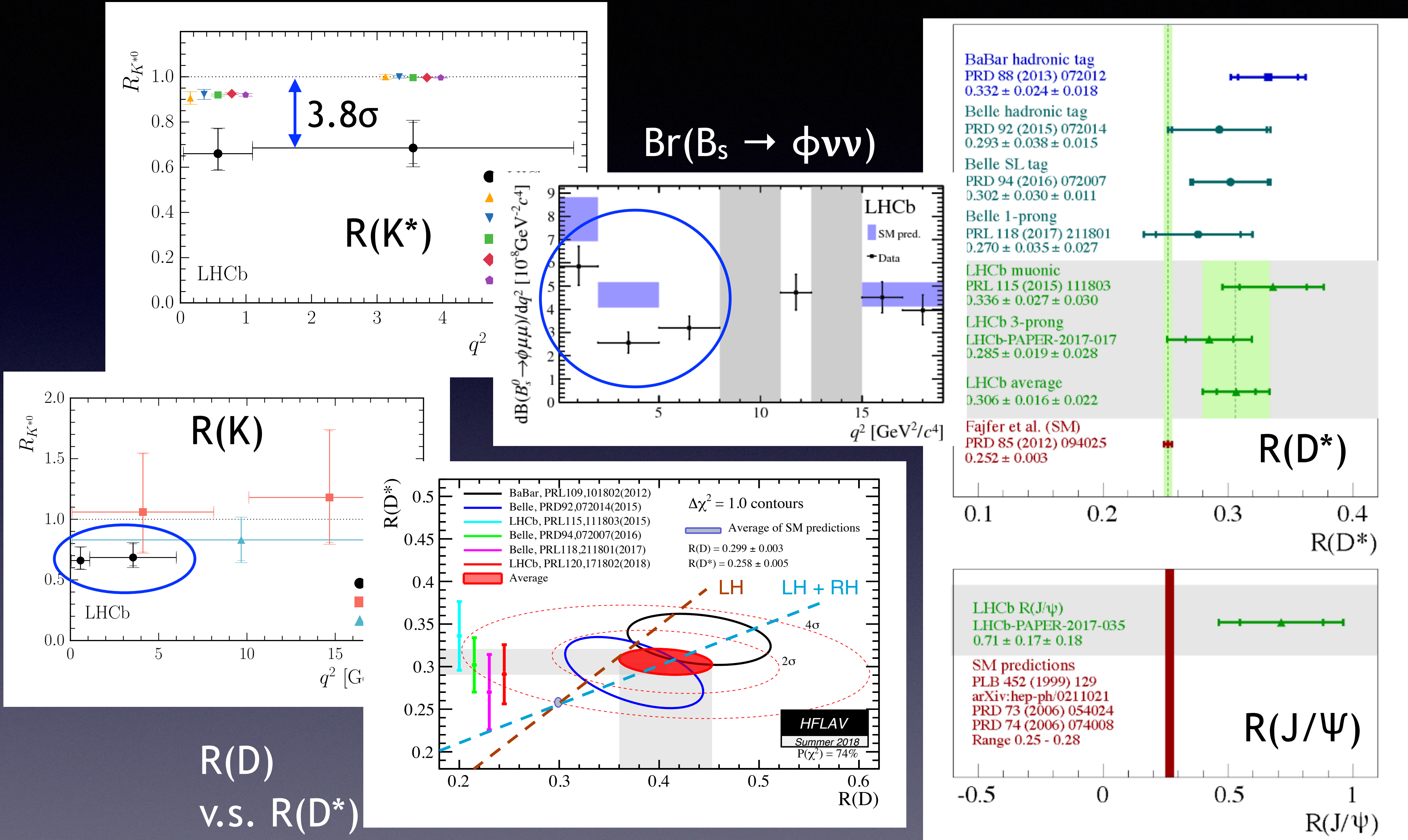
Testing B-anomaly at ATLAS & CMS

Yuta Takahashi
(Zurich)

Q. Why ATLAS & CMS care about B-anom. ?

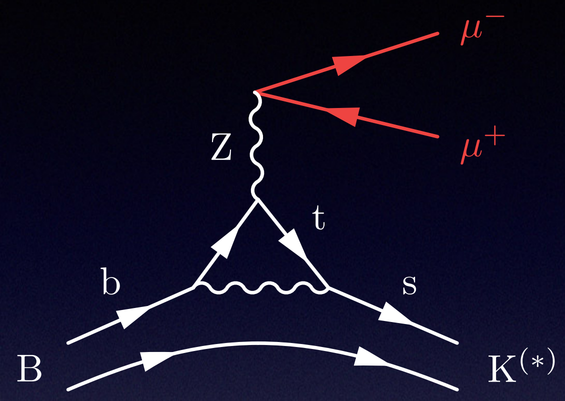


Indirect measurement with large statistics.

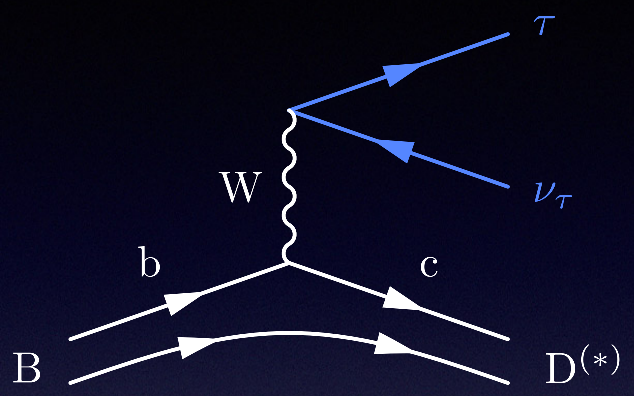
What is the advantage of ATLAS & CMS measurement ?

Answer: Λ, indicated by anom. might be within reach by ATLAS/CMS

$b \to s\mu\mu$



$b \to c\tau\nu$



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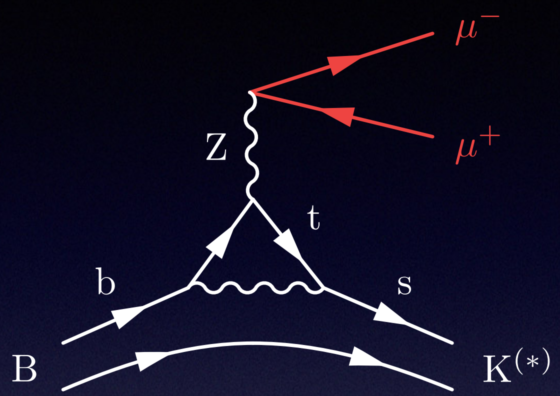
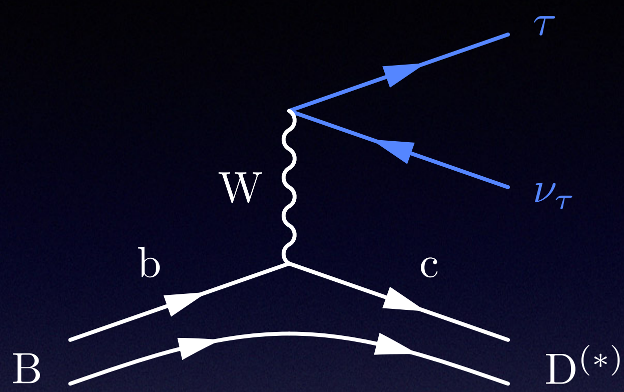
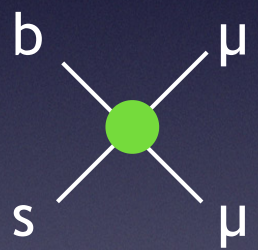
b → sμμ



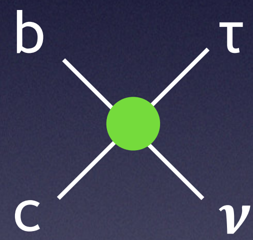
b → cτν



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



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



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

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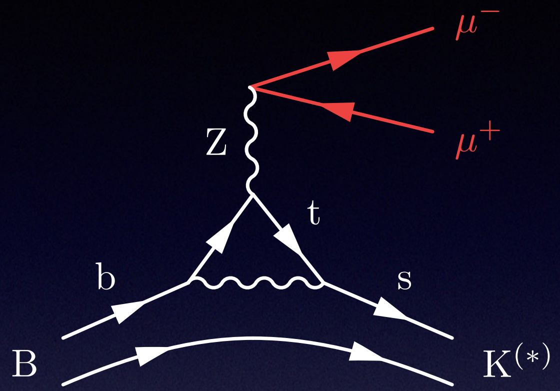

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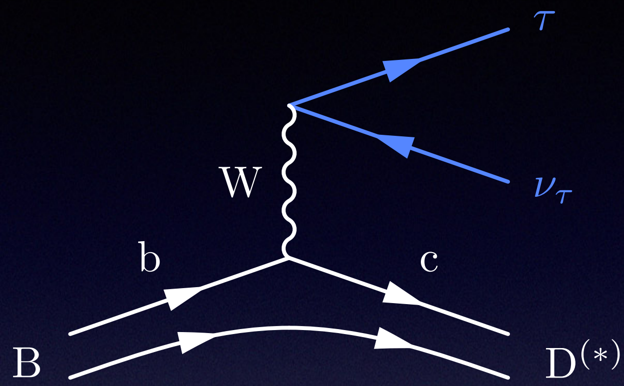

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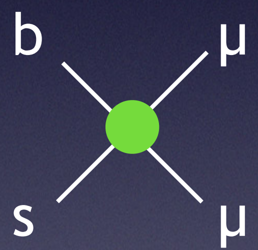

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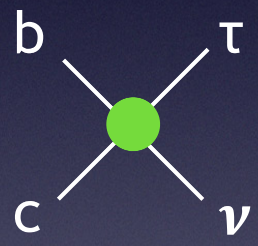

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↓

Within reach
at LHC

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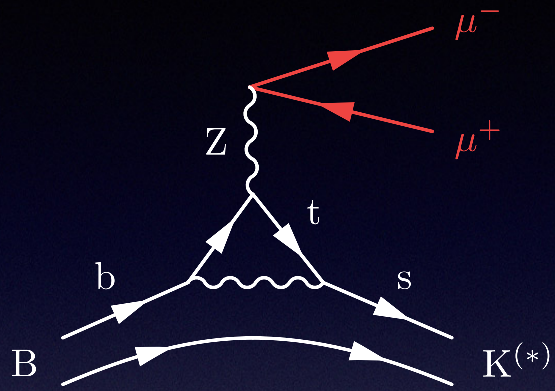

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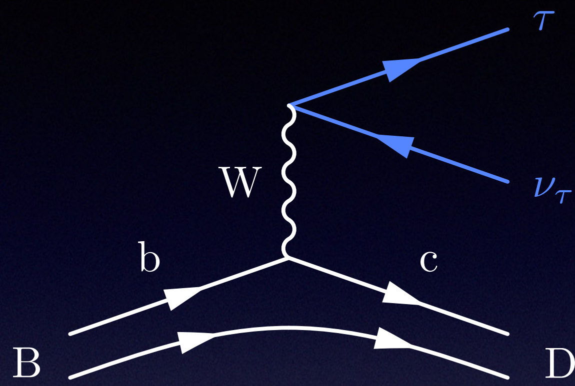

