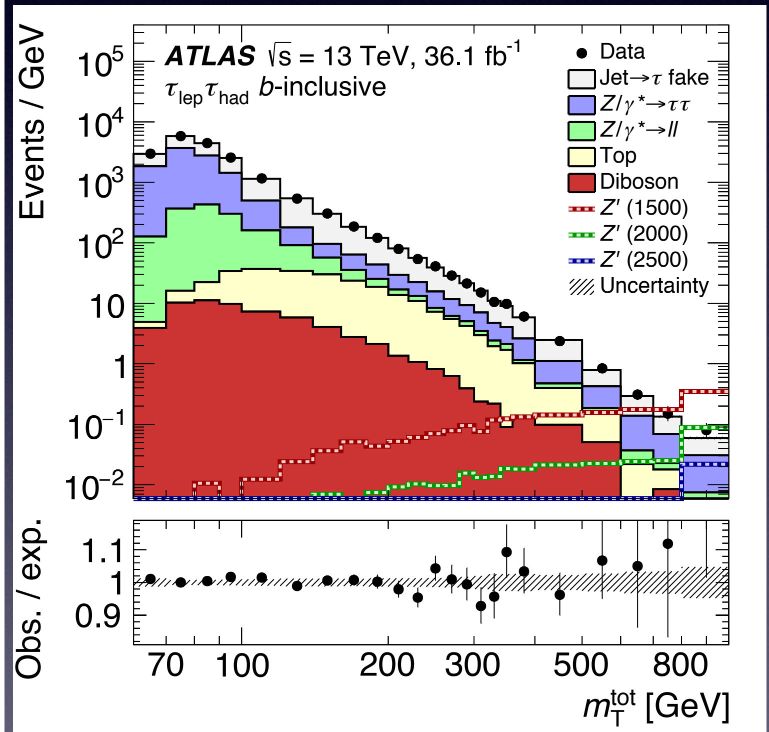
JHEP 01 (2018) 055



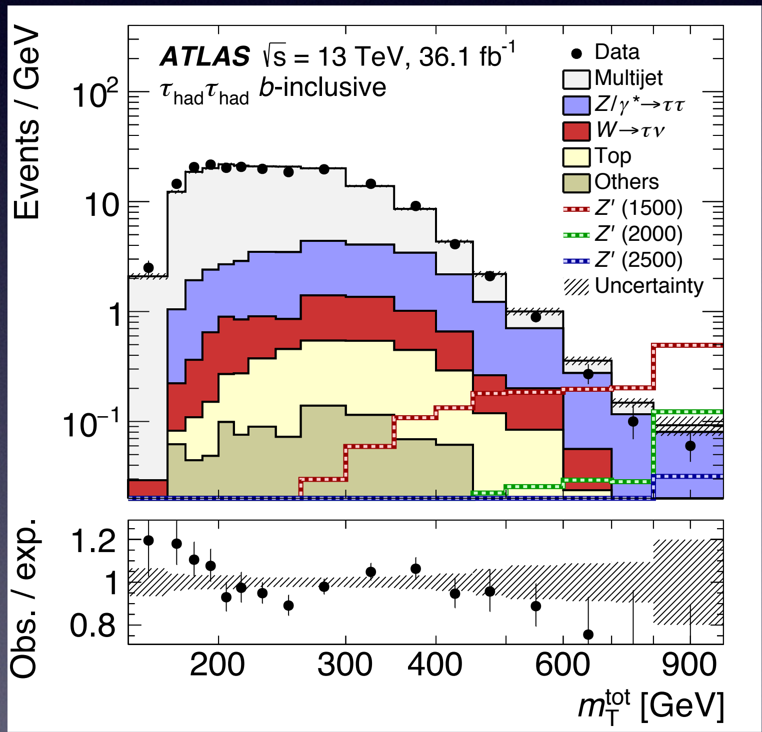
Note: It is not necessary to assume Z’ coupling to light-flavour quarks

- 35% $\tau \to l\nu\nu$ (l = e, μ): τ_{lep}
- 65% $\tau \to \pi^{\pm}$ ($+n\pi^{0}$) ν, $\pi^{\pm}\pi^{\mp}\pi^{\pm}\nu$: τ_{had}

$\tau_{lep}\ \tau_{had}$ (~40%)



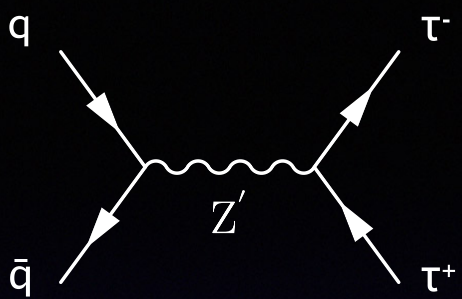
$\tau_{had}\ \tau_{had}$ (~40%)



- 2 high pT τ’s
- Back-to-back ($\Delta\phi$ > 2.7 rad)
- Opposite-sign

Z’ → ττ search (ATLAS, 35.9/fb)

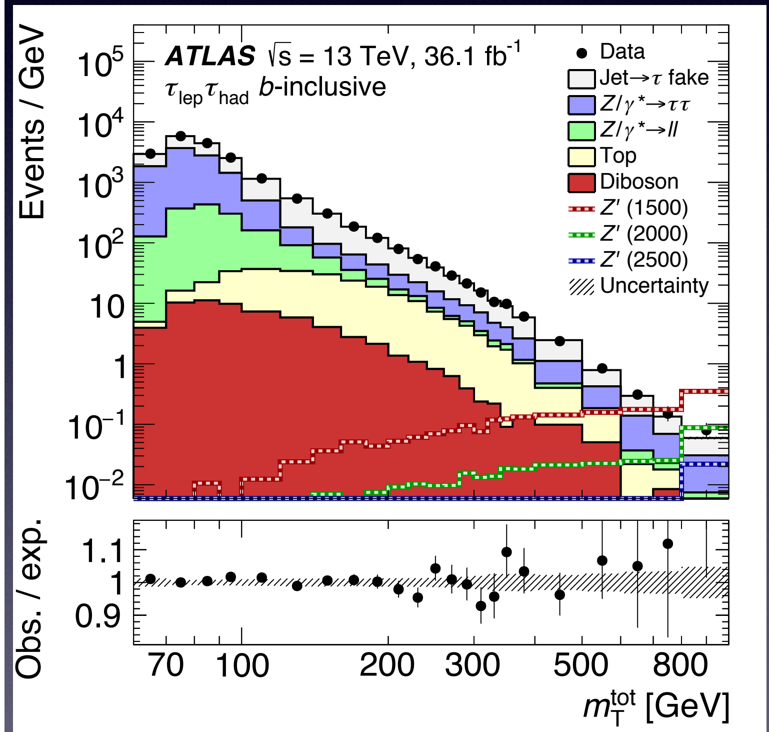
JHEP 01 (2018) 055



Note: It is not necessary to assume Z’ coupling to light-flavour quarks

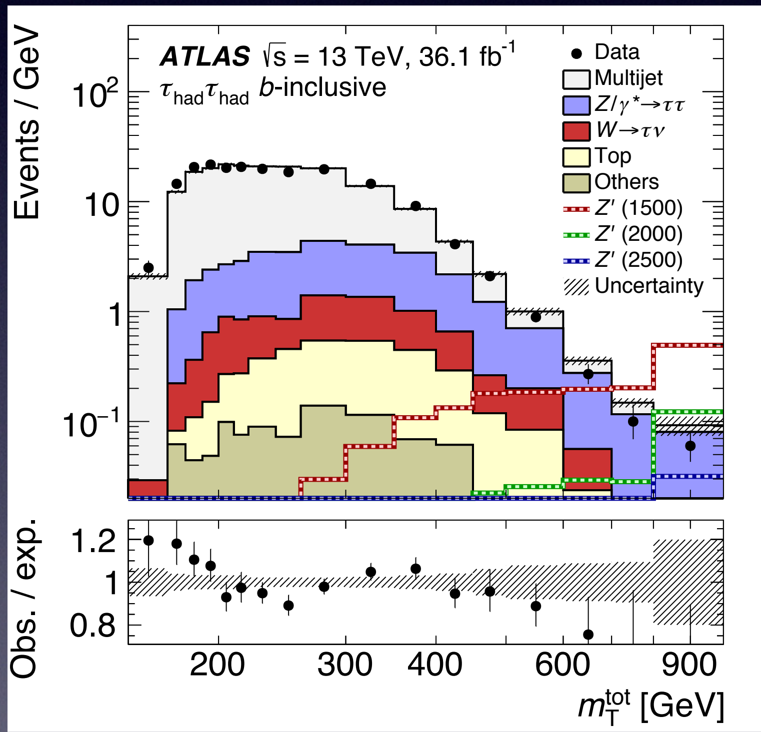
- 35% $\tau \to l\nu\nu$ (l = e, μ): τ_{lep}
- 65% $\tau \to \pi^{\pm}$ ($+n\pi^0$) ν, $\pi^{\pm}\pi^{\mp}\pi^{\pm}\nu$: τ_{had}

$\tau_{lep}\,\tau_{had}$ (~40%)



Good BG rejection but low acceptance

$\tau_{had}\,\tau_{had}$ (~40%)

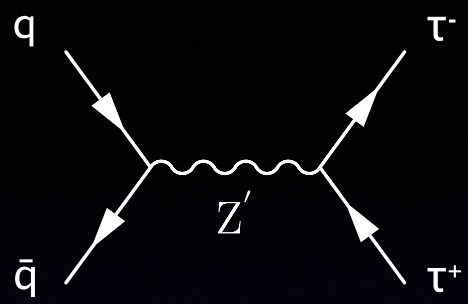


Worse BG rejection but good acceptance

- 2 high pT τ’s
- Back-to-back ($\Delta\phi$ > 2.7 rad)
- Opposite-sign

Z’ → ττ search
(ATLAS, 35.9/fb)

JHEP 01 (2018) 055

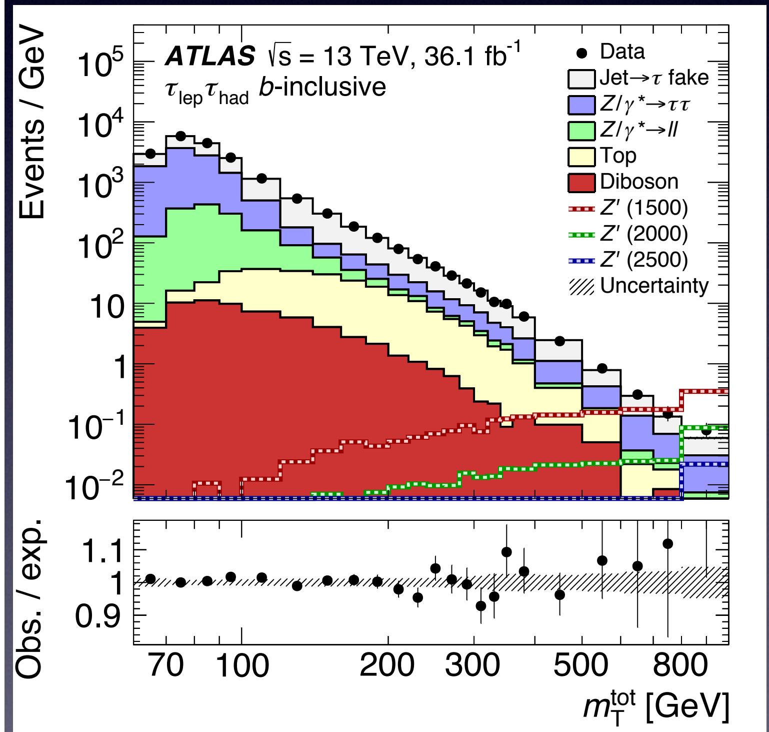


Note: It is not necessary to assume Z’ coupling to light-flavour quarks

35% $\tau \to l\nu\nu$ (l = e, μ): τ_{lep}

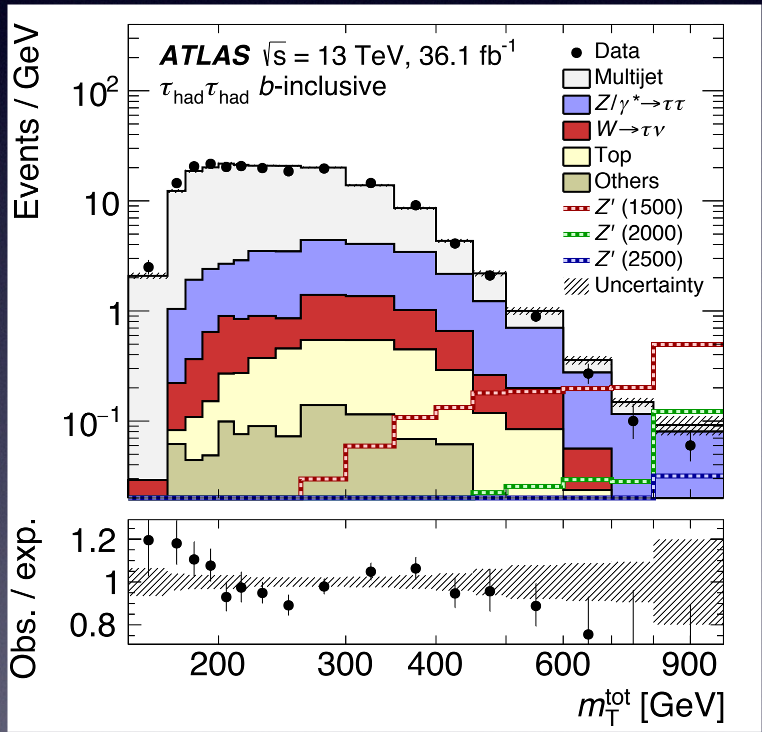
65% $\tau \to \pi^\pm (+n\pi^0)\,\nu$, $\pi^\pm\pi^\mp\pi^\pm\nu$: τ_{had}

$\tau_{lep}\,\tau_{had}$ (~40%)



Good BG rejection
but low acceptance

$\tau_{had}\,\tau_{had}$ (~40%)