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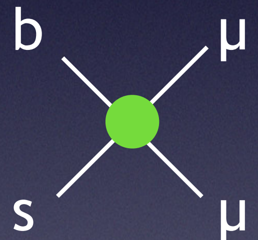

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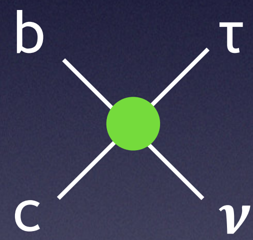

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$$\frac{c_{ij}}{\Lambda^2}(\overline{\psi}_i \psi_j)^2$$

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

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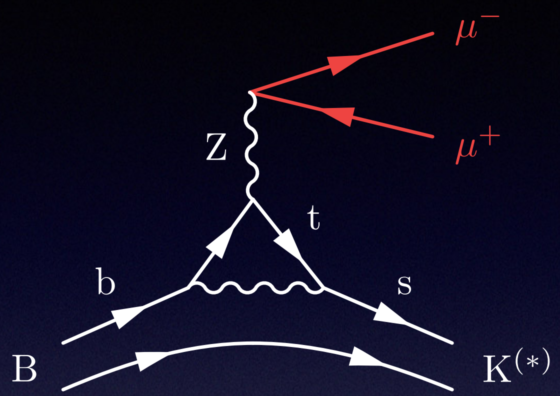

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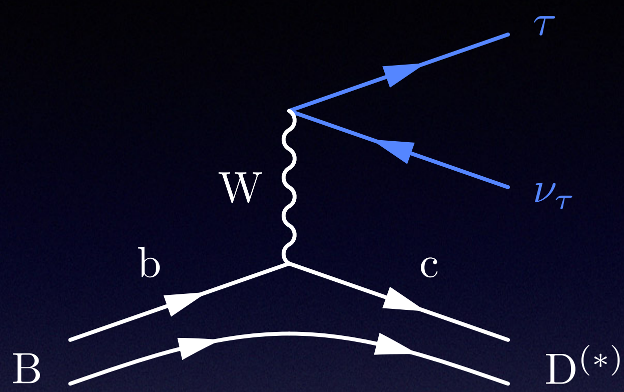

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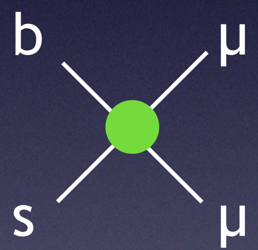

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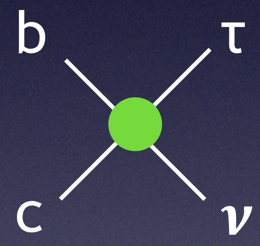

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Within reach at LHC

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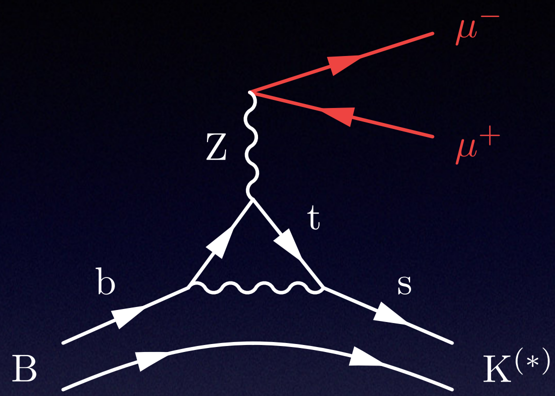

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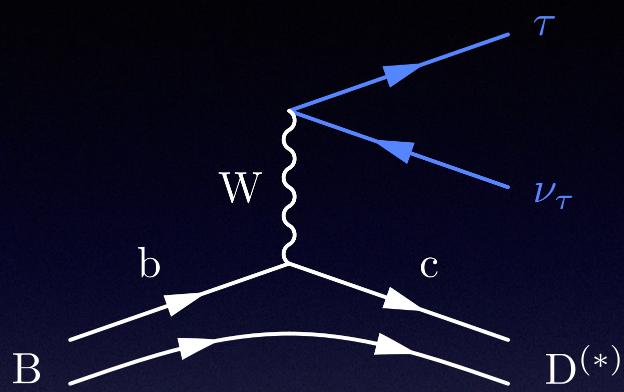

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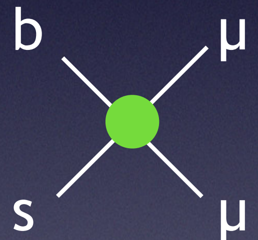

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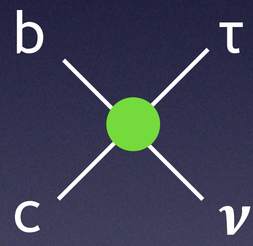

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Within reach at LHC

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

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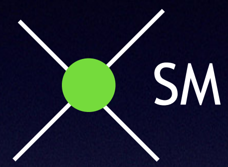
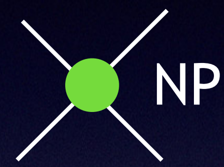
Possibility of Combined explanation

There are other reasons !

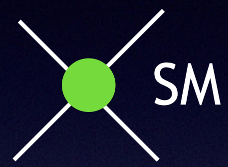
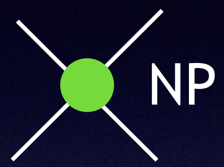
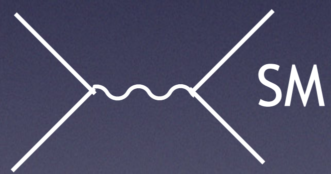
→ Related to S/B

Indirect measurements
(B-factory)

Background	Signal
	
$\sim G_F^2$	$\sim (G_F^{NP})^2$

There are other reasons !

→ Related to S/B

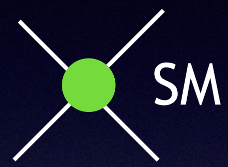
	Background	Signal
Indirect measurements (B-factory)	 $\sim G_F^2$	 $\sim (G_F^{NP})^2$
Direct measurements (ATLAS & CMS)	 $\sim \frac{(G_F m_{W/Z}^2)^2}{\hat{s}}$	 $\sim (G_F^{NP})^2 \hat{s}$

There are other reasons !

→ Related to S/B

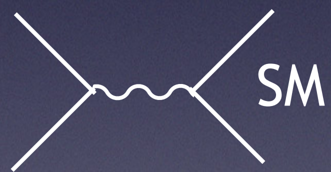
Background | Signal

Indirect measurements (B-factory)



$\sim G_F^2$ $\quad$ $\sim (G_F^{NP})^2$

Direct measurements (ATLAS & CMS)

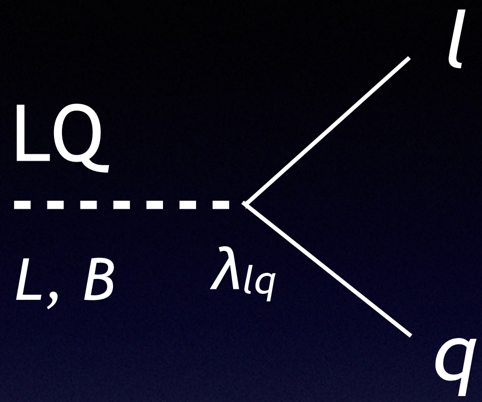


$$\sim \frac{(G_F m_{W/Z}^2)^2}{\hat{s}} \qquad \sim (G_F^{NP})^2 \hat{s}$$

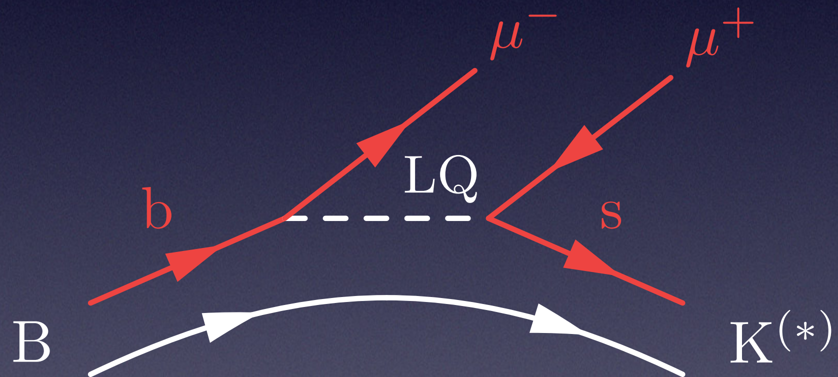
S/B ratio is enhanced

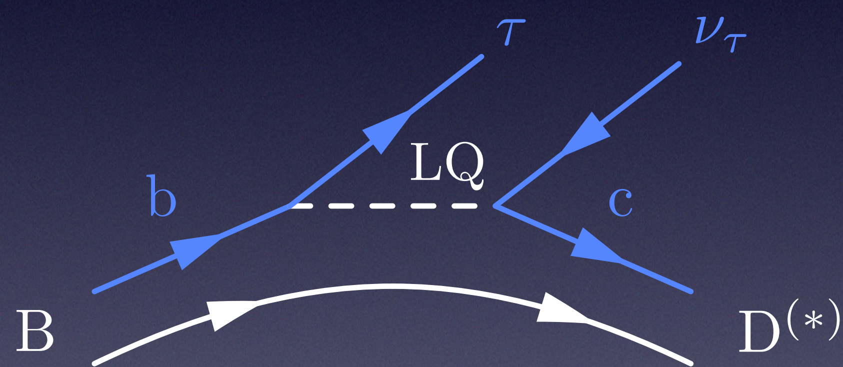
1. Review latest search results on
   - Leptoquark
   - Z’ and W’
2. Future prospects

Leptoquark (LQ)



- Fractional electric charge (±5/3, ±4/3, ±2/3, ±1/3 e)
- Spin 0 (scalar) or 1 (vector)





If we want to explain both anomalies at the same time, we need hierarchical coupling

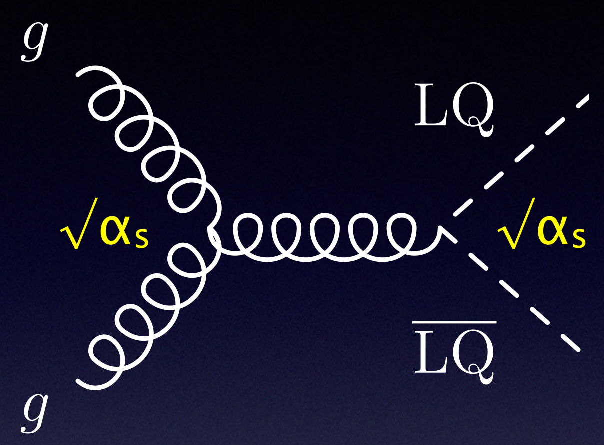
$$\lambda_{\ell q} \sim \begin{array}{c} \\ d/u' \\ s/c' \\ b/t' \end{array} \begin{array}{c} \begin{array}{ccc} e/\nu_e & \mu/\nu_\mu & \tau/\nu_\tau \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & \pm 0.01 & 0.1 \\ 0 & \mp 0.1 & 1 \end{pmatrix} \end{array}$$

Coupling to 3rd generation preferable !

How to find LQ at LHC ?

Production

- LQs are copiously pair-produced through strong interaction
- For scalar LQ, one can calculate cross-sections model independently (not the case for vector LQ)



Decay

Cover all possibilities

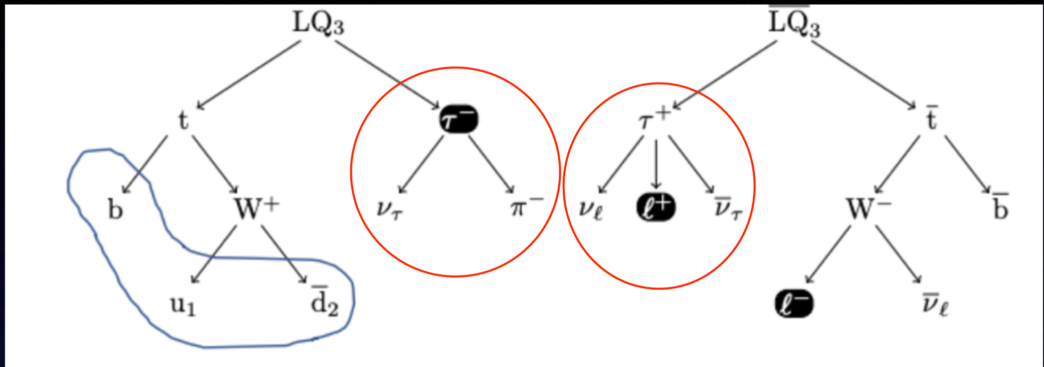
Lepton

LQLQ →	τ	ντ
t	2τ + 2t	2ν + 2t
b	2τ + 2b	2ν + 2b

Quark

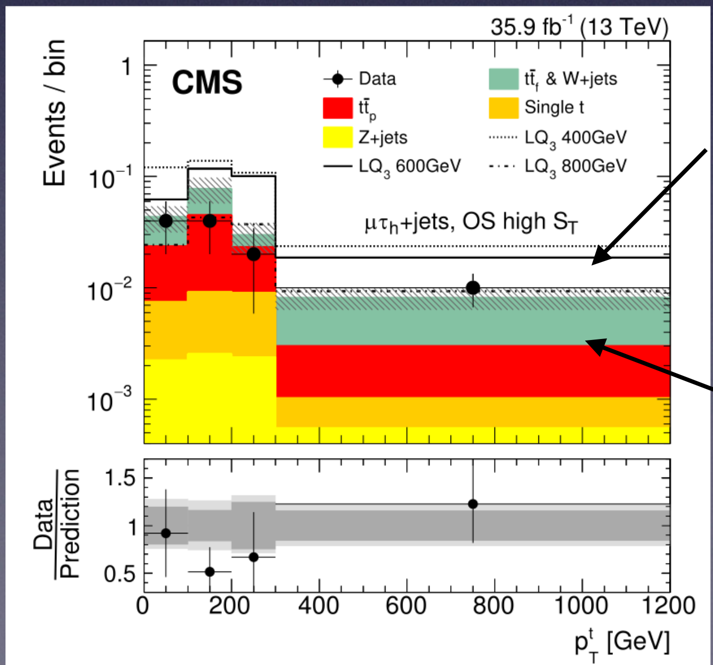
1 (2τ + 2t), 2 (2ν + 2t, 2ν + 2b), 3 (2τ + 2b)

LQLQ → 2τ + 2t



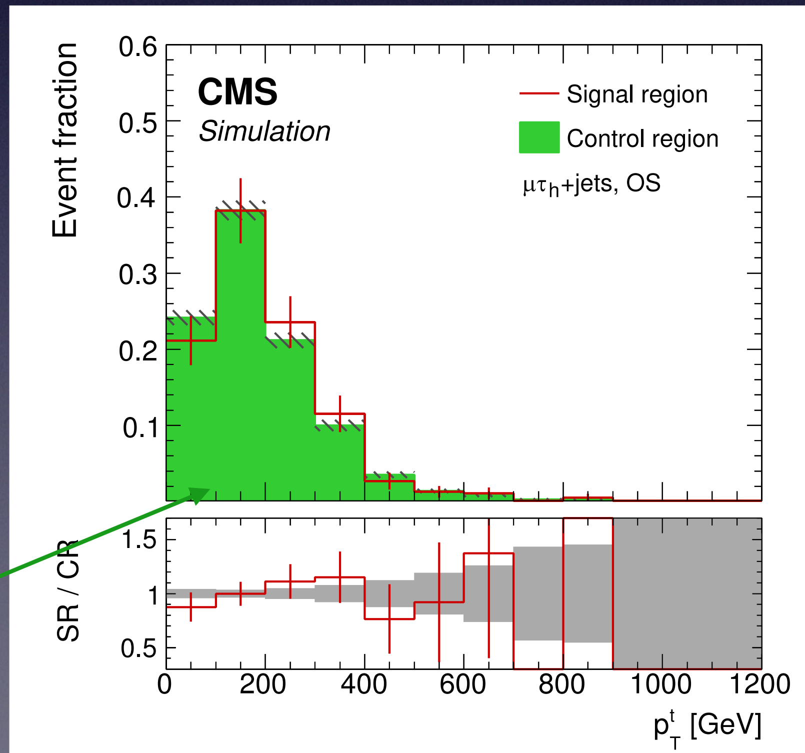
Defined 3 categories based on decay topology
- opposite sign $l\tau_h$
- Same-sign $l\tau_h$
- $l\tau_h\tau_h$

Construct p_T(top) by using jet triplet that gives best top-quark mass
→ use this for testing signal presence



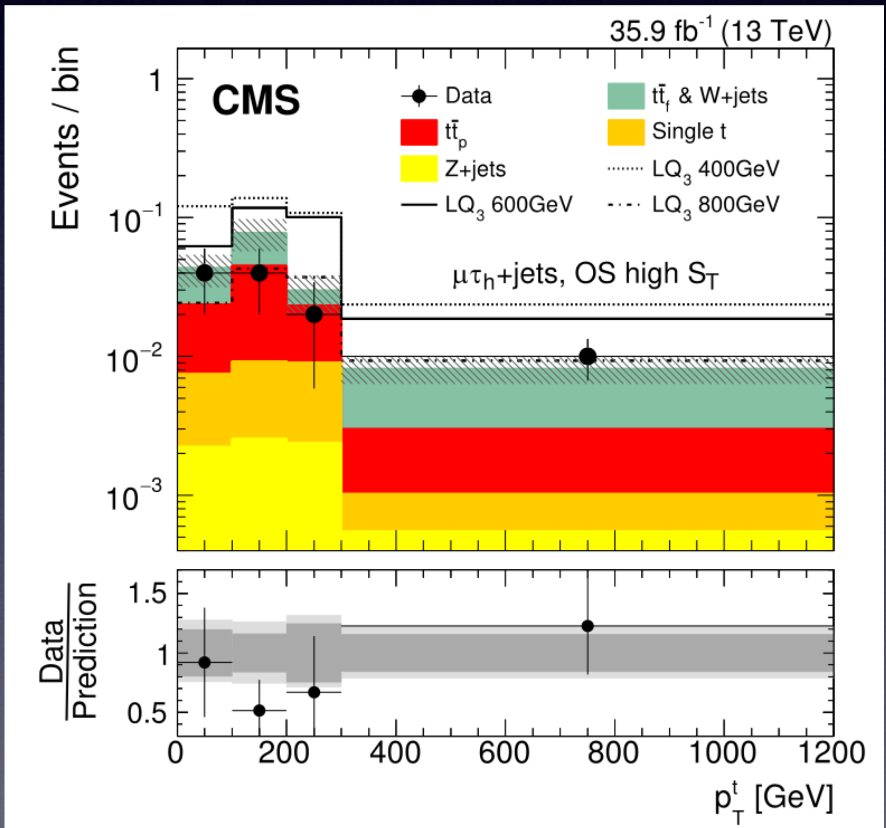
Signal has higher p_T(top)

ttbar with jets misidentified as τ_h
→ estimated using control region in data



(Inverted τ_h isolation)

To check signal presence,
prepare signal template and BG template
(signal template depends on LQ mass)
and we fit the data



# of signal events (for given LQ mass)

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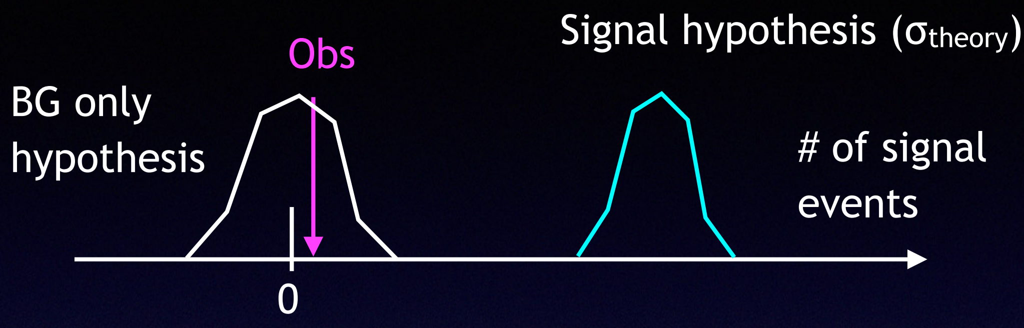