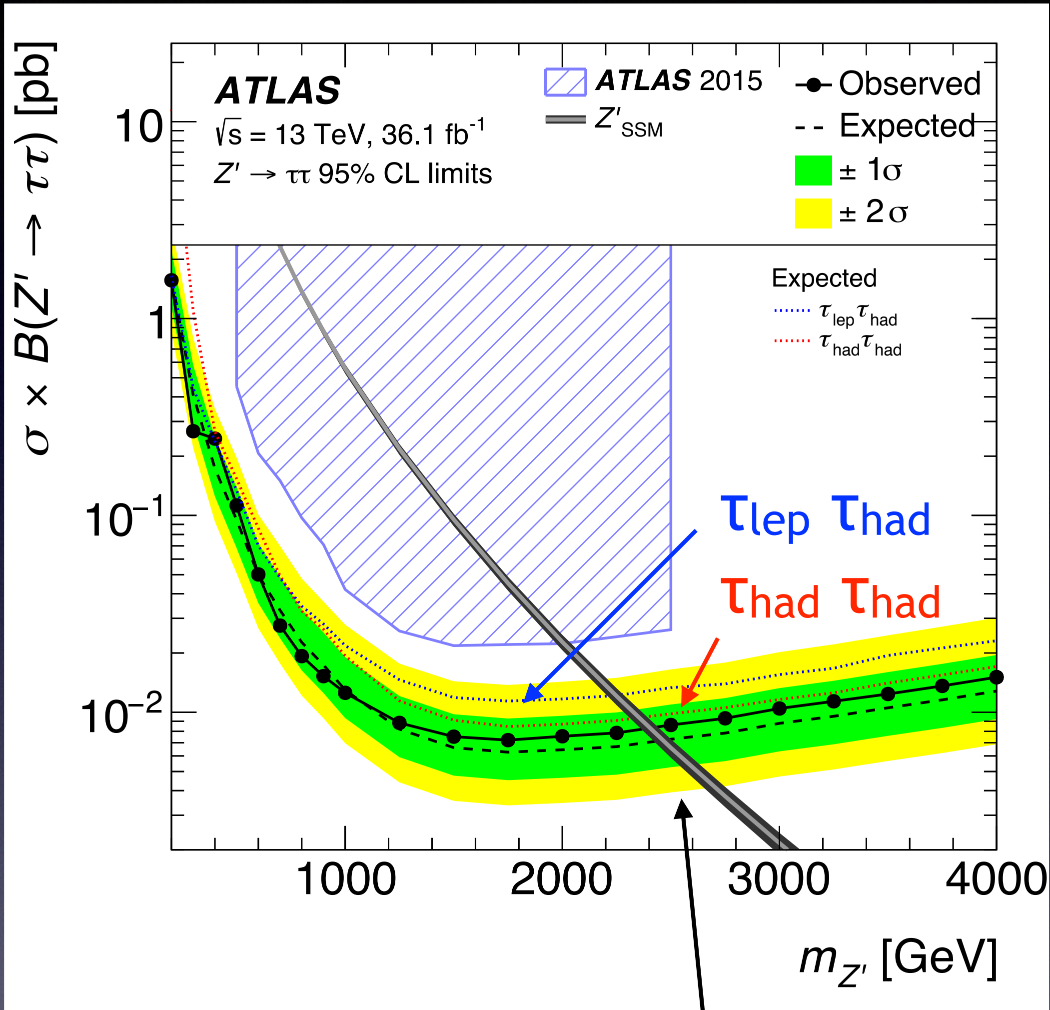
Worse BG rejection
but good acceptance

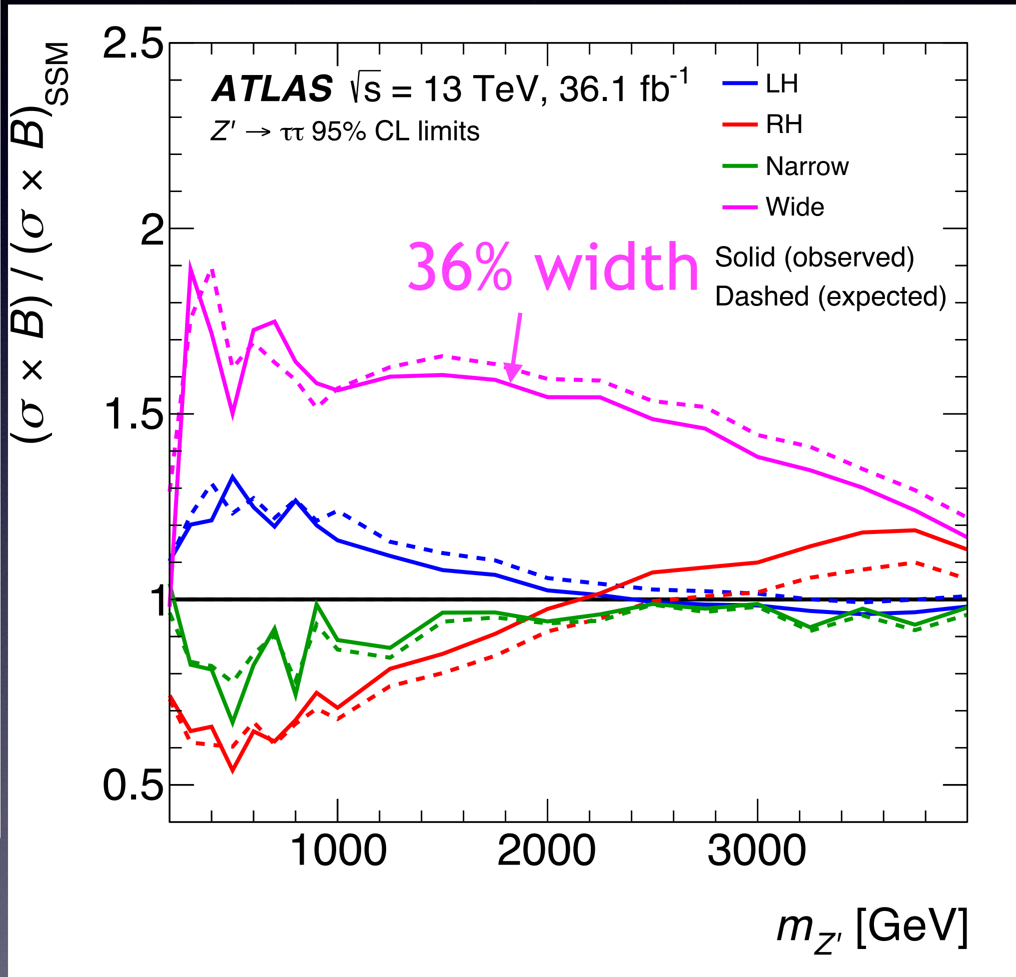
- 2 high pT τ’s
- Back-to-back ($\Delta\phi > 2.7$ rad)
- Opposite-sign

Strong in low mass (where BG is big)

Strong in high mass (where BG is low)

Upper limit on σ x Br

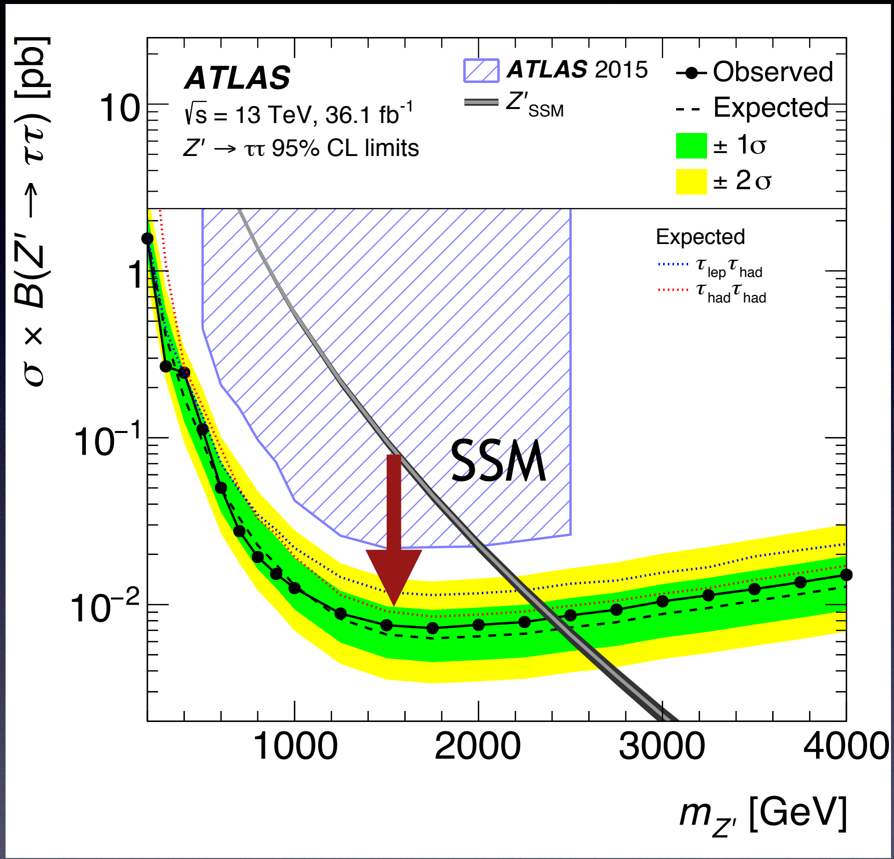




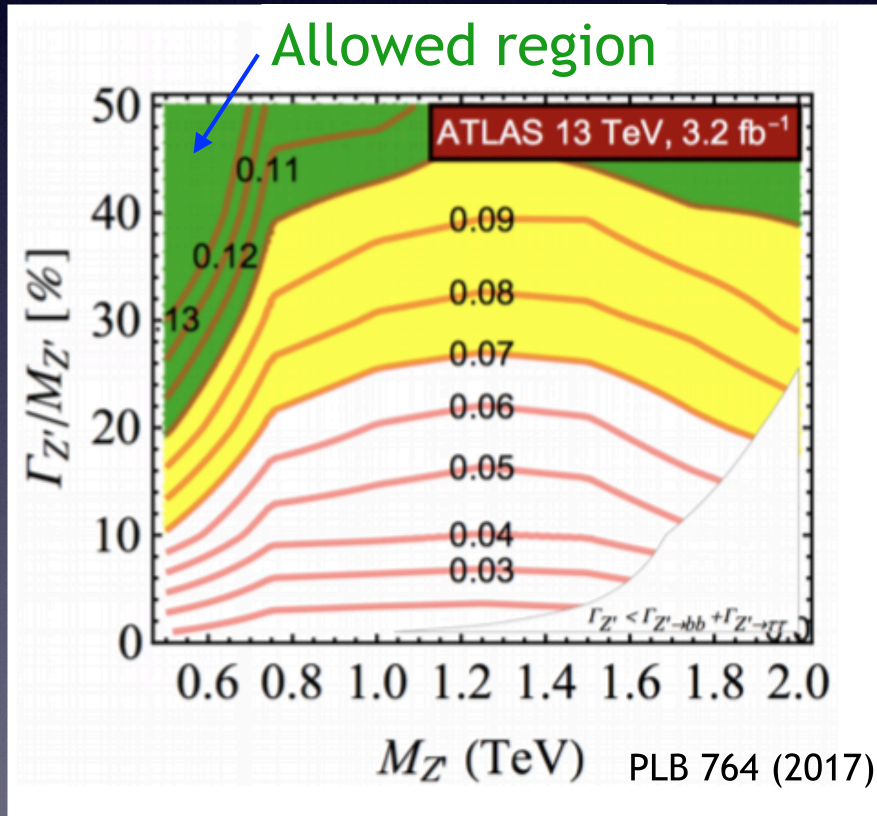
Sensitivity limited by stat.

Theoretical cross-section
for SM-like coupling of the Z'
(Sequential SM; SSM)

Put this into the context of B-anom.

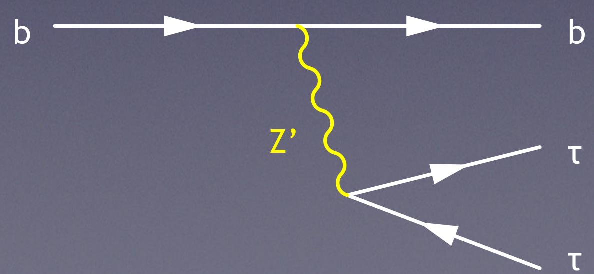


→ We should recast this result, assuming minimum coupling (e.g. Z' predominantly couples to b and τs) → Reduced cross-section



PLB 764 (2017) 126

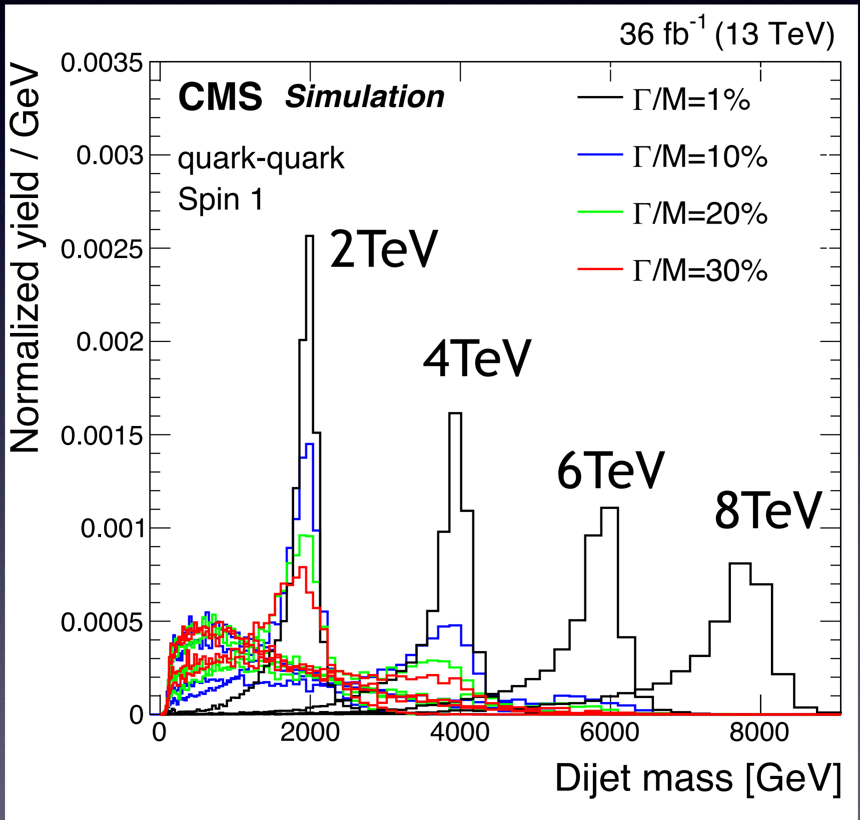
SSM is not a "must" scenario in the context of B-phys. anomaly !