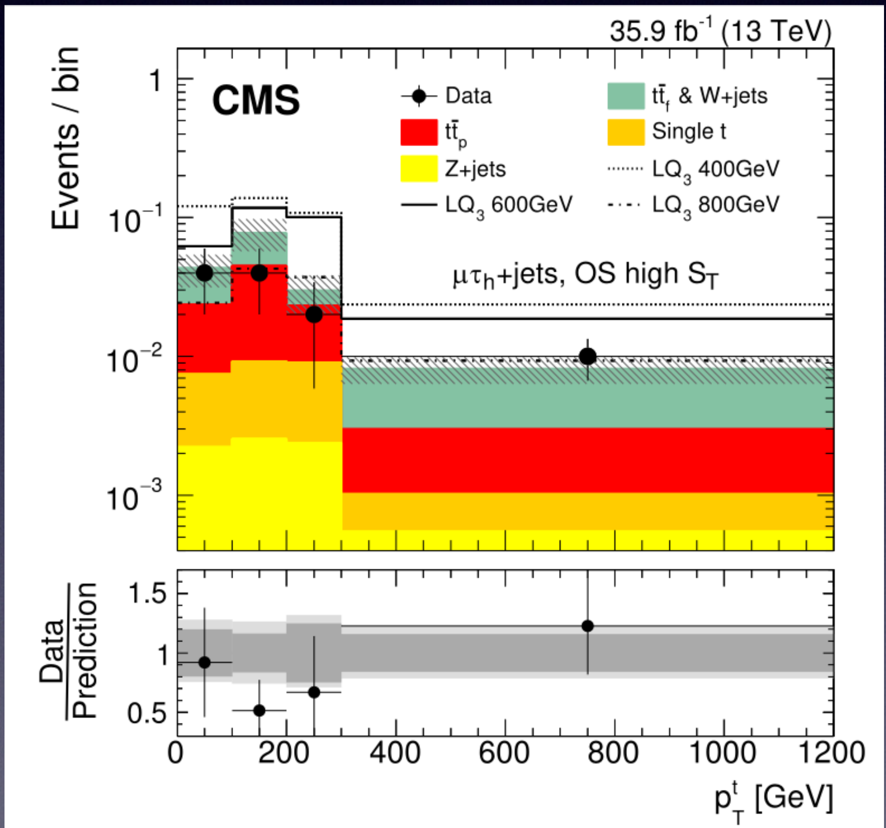

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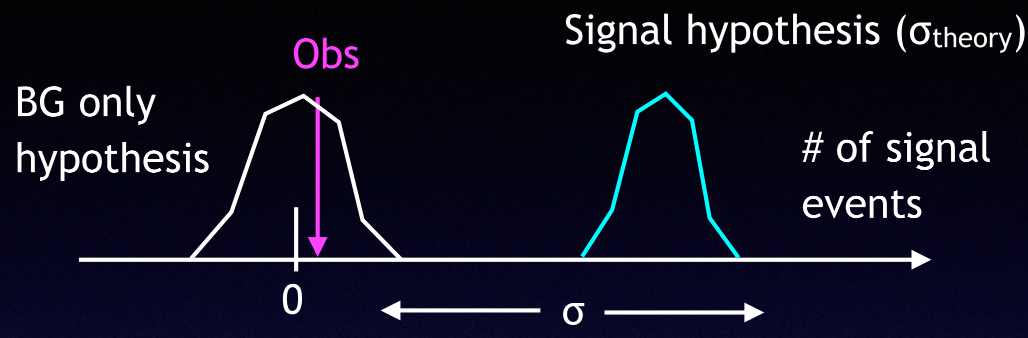

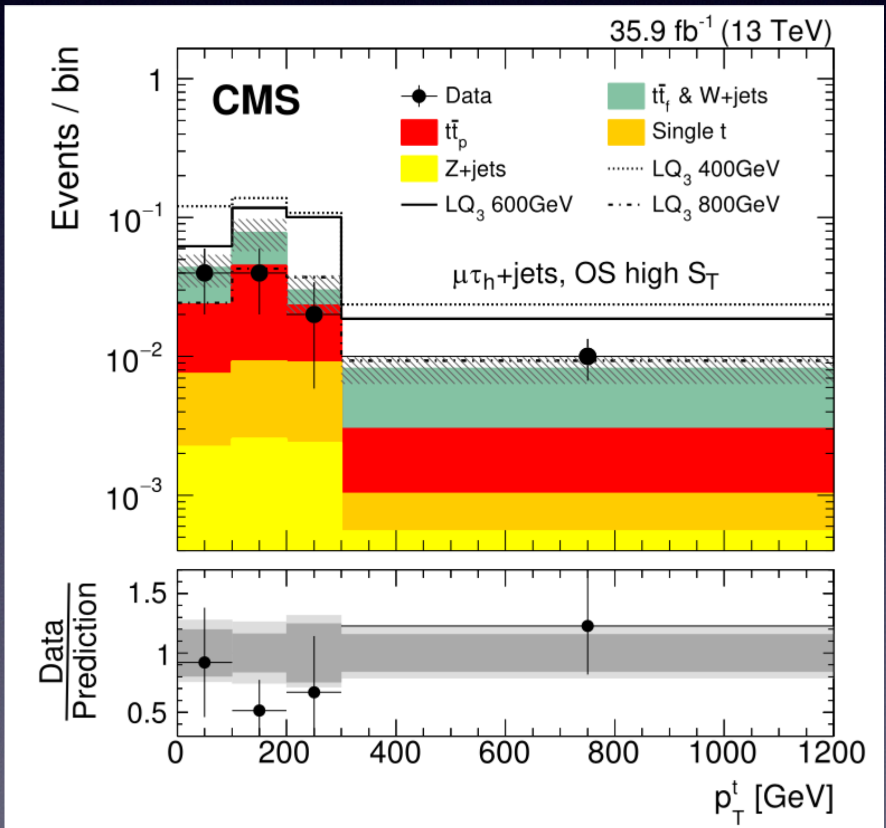

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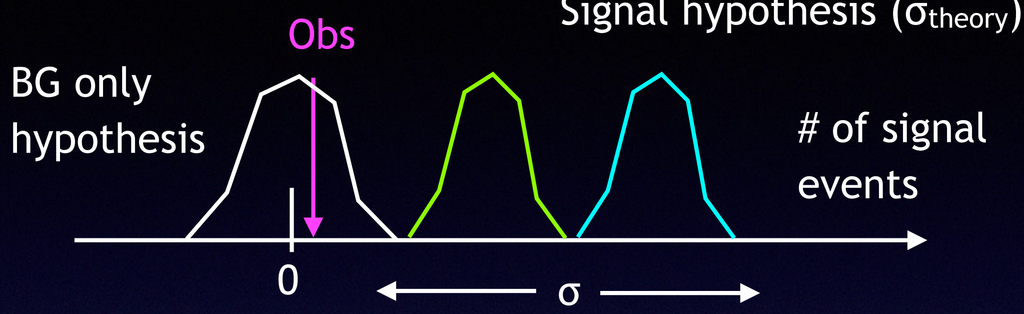

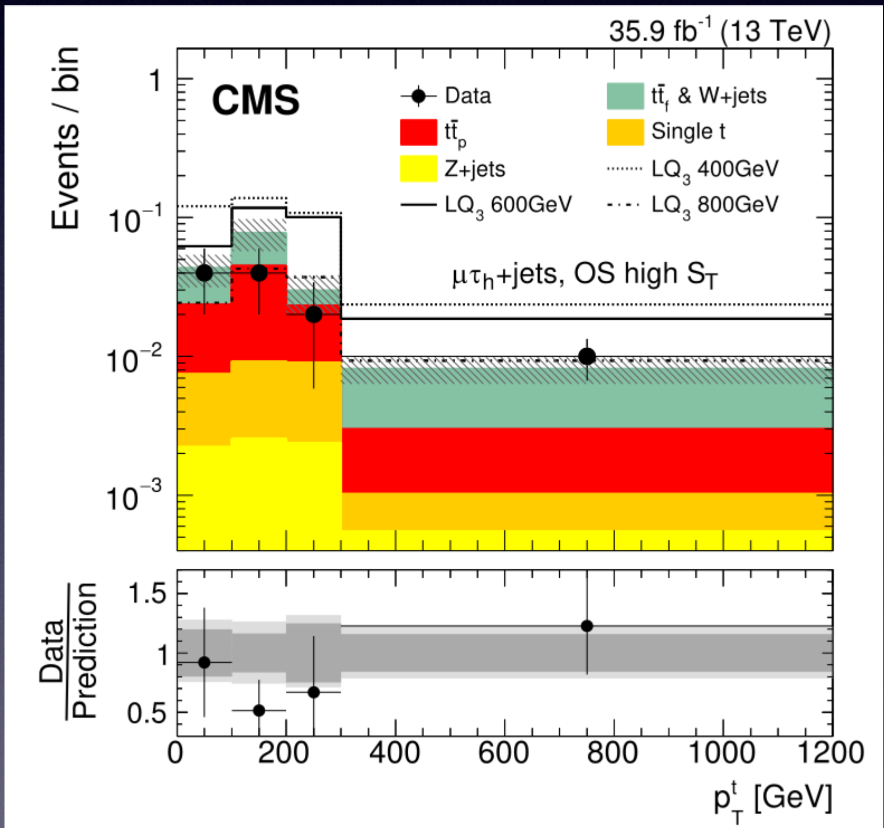

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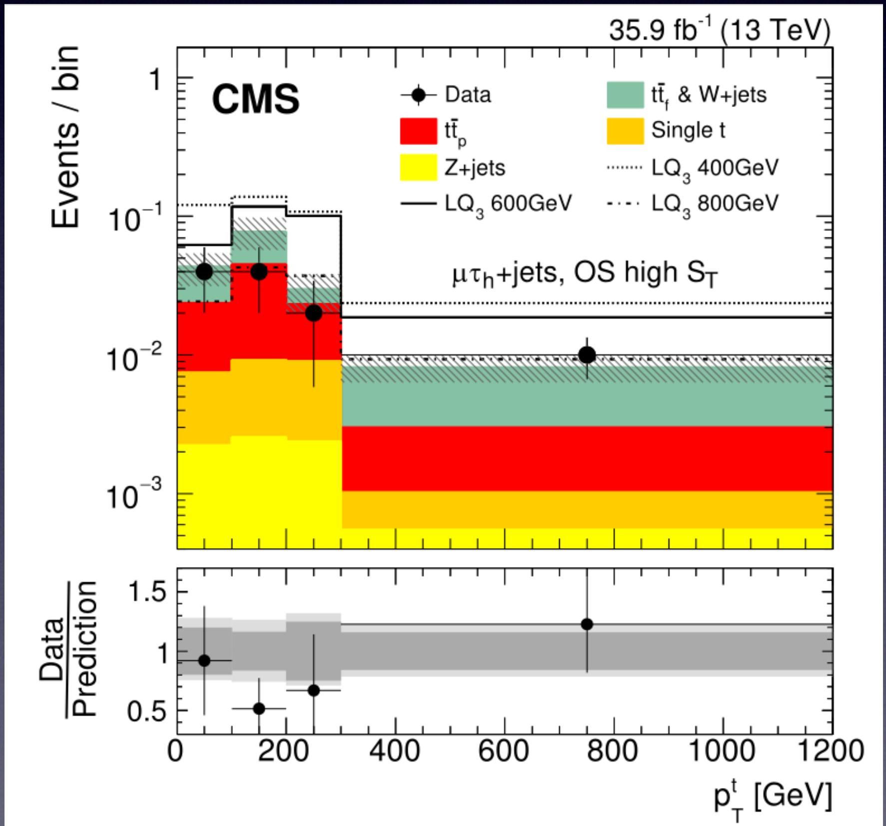