We should challenge wide resonance

Started our challenges to the wide resonance

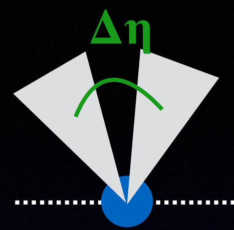
e.g.) di-jet resonance search



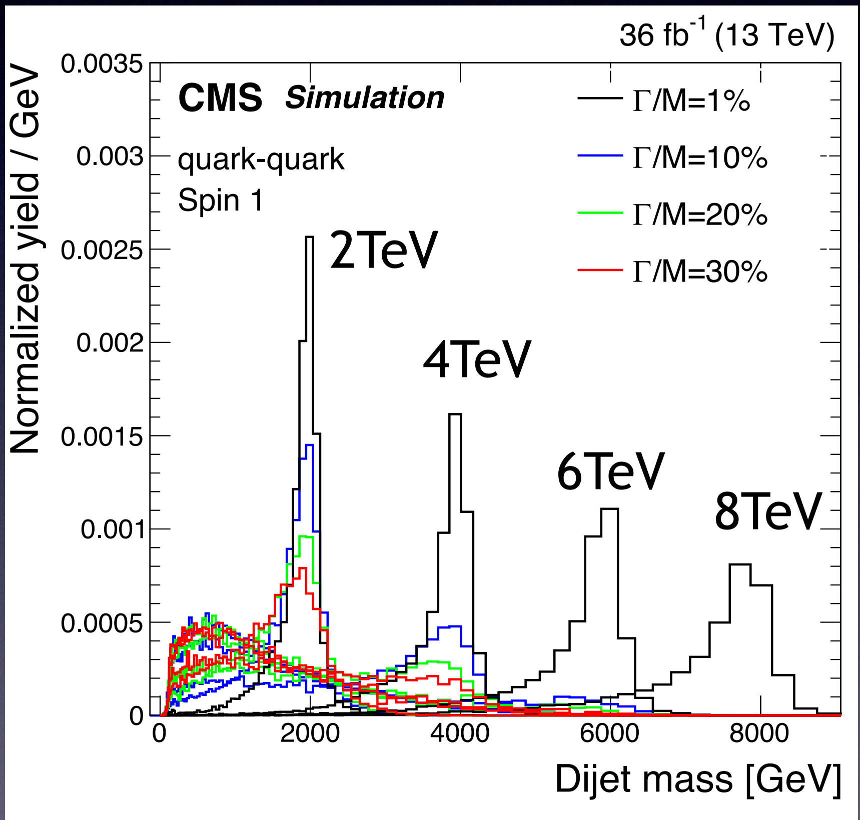
JHEP 08 (2018) 130

Started our challenges to the wide resonance

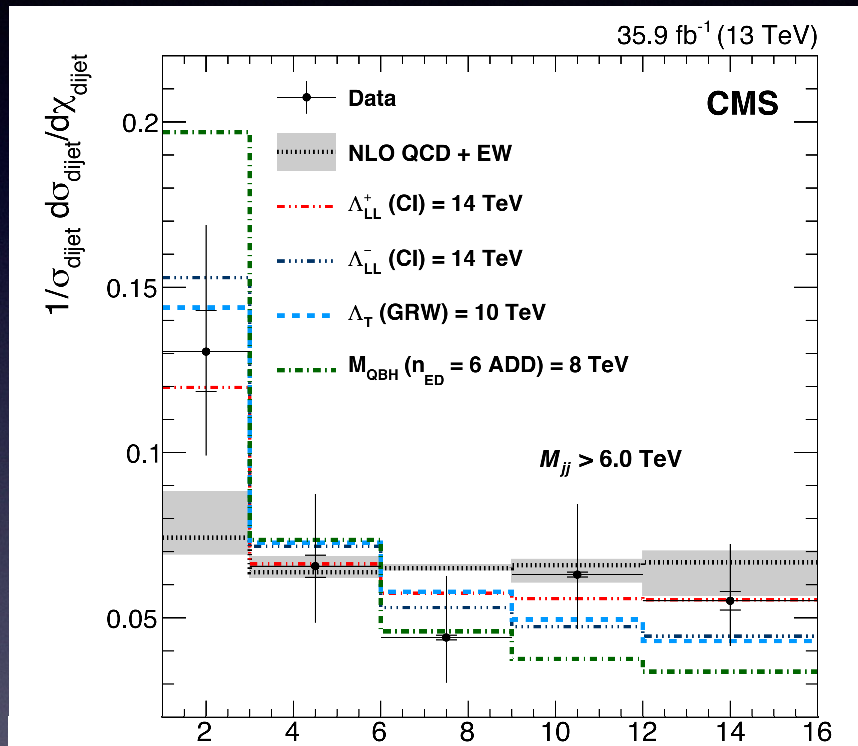
One can look at rapidity separation between jets (width independent)



e.g.) di-jet resonance search



JHEP 08 (2018) 130

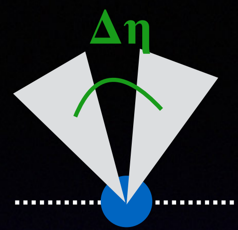


EPJC 78 (2018) 789

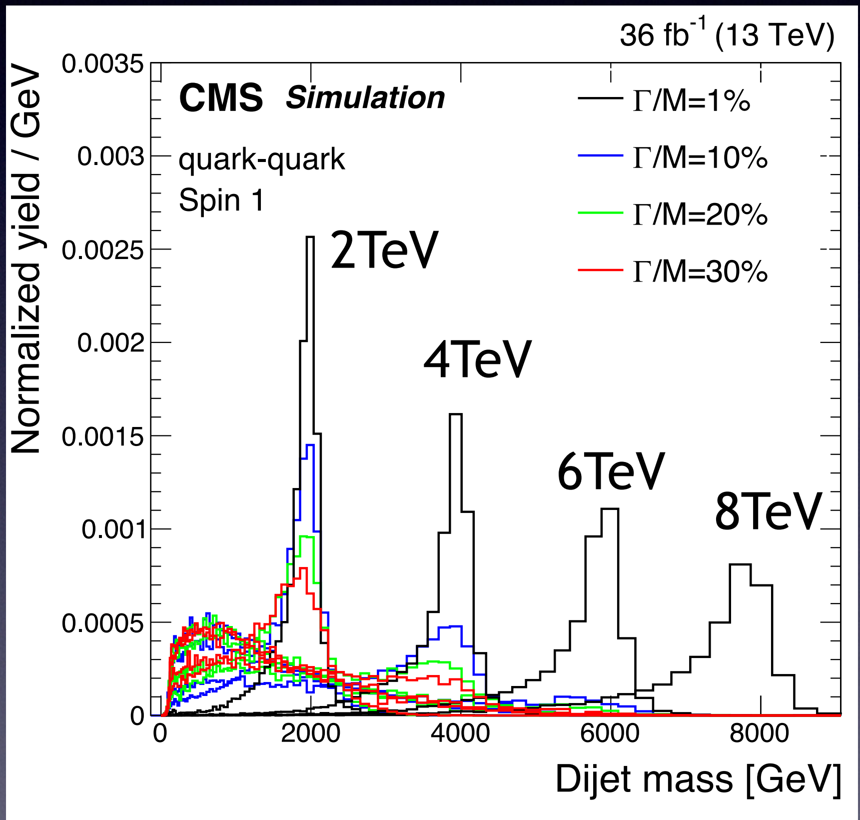
$e^{2\Delta\eta}$

Started our challenges to the wide resonance

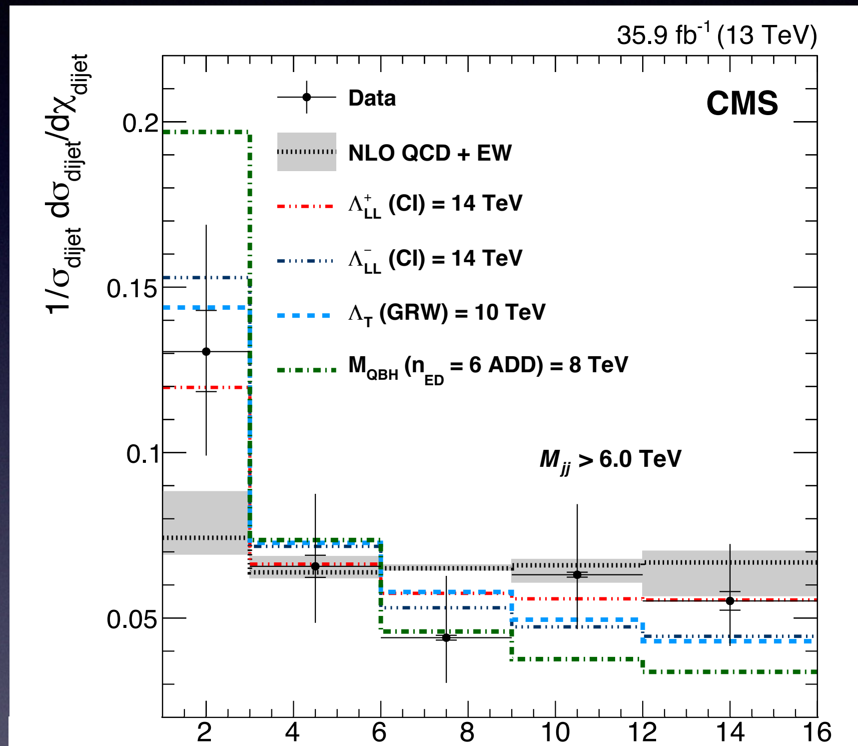
One can look at rapidity separation between jets (width independent)



e.g.) di-jet resonance search



JHEP 08 (2018) 130



EPJC 78 (2018) 789

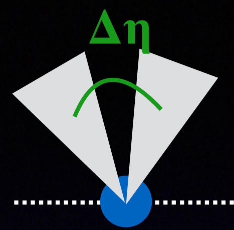
$$e^{2\Delta\eta}$$

Narrow resonance 

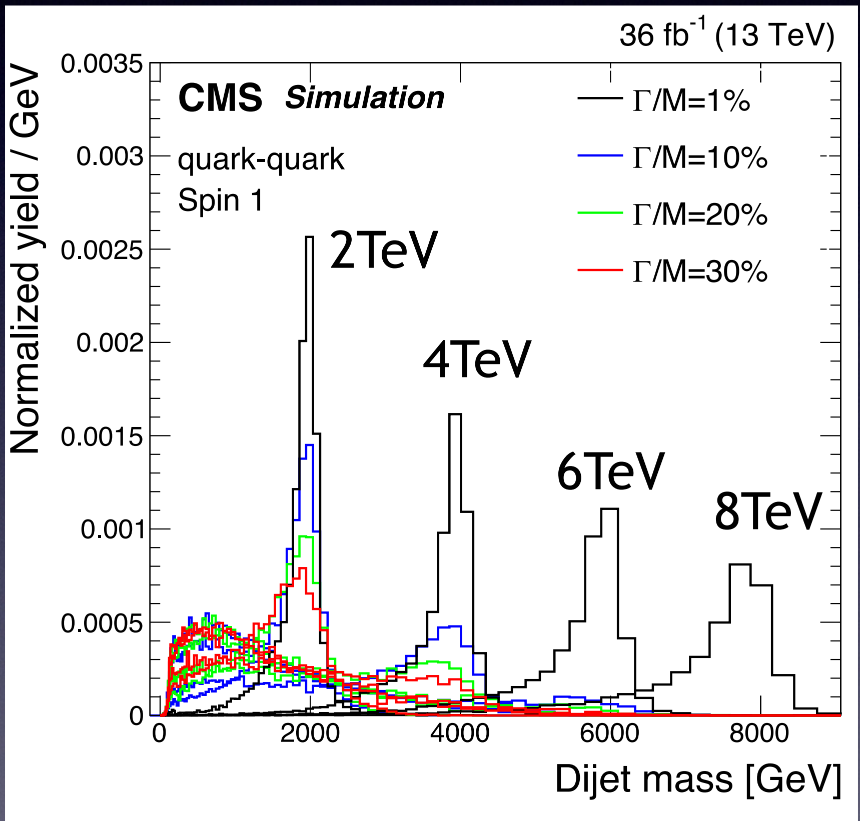
Wide resonance 

Started our challenges to the wide resonance

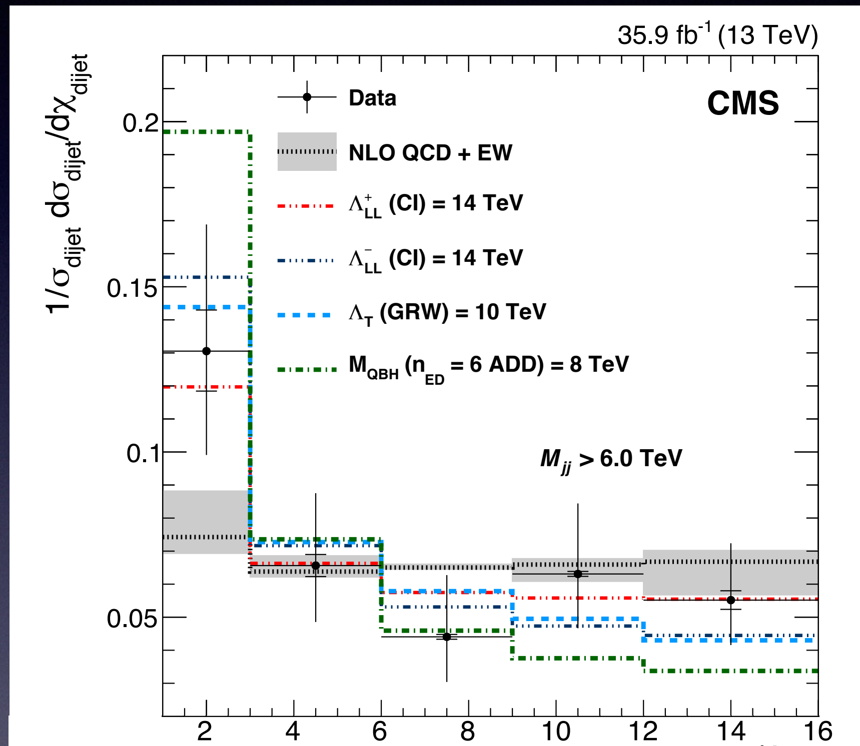
One can look at rapidity separation between jets (width independent)



e.g.) di-jet resonance search



JHEP 08 (2018) 130



EPJC 78 (2018) 789

$e^{2\Delta\eta}$

Narrow resonance 

Wide resonance

Do this using ττ final state

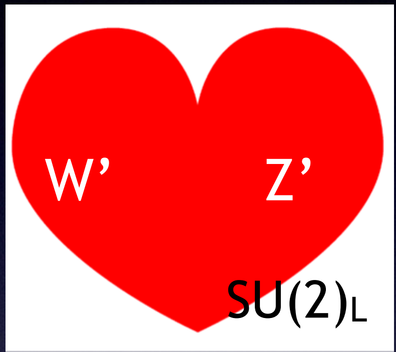
Universität Zürich UZH

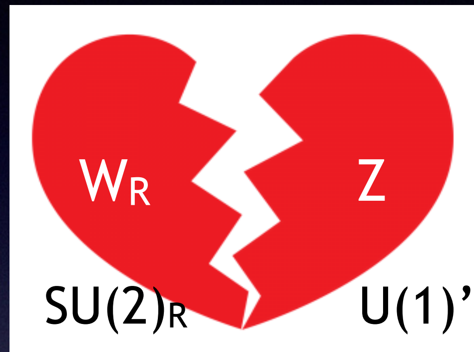
Independent explanation

* Combined explanation using $SU(2)_L$ doublet seems not work
* One of the R(K) or R(D) anomalies might be just false alarm !

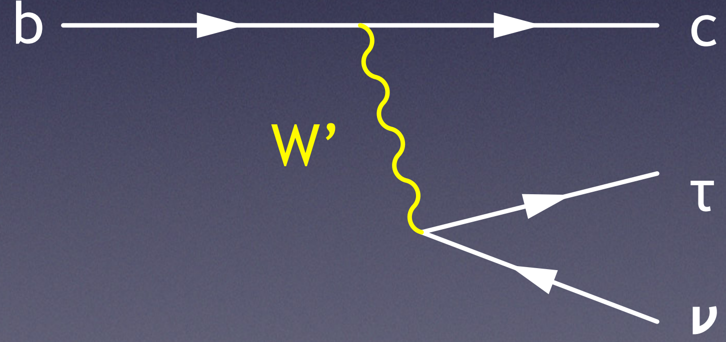
Independent explanation

* Combined explanation using $SU(2)_L$ doublet seems not work
* One of the R(K) or R(D) anomalies might be just false alarm !





Q. Experimentally, where to search for (e.g. W') ?

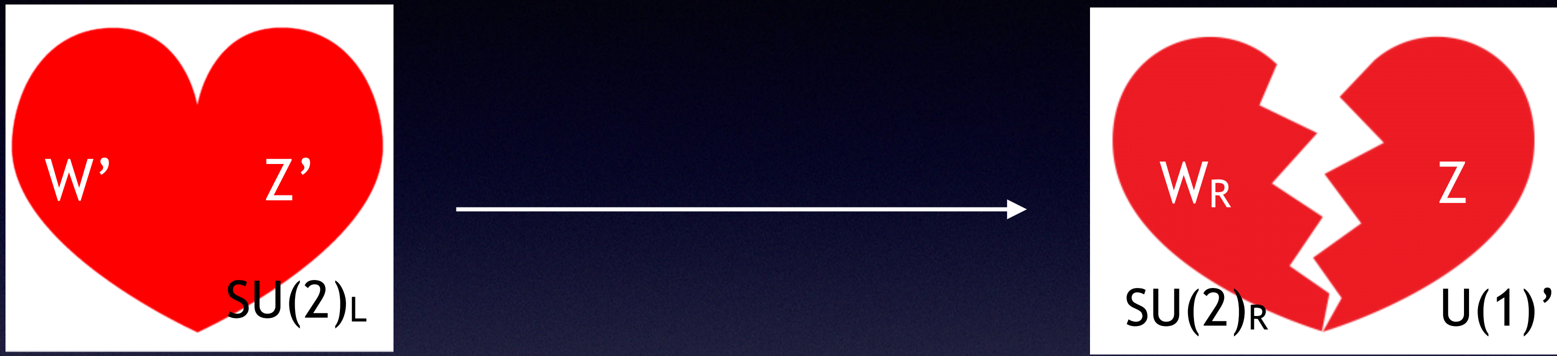


$\propto g_{bc} g_{\tau\nu} / m_{W'}^2$

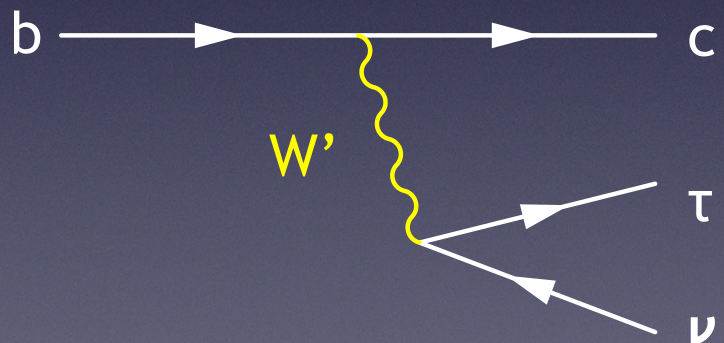
Whatever combination of $m_{W'}$ and coupling (g) that explains B-anomalies should be searched for

Independent explanation

* Combined explanation using $SU(2)_L$ doublet seems not work
* One of the R(K) or R(D) anomalies might be just false alarm !



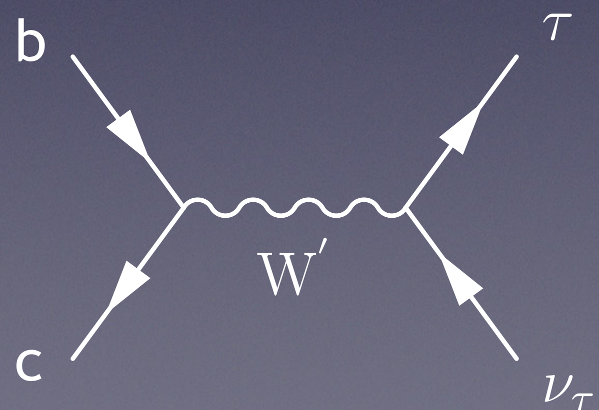
Q. Experimentally, where to search for (e.g. W') ?



$\propto g_{bc} g_{\tau\nu} / m_{W'}^2$

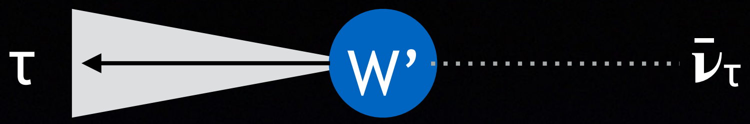
Whatever combination of $m_{W'}$ and coupling (g) that explains B-anomalies should be searched for

@ ATLAS, CMS



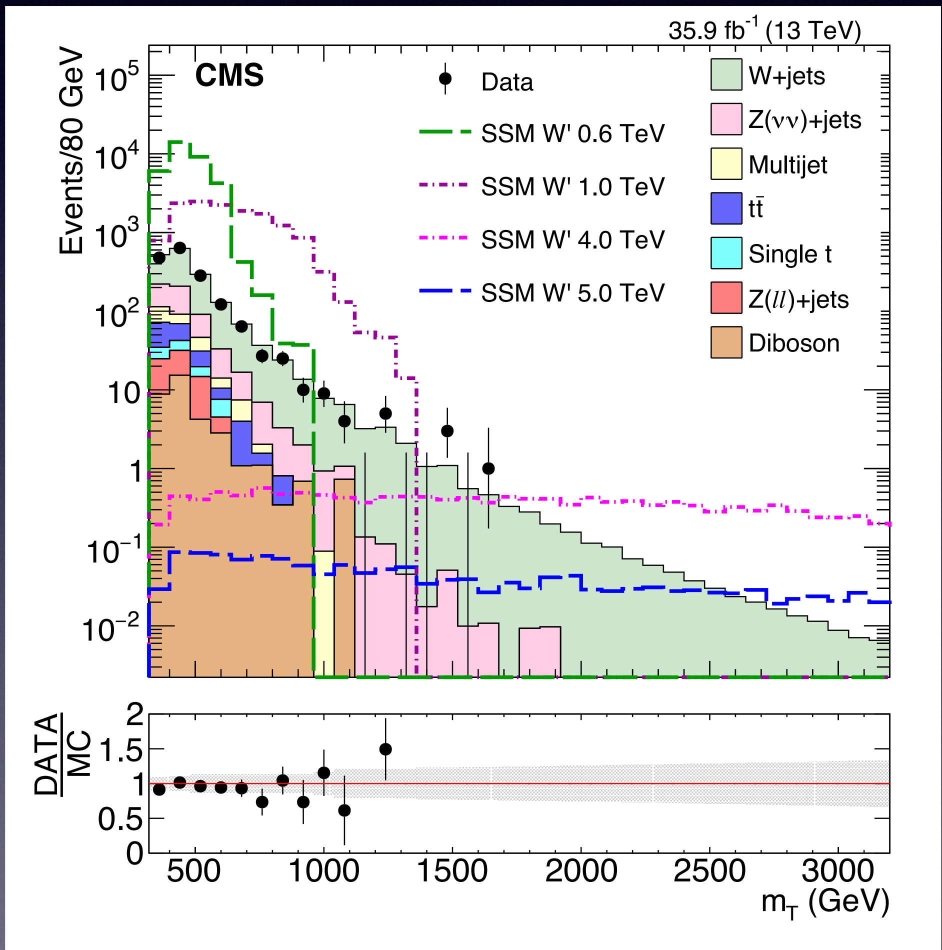
Crossing symm.

W’ → τν search (CMS, 35.9/fb)



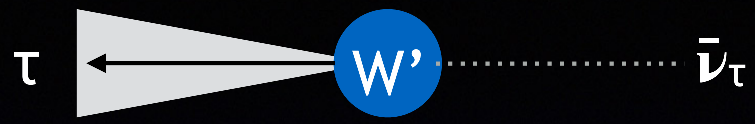
Balanced in p_T and back-to-back ($\Delta\phi$ > 2.4 rad)

$$m_T = \sqrt{2 p_T^{\tau} E_T^{miss} (1 - \cos \Delta\phi(\overrightarrow{p_T^{\tau}}, \overrightarrow{p_T^{miss}}))}$$



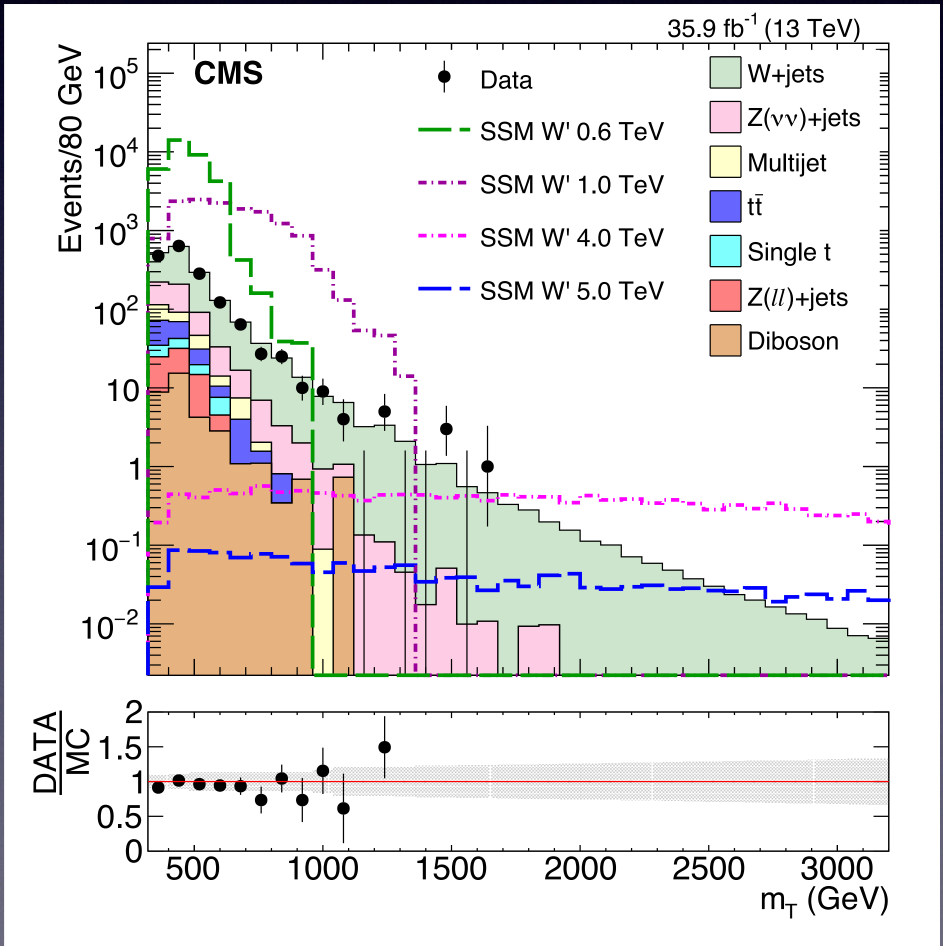
PLB 792 (2019) 107 (CMS)
PRL 120 (2018) 161802 (ATLAS)

W' → τν search (CMS, 35.9/fb)