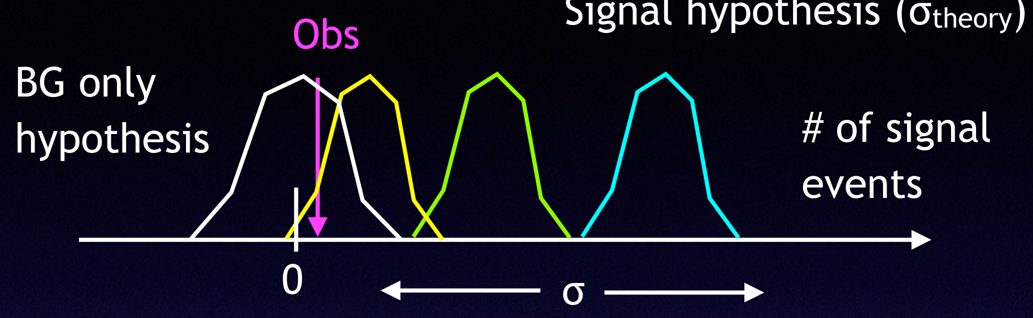

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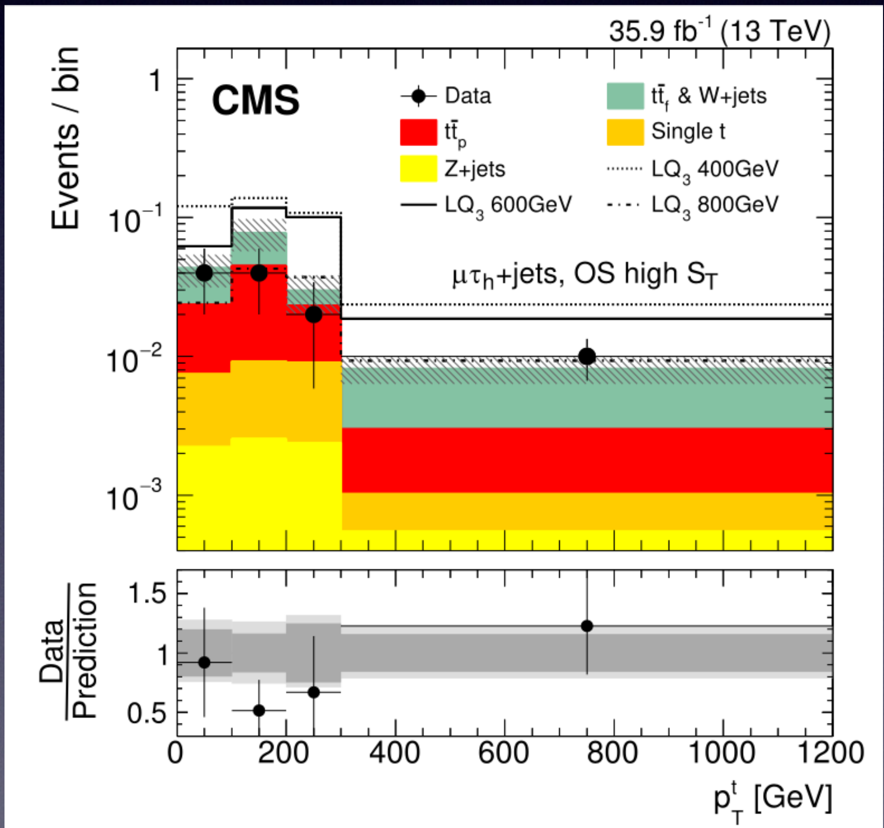

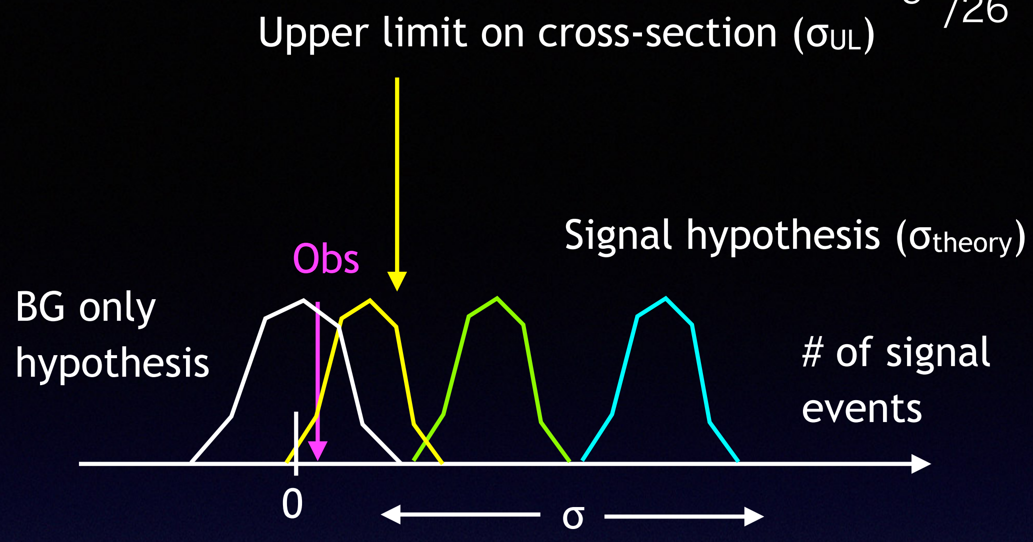

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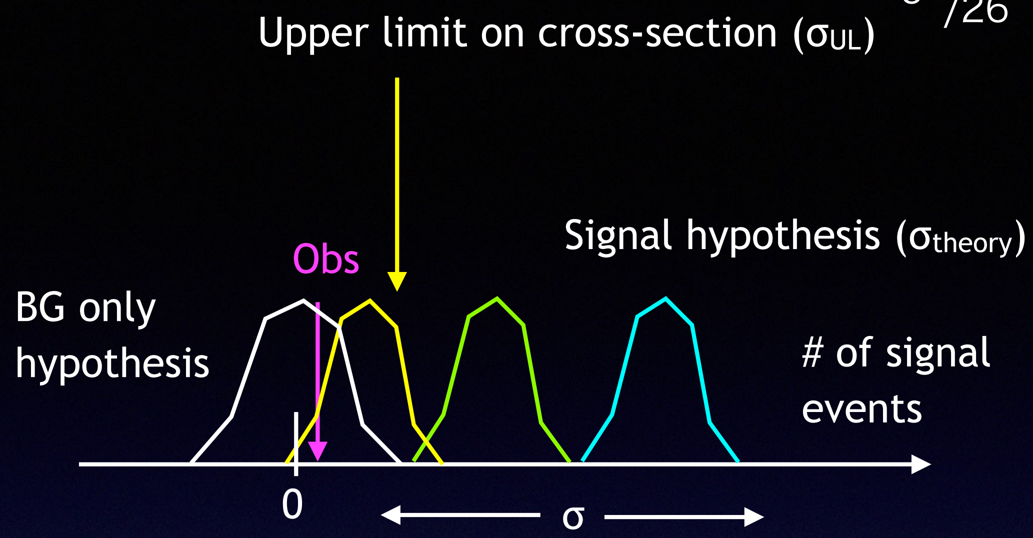
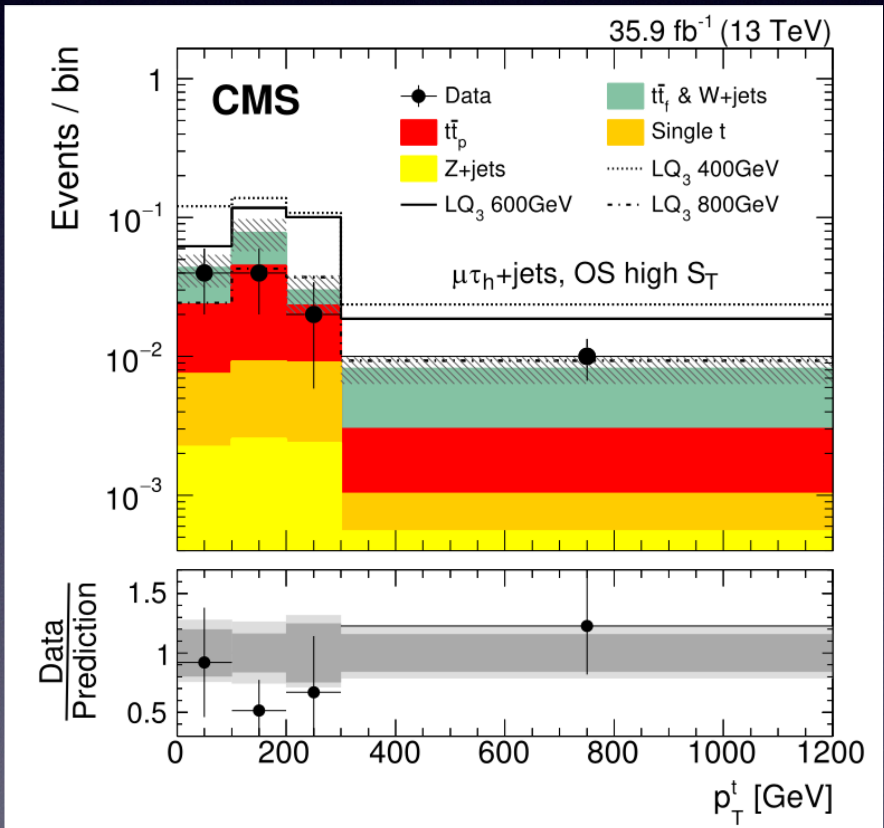


If $\sigma_{UL} < \sigma_{theory}$ → we can exclude signals



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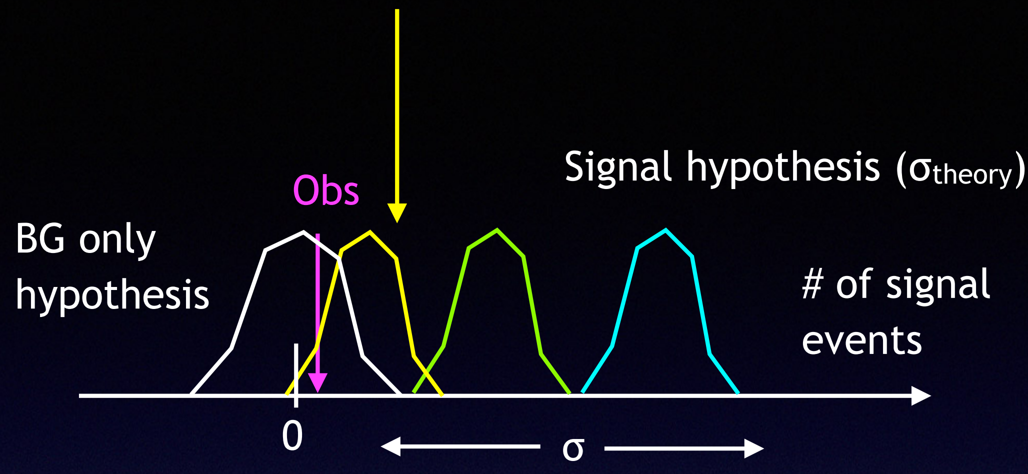