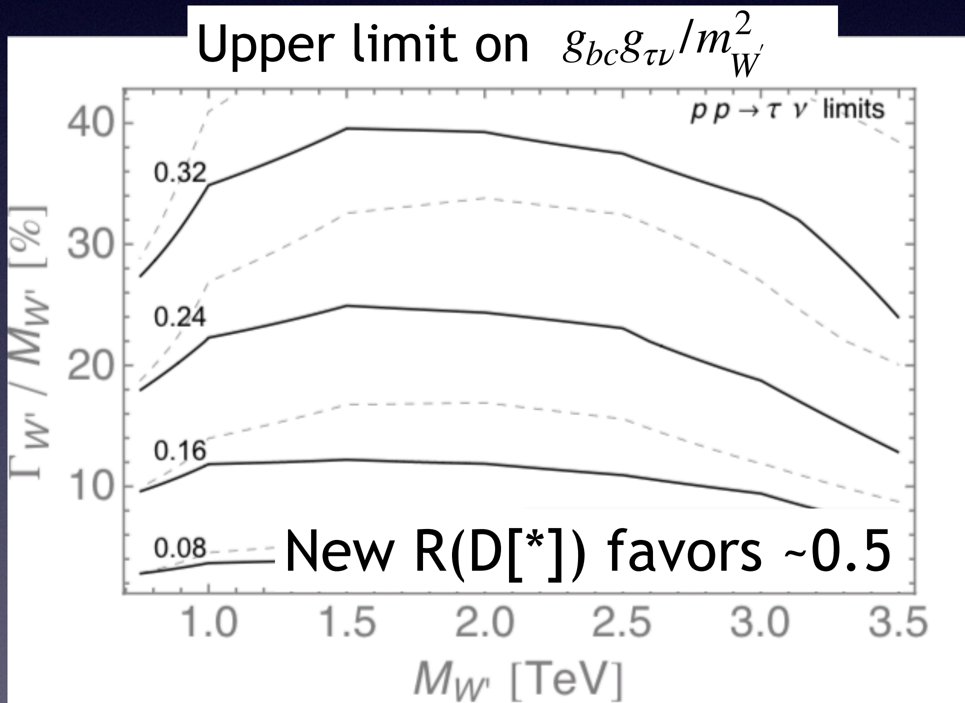
Balanced in p_T and back-to-back (Δϕ > 2.4 rad)

$$m_T = \sqrt{2p_T^\tau E_T^{miss}(1 - \cos\Delta\phi(\vec{p_T^\tau}, \vec{p_T^{miss}}))}$$



PLB 792 (2019) 107 (CMS)
PRL 120 (2018) 161802 (ATLAS)

In the context of B-anomaly, recast this result, assuming W' only couples to bc and τν

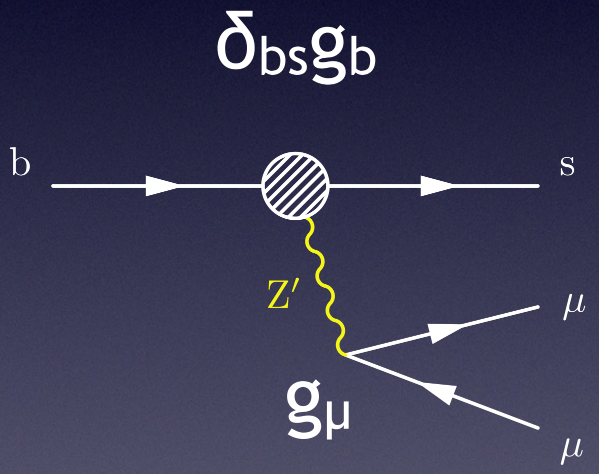


arXiv:1811.07920

W' highly constrained
(except for non-perturbative region)

Search for Z'

Q. Experimentally, where to search for ?



$$\propto \delta_{bs} g_b g_\mu / m_{Z'}^2$$

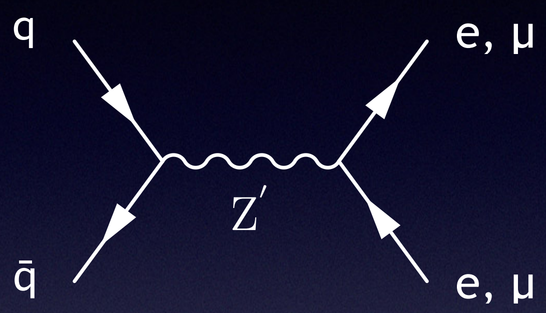
→ any combination of $m_{Z'}$, g that can explain B-anom. Should be searched for

Note: δ_{bs} should be kept small not to conflict with Bs mixing through bs → Z' → bs

Generic Z' search

Z' → ee, μμ search
(ATLAS, 139/fb)

arXiv:1903.06248

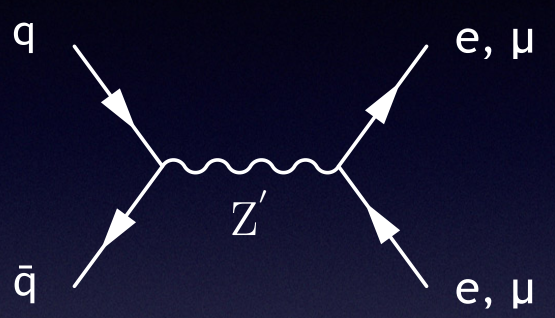


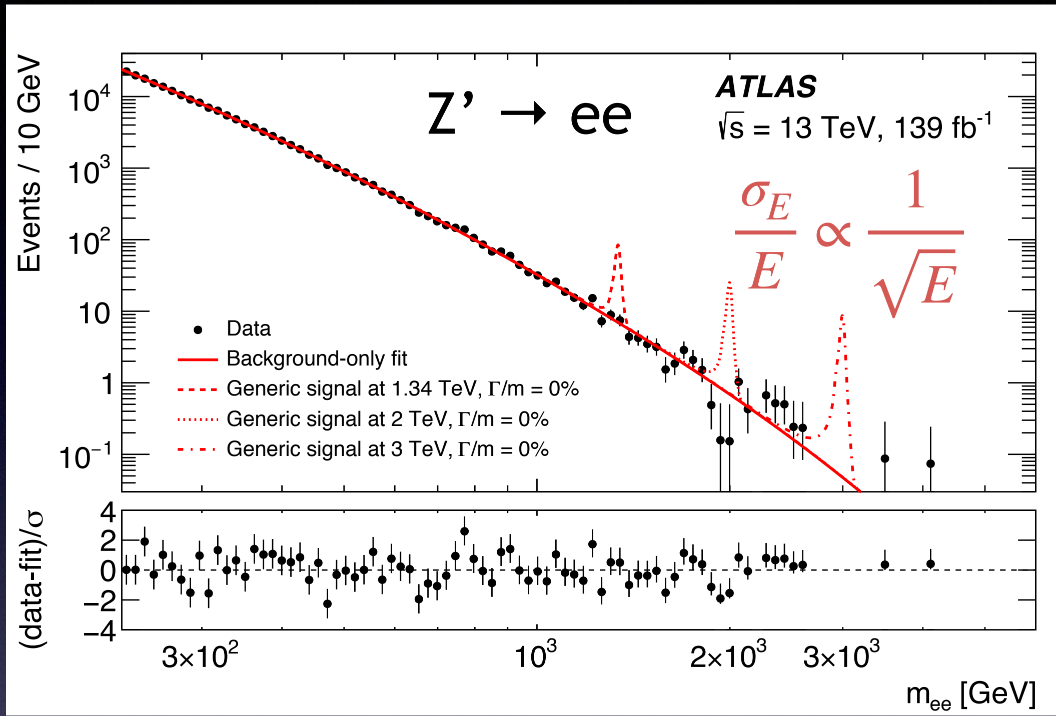
- 2 same-flavour leptons
- Opposite-sign for μμ
  (no requirement for ee)

Generic Z' search

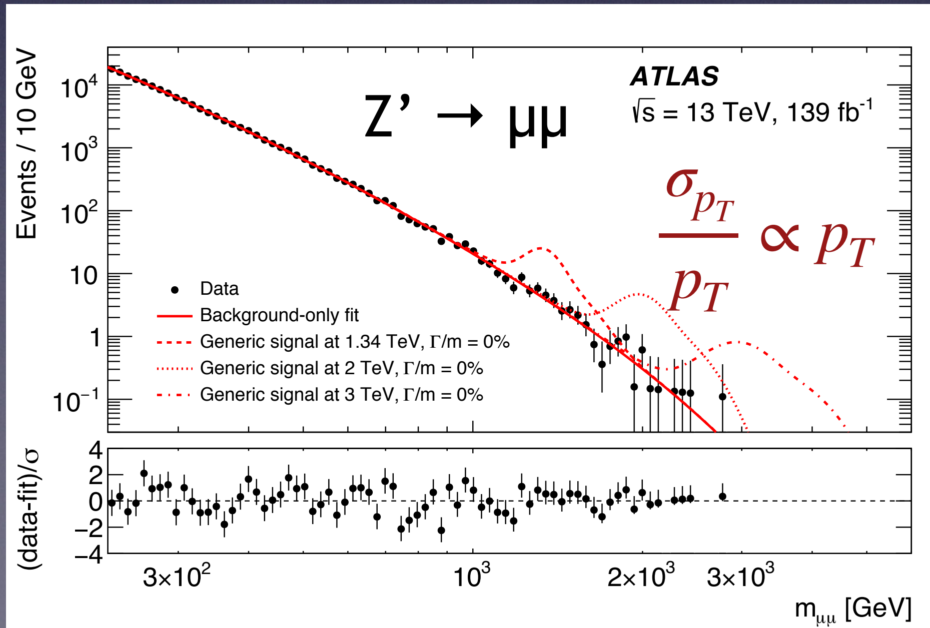
Z' → ee, μμ search
(ATLAS, 139/fb)

arXiv:1903.06248





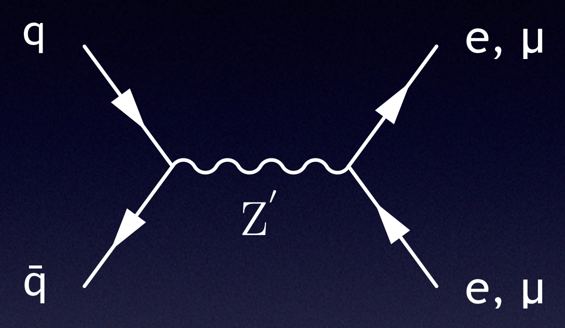
- 2 same-flavour leptons
- Opposite-sign for μμ
  (no requirement for ee)

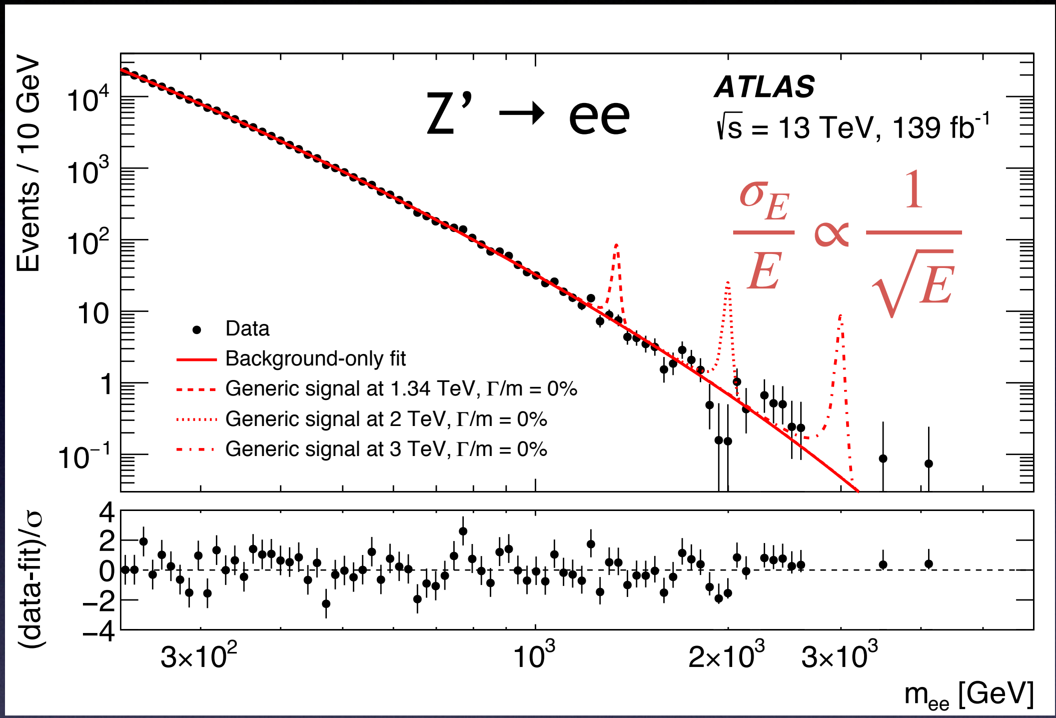


Generic Z' search

Z' → ee, μμ search
(ATLAS, 139/fb)

arXiv:1903.06248





- 2 same-flavour leptons
- Opposite-sign for μμ
  (no requirement for ee)

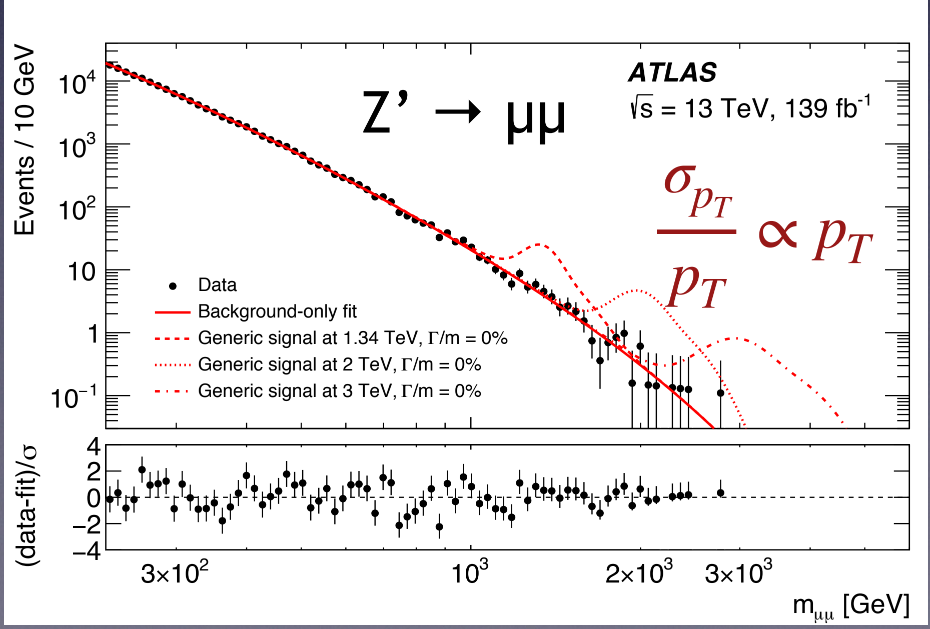
Signal: Cauchy (with various width)
+ Cristal Ball

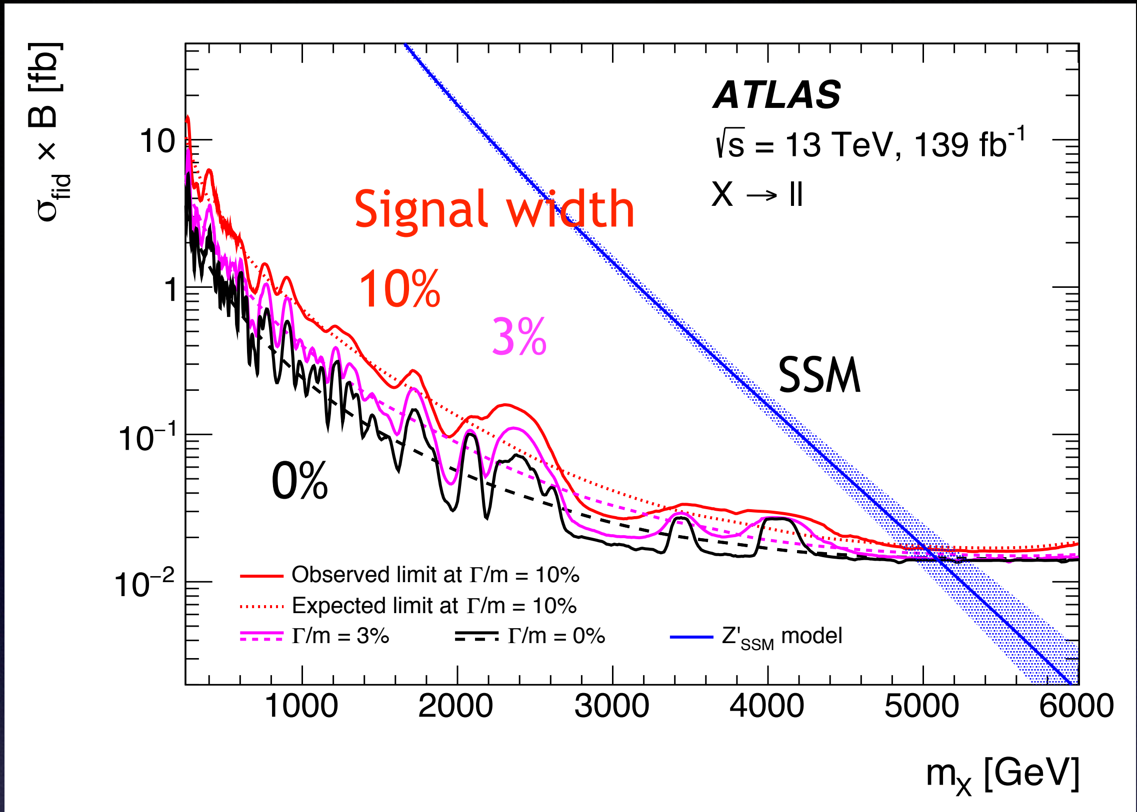
BG: $a \cdot BW(m_{\ell\ell}) \cdot (1-x)^b \cdot x^{\sum_{i=0}^{3} p_i \log x^i}$

Total # of BG events

$m_{ll}/\sqrt{s}$

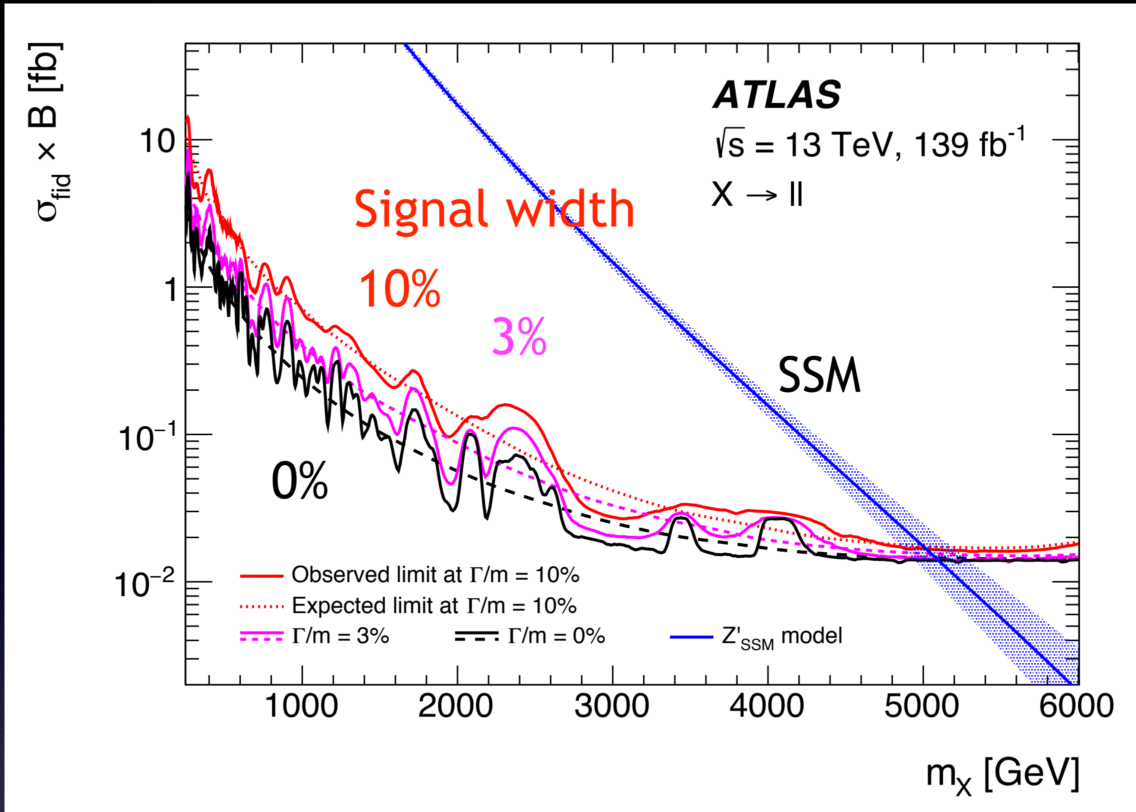
Determined
by the fit (float)





Lower limit on $m_{Z'}$

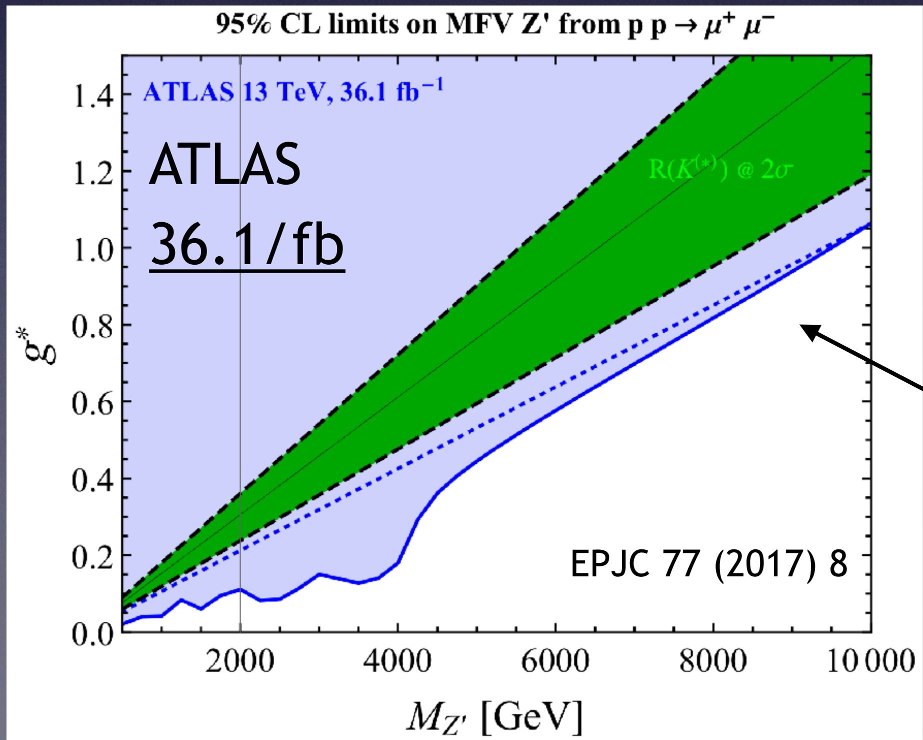
	width	obs.	exp.
Z'_{ψ}	0.5%	4.5 TeV	4.5 TeV
Z'_{χ}	1.2%	4.8	4.8
Z'_{SSM}	3.0%	5.1	5.1

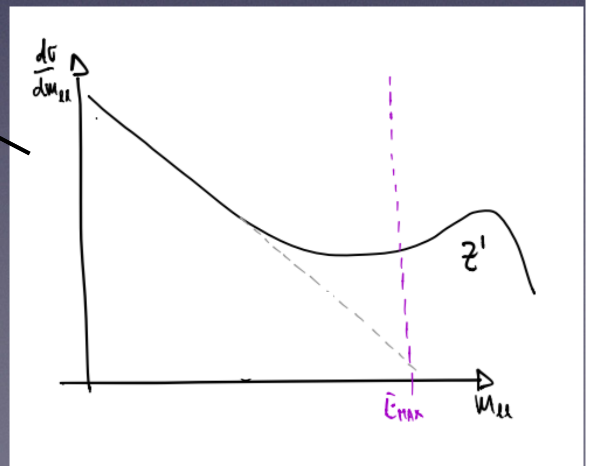


Lower limit on $m_{Z'}$

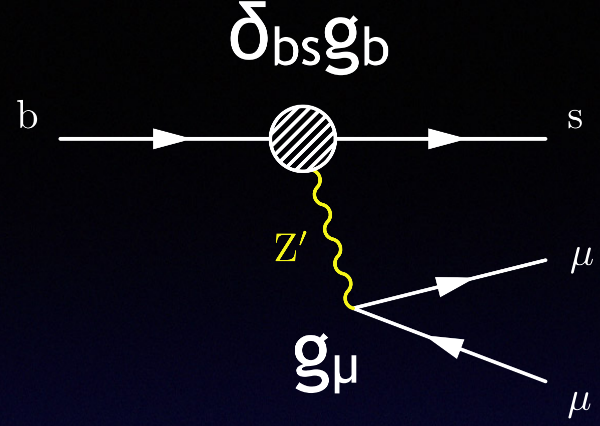
	width	obs.	exp.
Z'_ψ	0.5%	4.5 TeV	4.5 TeV
Z'_χ	1.2%	4.8	4.8
Z'_{SSM}	3.0%	5.1	5.1

In the context of B-anomaly …
We can recast this result into one of the plausible Z' models
(e.g. MFV Z')





- We have to assume minimum coupling scenario

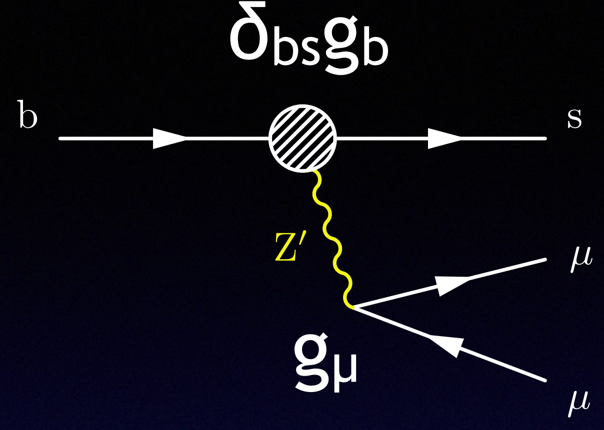


- Starting from minimum Lagrangian

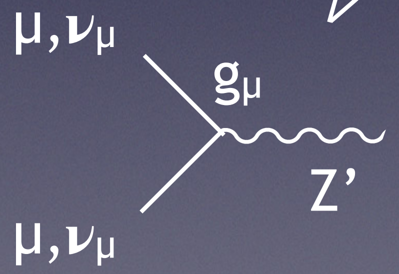
$$\mathscr{L} \supset Z'^{\mu}[g_\mu \bar{\mu}\gamma^\mu \mu + g_\mu \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu + g_b \sum_{q=t,b} \bar{q}\gamma^\mu P_L q + (g_b \delta_{bs} \bar{s}\gamma^\mu P_L b)]$$

- We have to assume minimum coupling scenario

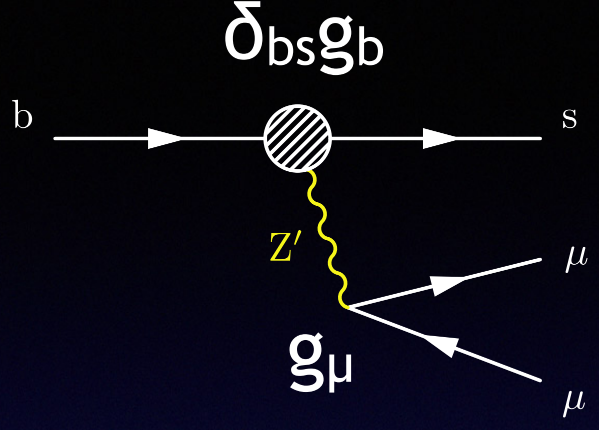
- Starting from minimum Lagrangian



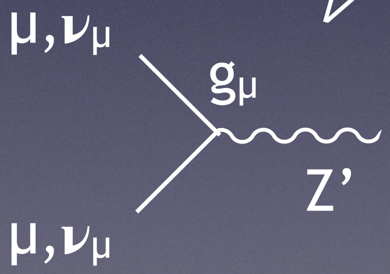
$$\mathscr{L} \supset Z'^{\mu}[g_\mu \bar{\mu}\gamma^\mu \mu + g_\mu \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu + g_b \sum_{q=t,b} \bar{q}\gamma^\mu P_L q + (g_b \delta_{bs} \bar{s}\gamma^\mu P_L b)]$$