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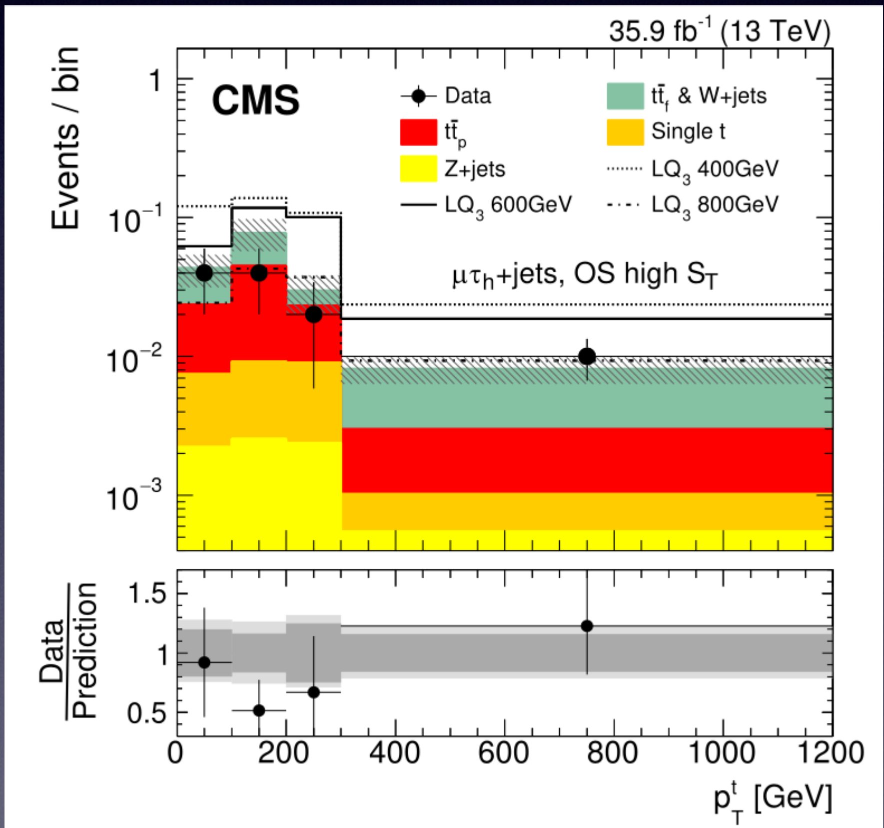

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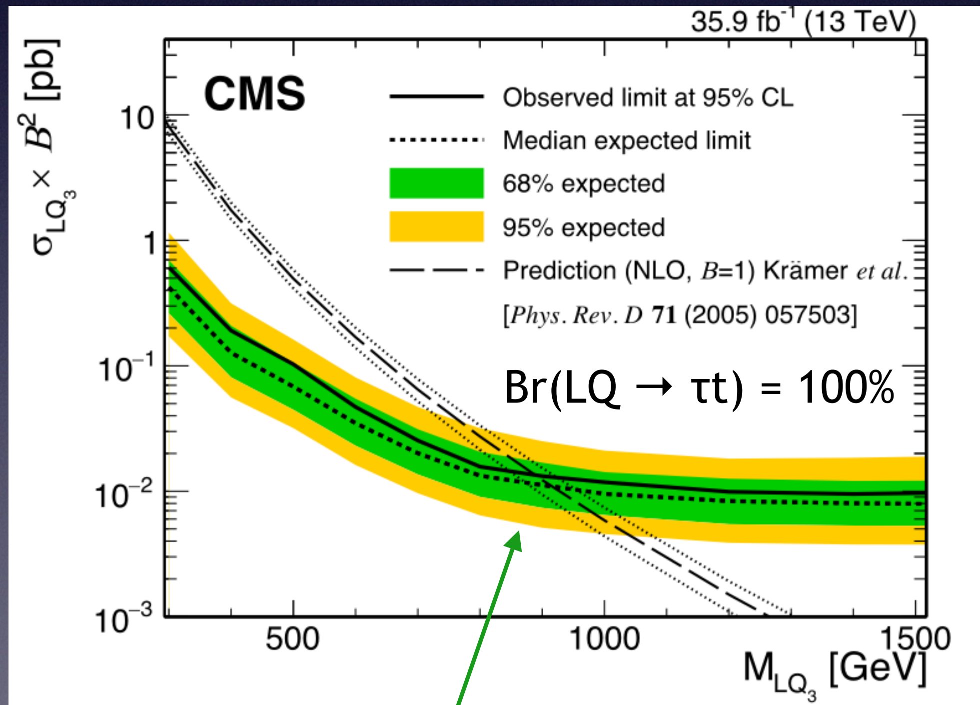
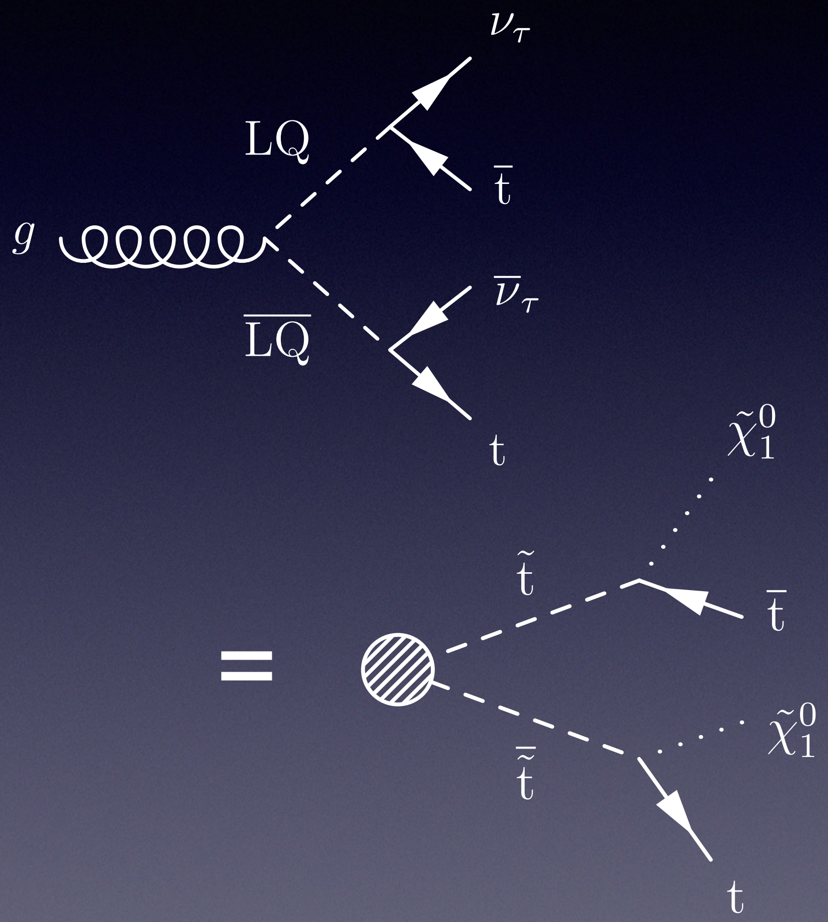


Lower limit
on m_{LQ} = 900 GeV

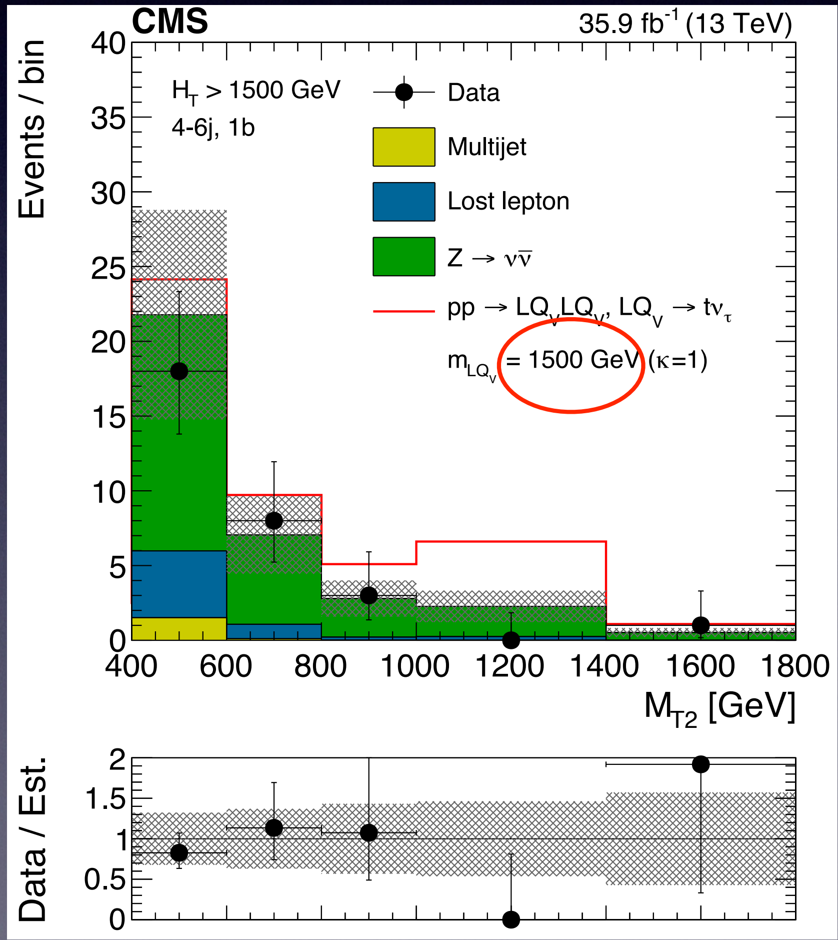
LQLQ → 2ν + 2t, 2ν + 2b

Re-interpret existing SUSY searches ($\tilde{b}$, $\tilde{t}$) in terms of scalar LQ