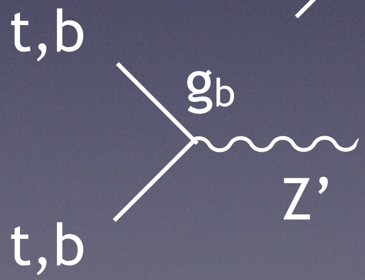


- We have to assume minimum coupling scenario
- Starting from minimum Lagrangian

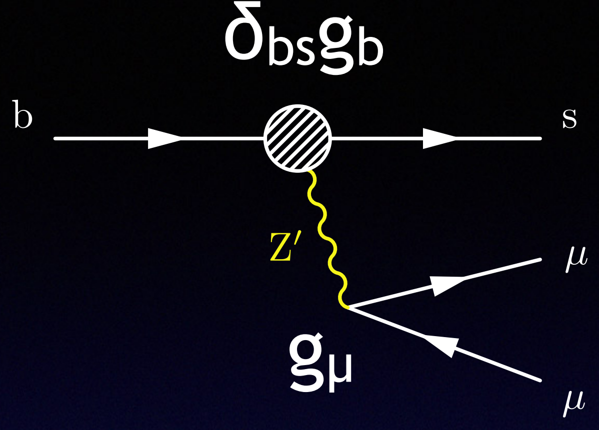


$$\mathscr{L} \supset Z'^{\mu}\Big[g_\mu \bar{\mu}\gamma^\mu \mu + g_\mu \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu + g_b \sum_{q=t,b} \bar{q}\gamma^\mu P_L q + (g_b \delta_{bs} \bar{s}\gamma^\mu P_L b)\Big]$$

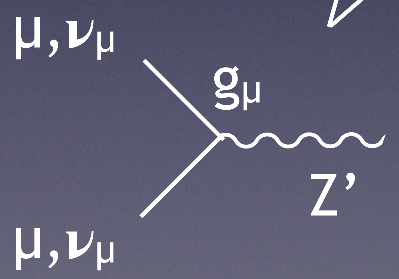


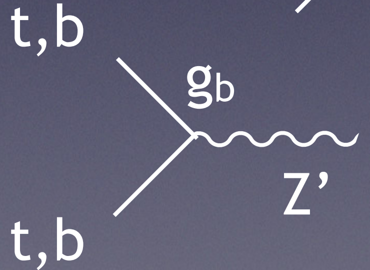


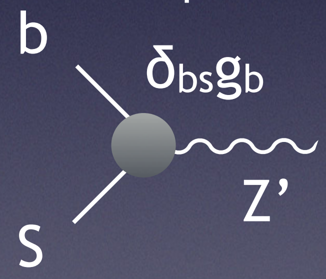
- We have to assume minimum coupling scenario
- Starting from minimum Lagrangian



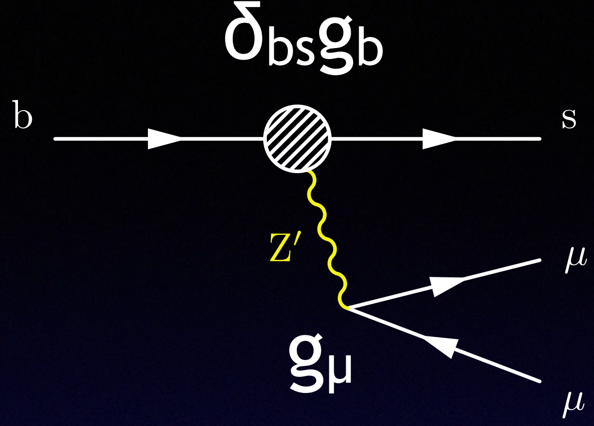
$$\mathscr{L} \supset Z'^{\mu}\left[g_\mu \bar{\mu}\gamma^\mu \mu + g_\mu \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu + g_b \sum_{q=t,b} \bar{q}\gamma^\mu P_L q + (g_b \delta_{bs} \bar{s}\gamma^\mu P_L b)\right]$$



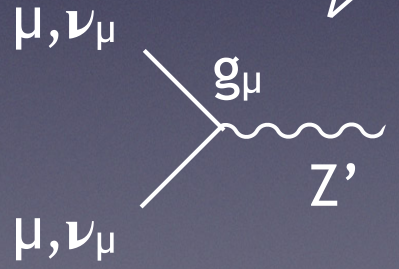


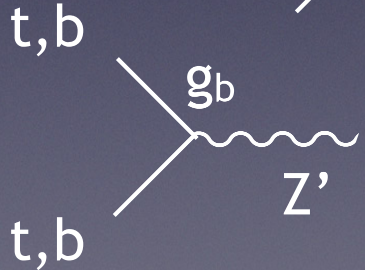


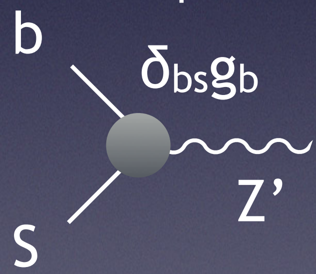
- We have to assume minimum coupling scenario
- Starting from minimum Lagrangian



$$\mathscr{L} \supset Z'^{\mu}\Big[g_\mu \bar{\mu}\gamma^\mu \mu + g_\mu \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu + g_b \sum_{q=t,b} \bar{q}\gamma^\mu P_L q + (g_b \delta_{bs} \bar{s}\gamma^\mu P_L b)\Big]$$







Search signature:
$Z' \to \mu\bar{\mu}$, $t\bar{t}$, $b\bar{b}$

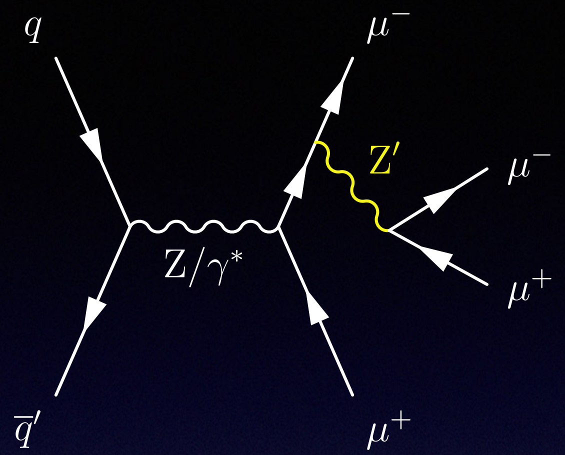
Flavoured Z’

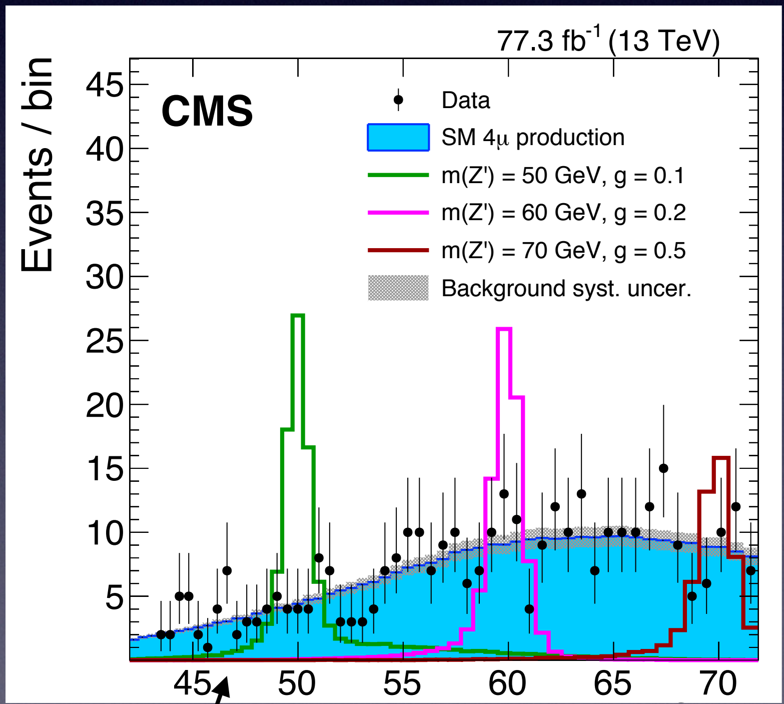
CMS, 77.3/fb

PLB 792 (2019) 345

Search for Z’ that only couples to μ

- Require 4 muons with m(4μ) ~ m_Z
- Search for the “bump” in m(μμ)

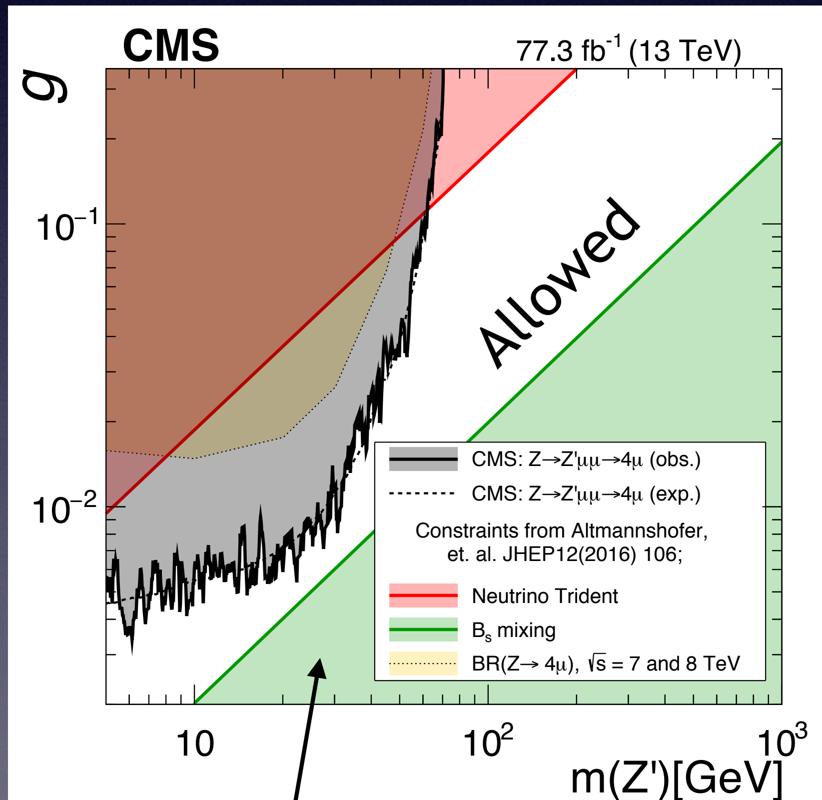




m(μμ) GeV

Main BG: Z → μμɣ* → 4μ,
evaluated by simulation

Coupling strength to muon (g)

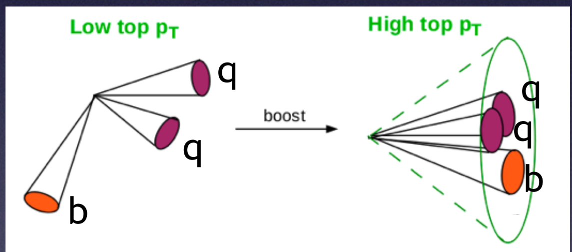


Small coupling to muon → large δ_{bs} to explain B-anom. → conflict with Bs mixing

Experimental challenges - boosted object tagging

- Search for high-mass Z’ → $t\bar{t}$, $b\bar{b}$ is motivated
- As the Z’ becomes heavier, t/b-quark carry more p_T, which makes them difficult to identify

Top-quark

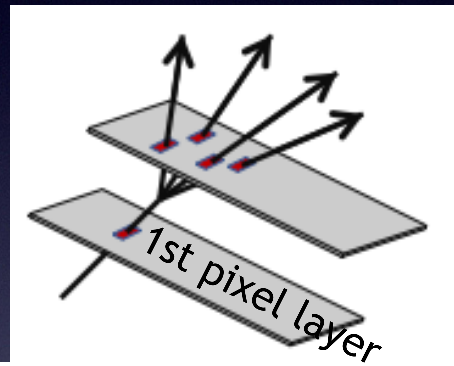


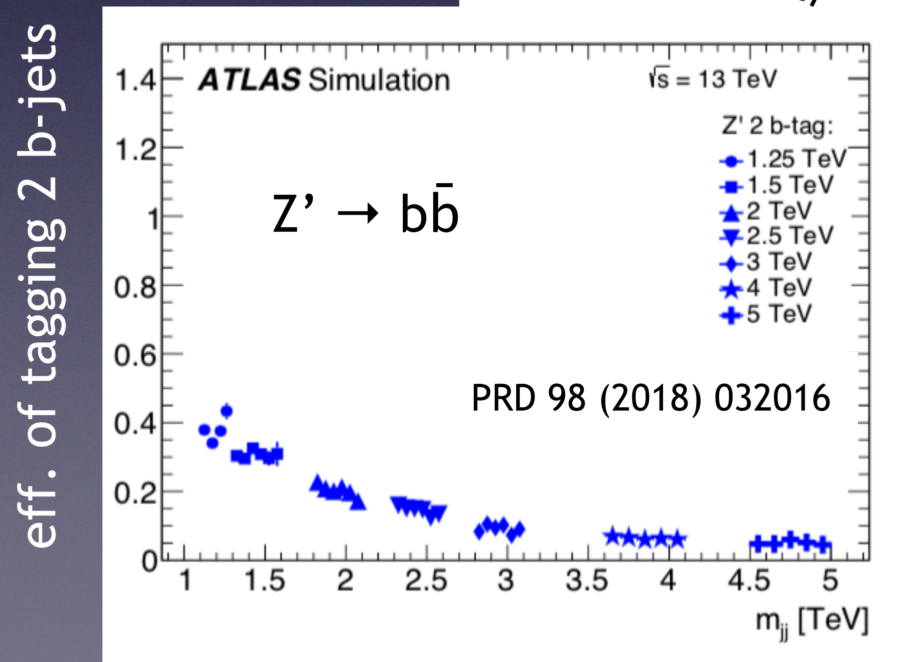
eff. ~ 50% @ fake rate ~ 3%

arXiv:1902.10077 (ATLAS)
EPJC 78 (2018) 565 (ATLAS)
JHEP 07 (2017) 001 (CMS)

b-quark

High p_T b-jet can travel a lot, and one cannot reconstruct secondary vertex



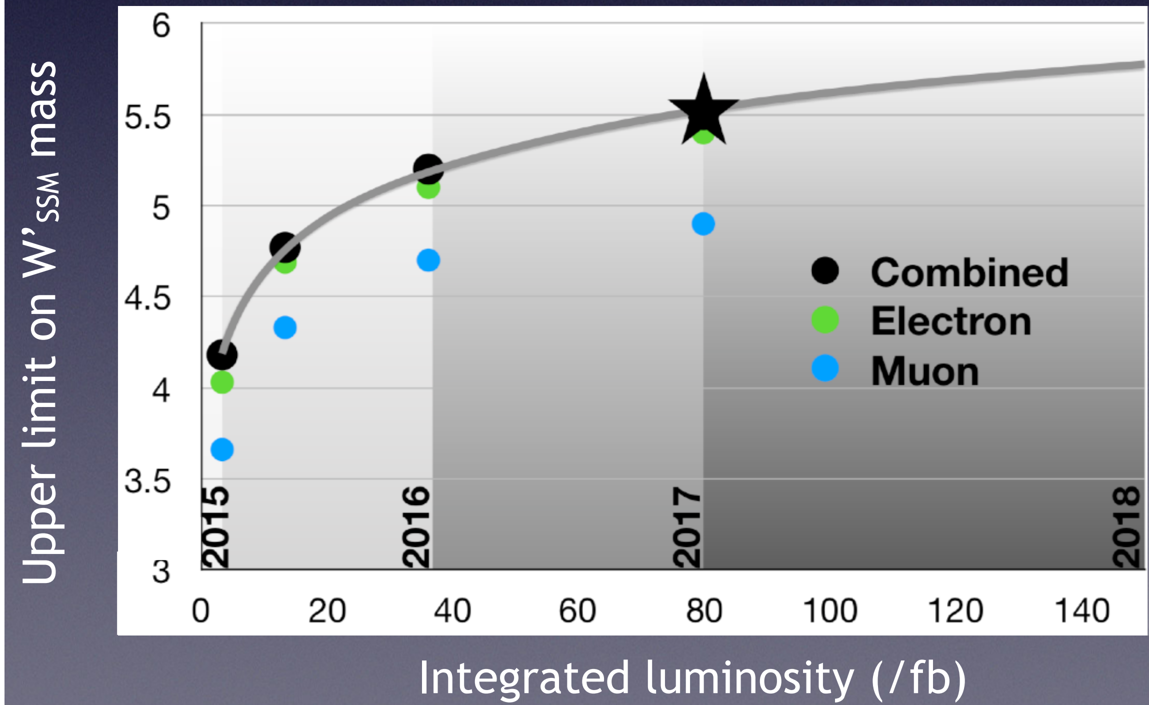


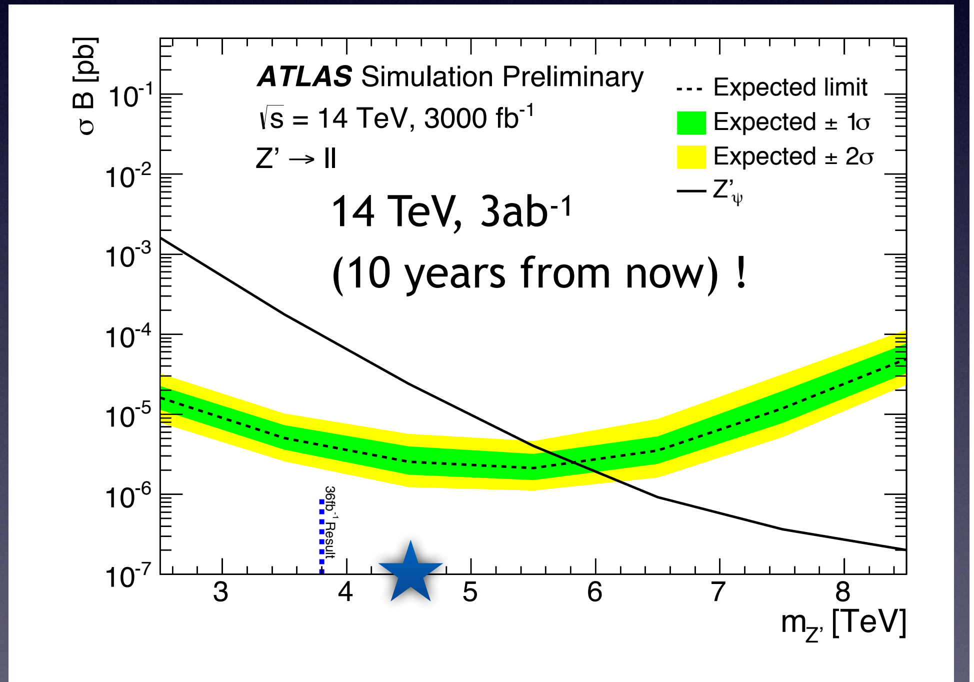
Universität Zürich UZH

Summary

- Given the B-physics anomalies, we started dedicated searches
    - assume minimum coupling (i.e. limit production mode/final state)
    - Search for wide resonance

arXiv: 1812.07831



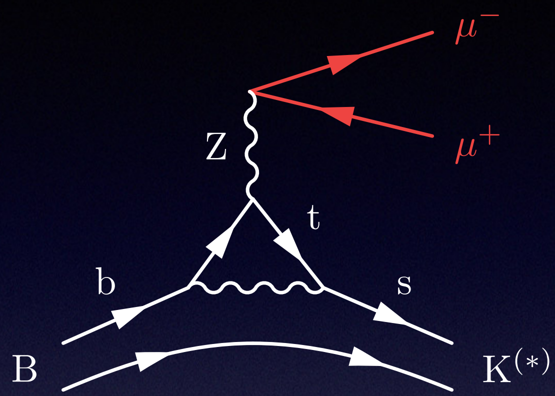


We need new idea, new final states …

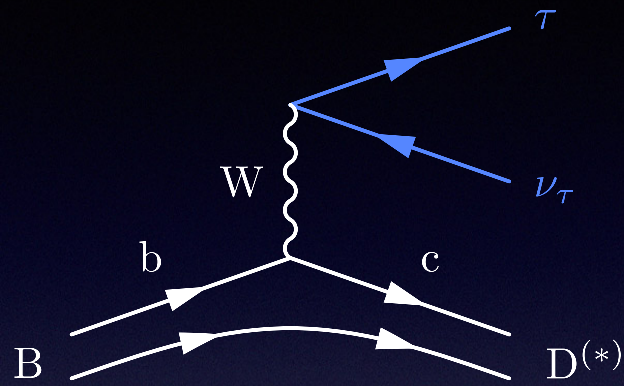
(rather than just relying on increased luminosity)

NP scale (Λ), indicated by anom. might be within reach by ATLAS/CMS

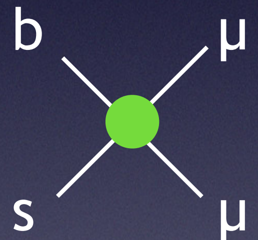
b → sμμ



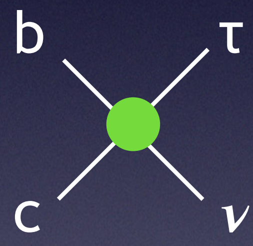
b → cτν



$$\frac{1}{\Lambda^2}(\overline{\psi}_i \psi_j)^2$$



$$\frac{1}{30\text{TeV}^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma^\mu \mu_L)$$



$$\frac{1}{2.5\text{TeV}^2}(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu \nu_L)$$

Within reach at LHC

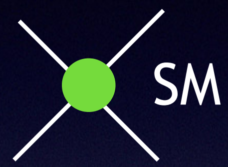
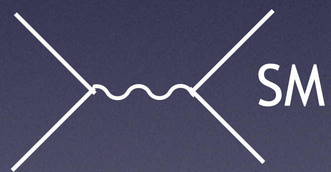
$$\frac{c_{ij}}{\Lambda^2}(\overline{\psi}_i \psi_j)^2$$

if Yukawa-type coupling …
Λ ~ O(a few) TeV

Possibility of Combined explanation

There are other reasons !

→ Related to S/B

	Background	Signal
Indirect measurements (B-factory)	 $\sim G_F^2$	 $\sim (G_F^{NP})^2$
Direct measurements (ATLAS & CMS)	 $\sim \dfrac{(G_F m_{W/Z}^2)^2}{\hat{s}}$	 $\sim (G_F^{NP})^2 \hat{s}$

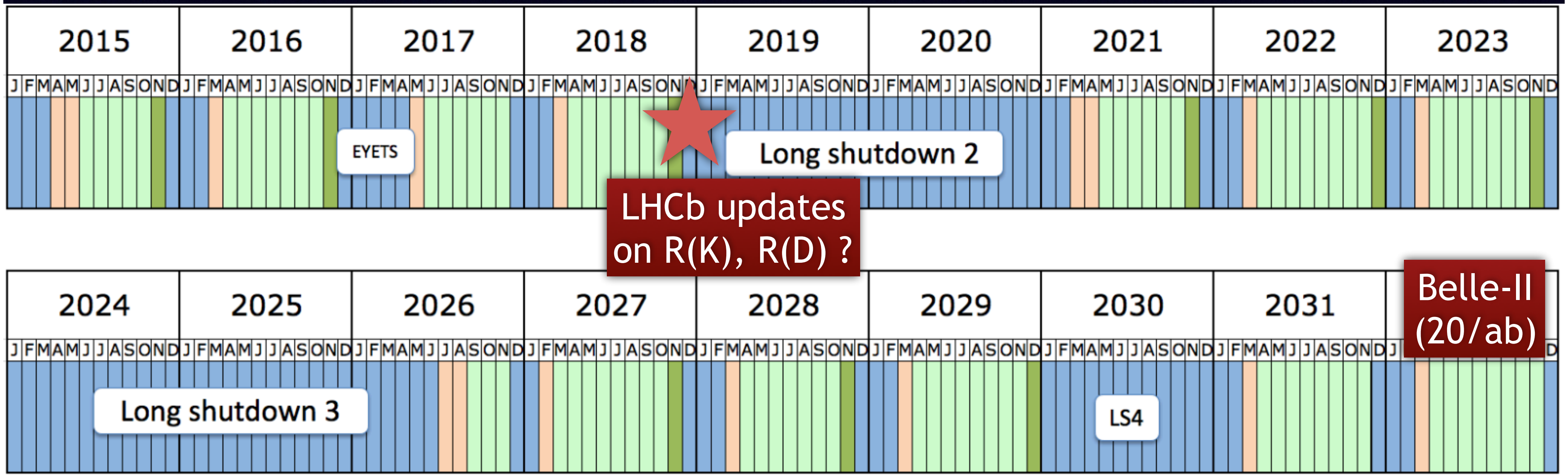
S/B ratio is enhanced

Run-2

13 TeV, **150/fb**

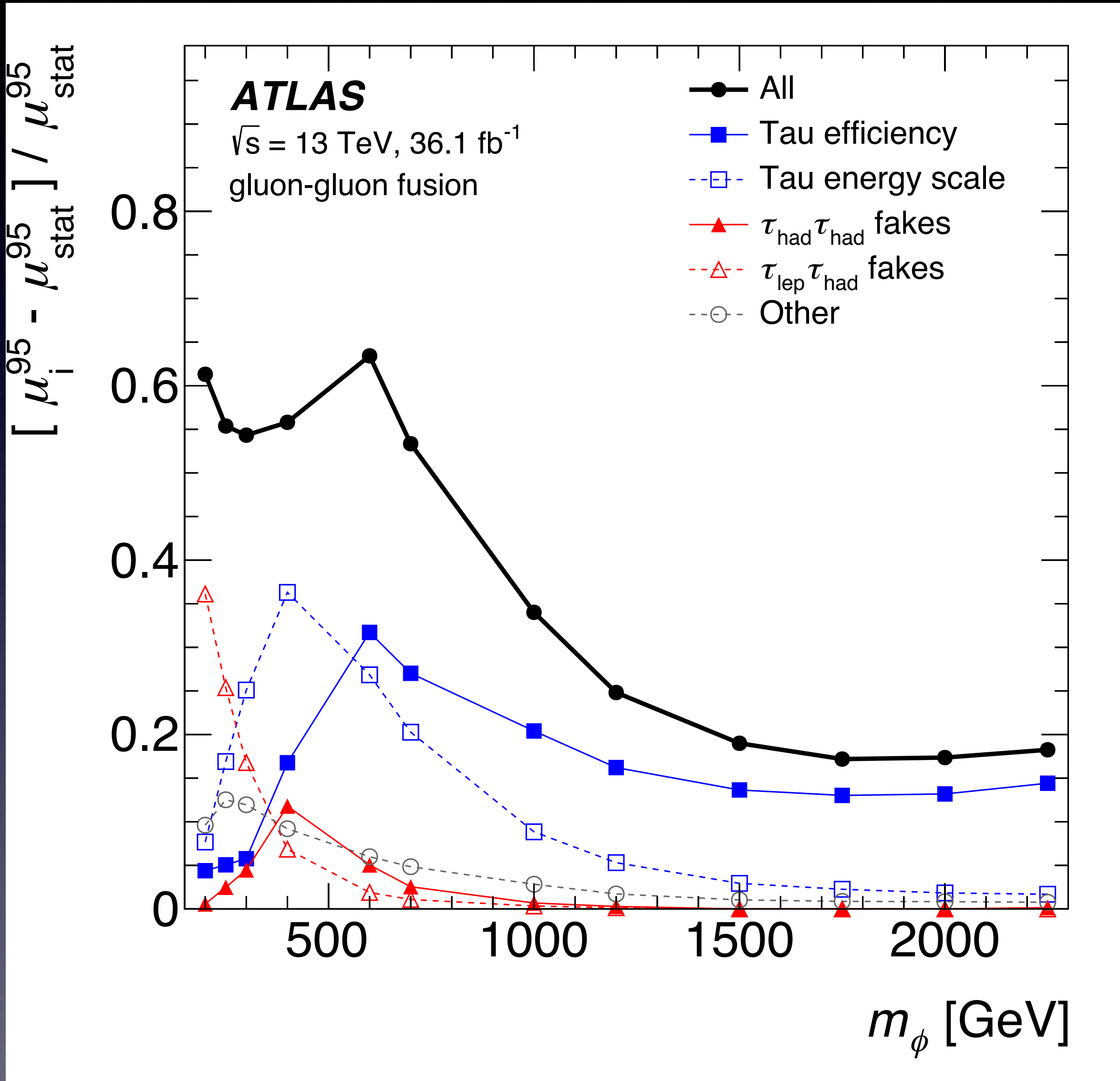
Run-3

14 TeV, 300/fb



HL-LHC

14 TeV, 3000/fb



ATLAS
√s = 13 TeV, 36.1 fb-1
gluon-gluon fusion
All
Tau efficiency
Tau energy scale
τhad τhad fakes
τlep τhad fakes
Other
[μi95 - μstat95] / μstat95
0
0.2
0.4
0.6
0.8
500
1000
1500
2000
mφ [GeV]