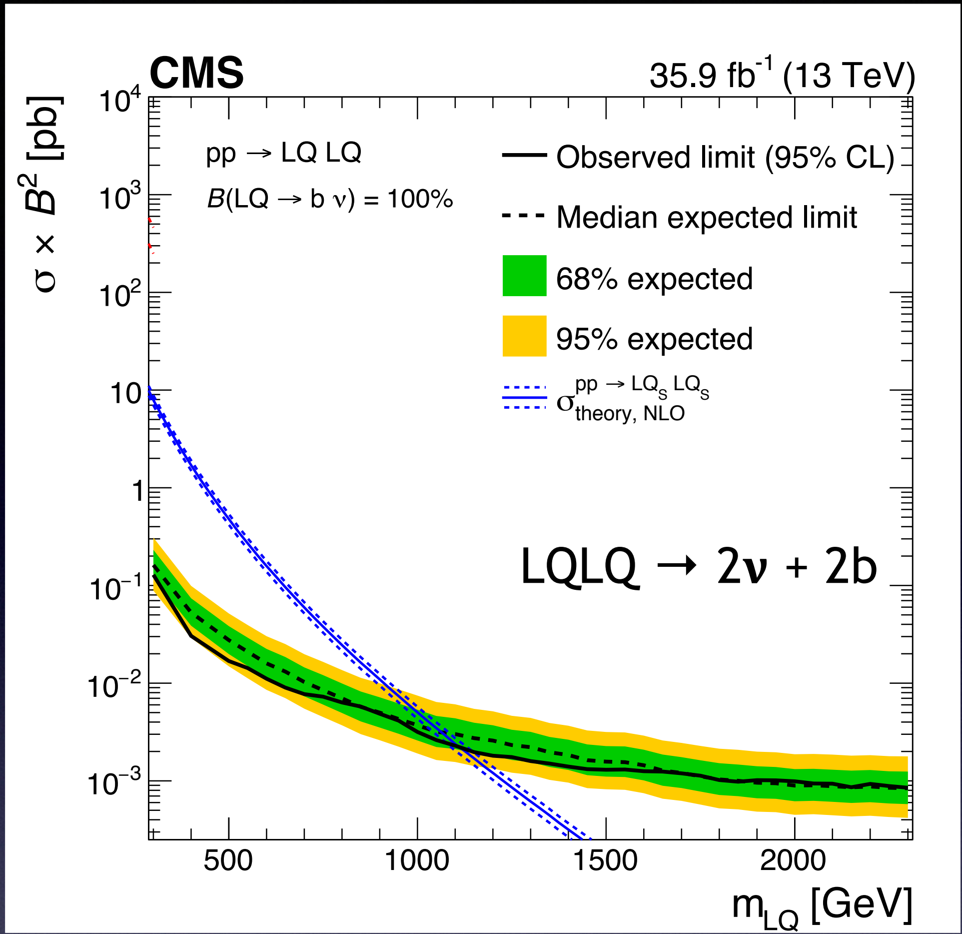


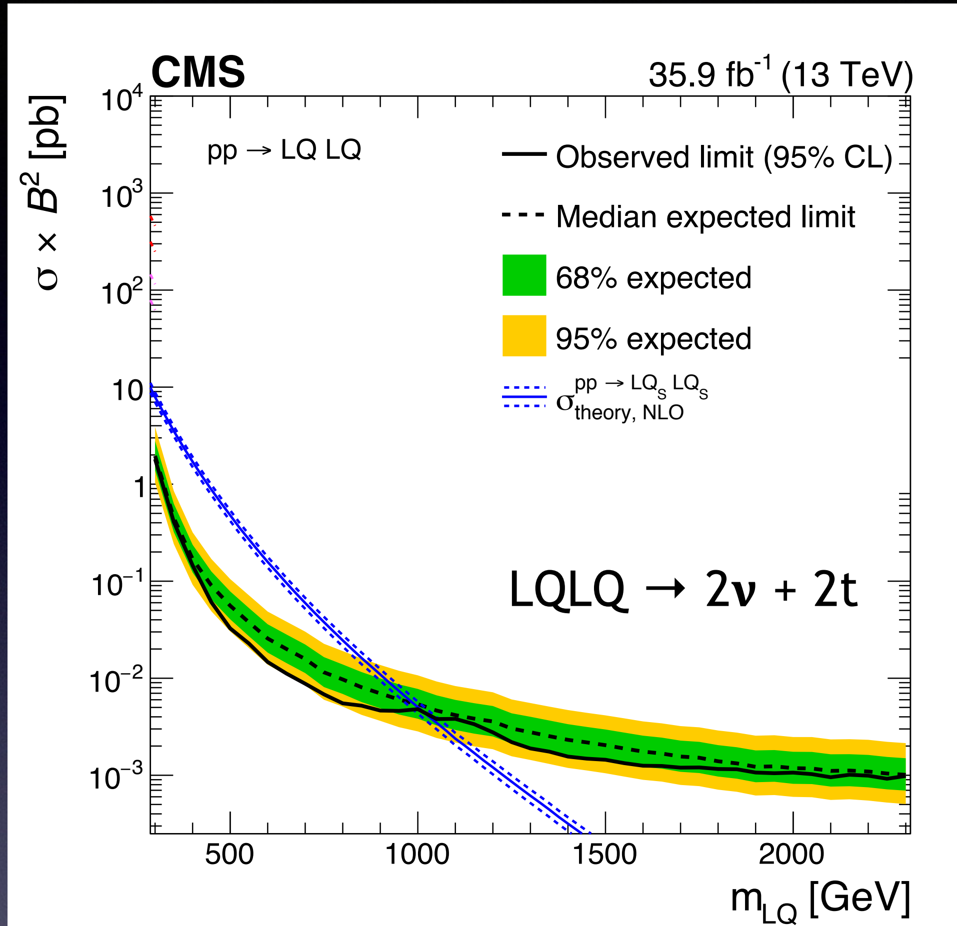
If $m(\tilde{\chi}_1^0) = 0$, both are equivalent
(as far as scalar LQ concerns)

How the signal looks like ?

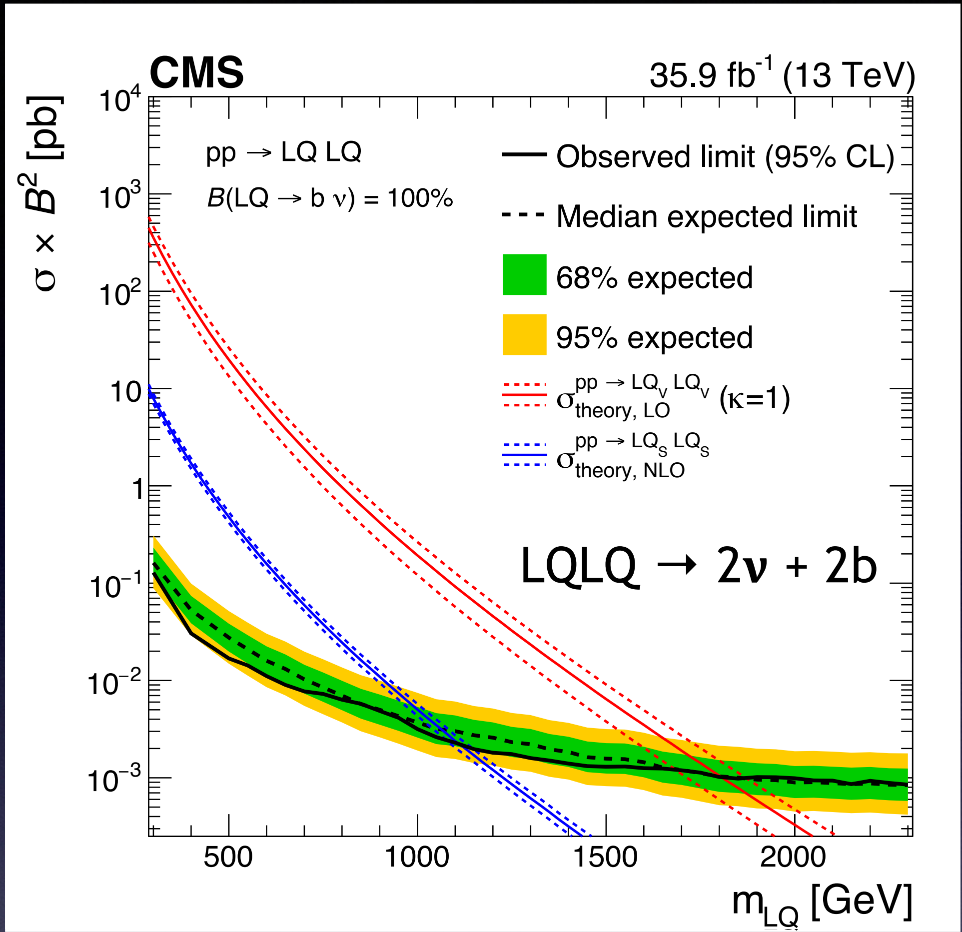


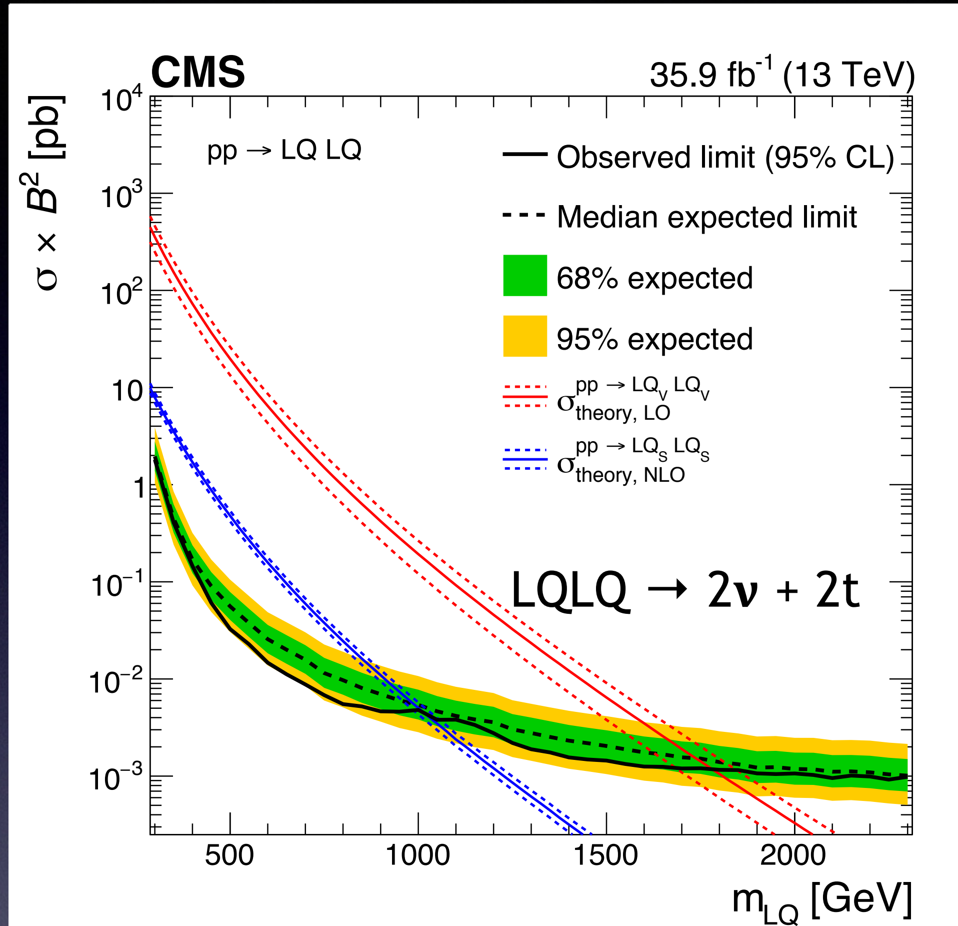
Imbalance of the events





Scalar LQ (for both types) → 1 TeV

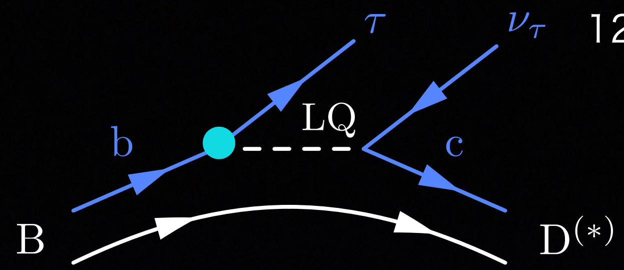


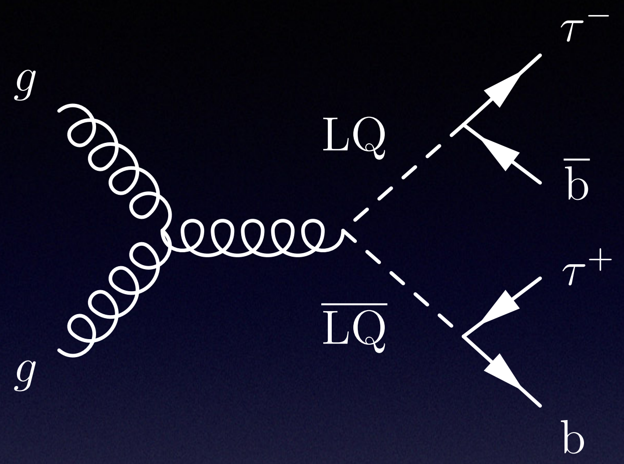


Scalar LQ (for both types) → 1 TeV

- A-priori, there is no guarantee that kinematics are same between scalar and vector LQ
- We checked using MC simulation and found they are similar
- Instead of redoing the analysis, we set the limit for vector LQ using its cross-section (arXiv:1706.07641) → 1.8 TeV

LQLQ → 2τ + 2b



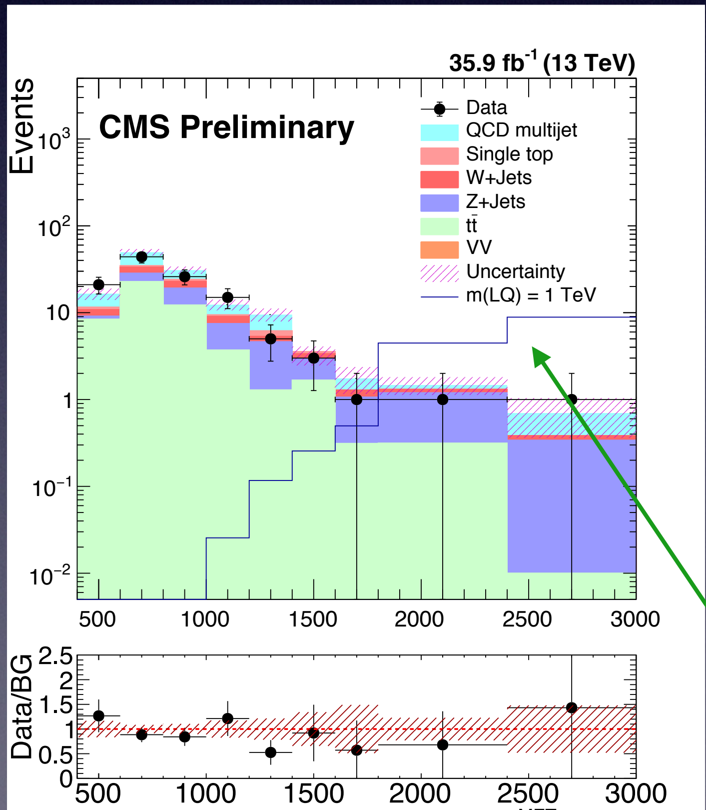


Depending on the tau decay

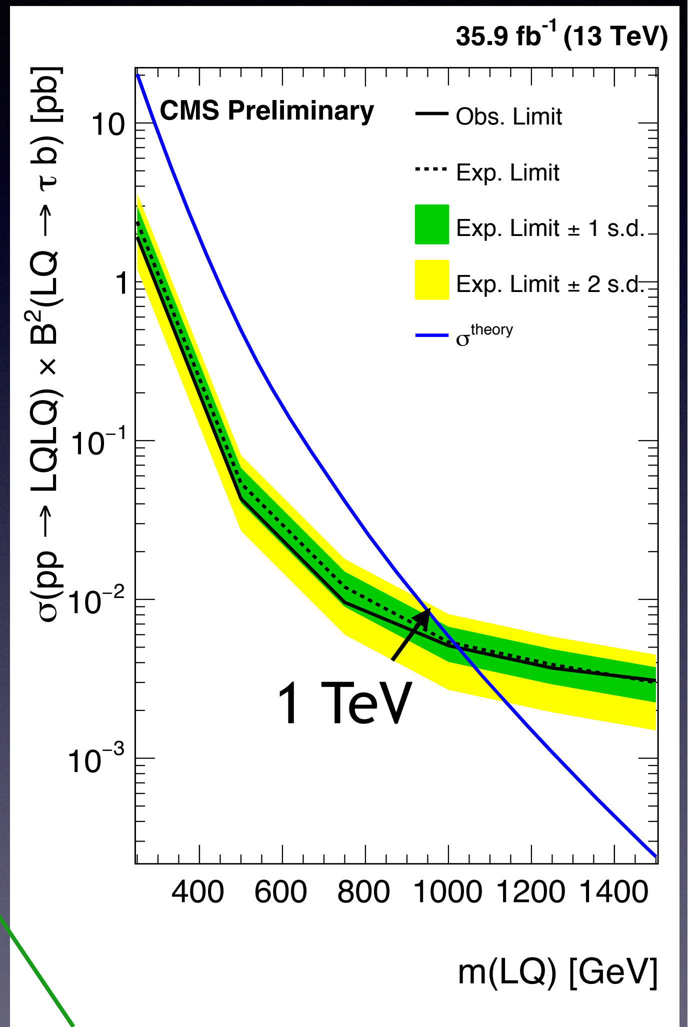
- $\tau_e \tau_h$
- $\tau_\mu \tau_h$
- **$\tau_h \tau_h$ (most sensitive)**

↓

- 2 τ_h + 2 jets
- To reduce QCD BG, require missing E_T > 50 GeV

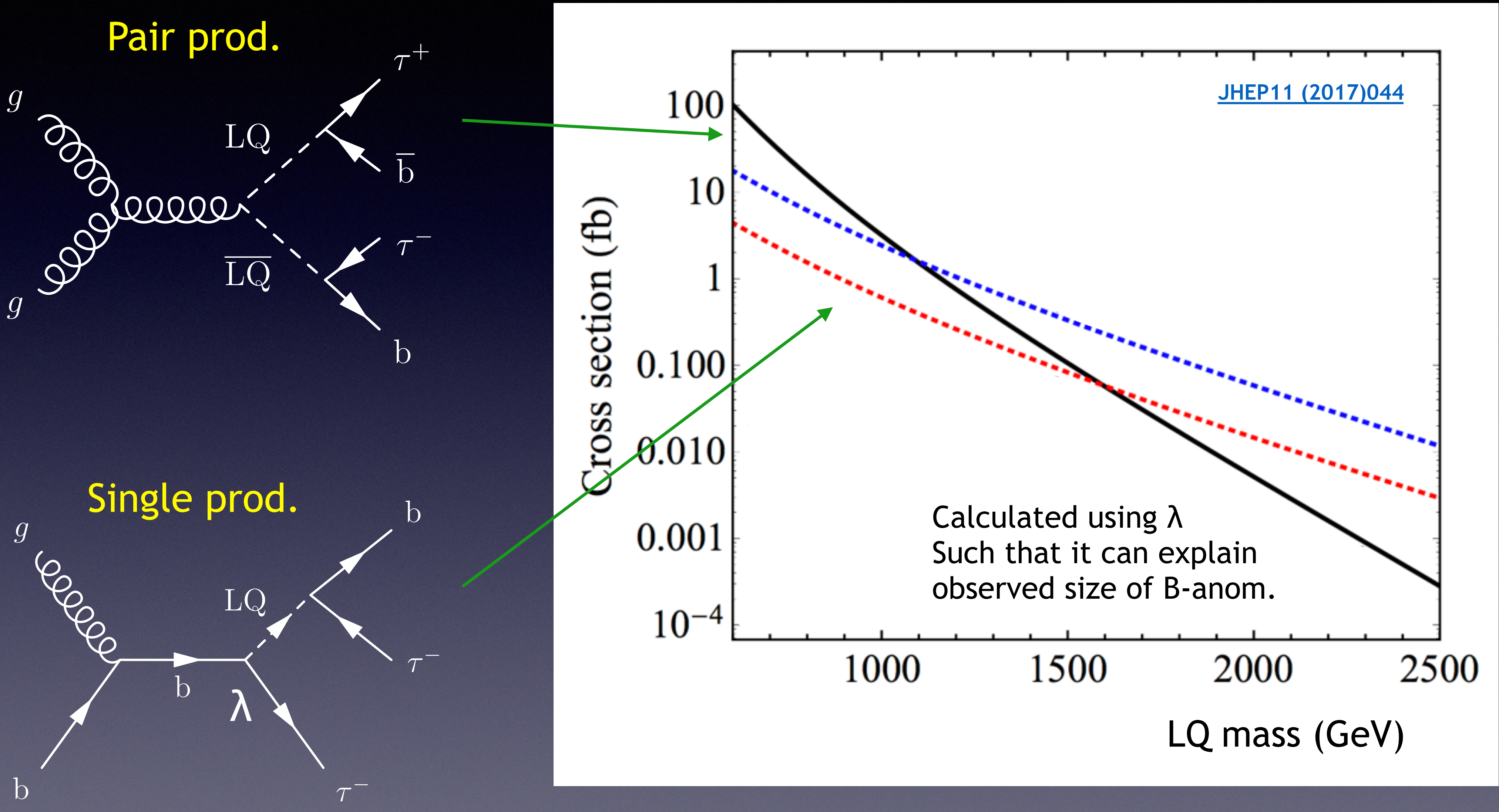


Σ p_T (GeV)



Sensitivity dominated by data stat.

Single LQ production

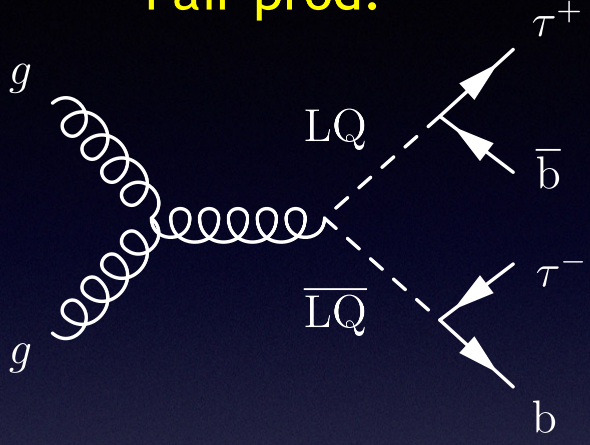


Cross-section depends on (unknown) LQ coupling λ

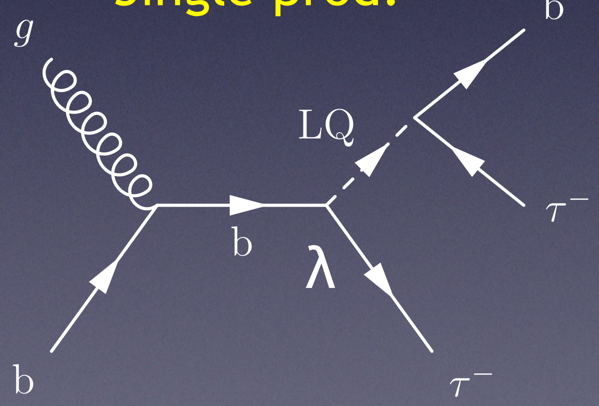
+ for LQ3, suppression due to b-quark PDF

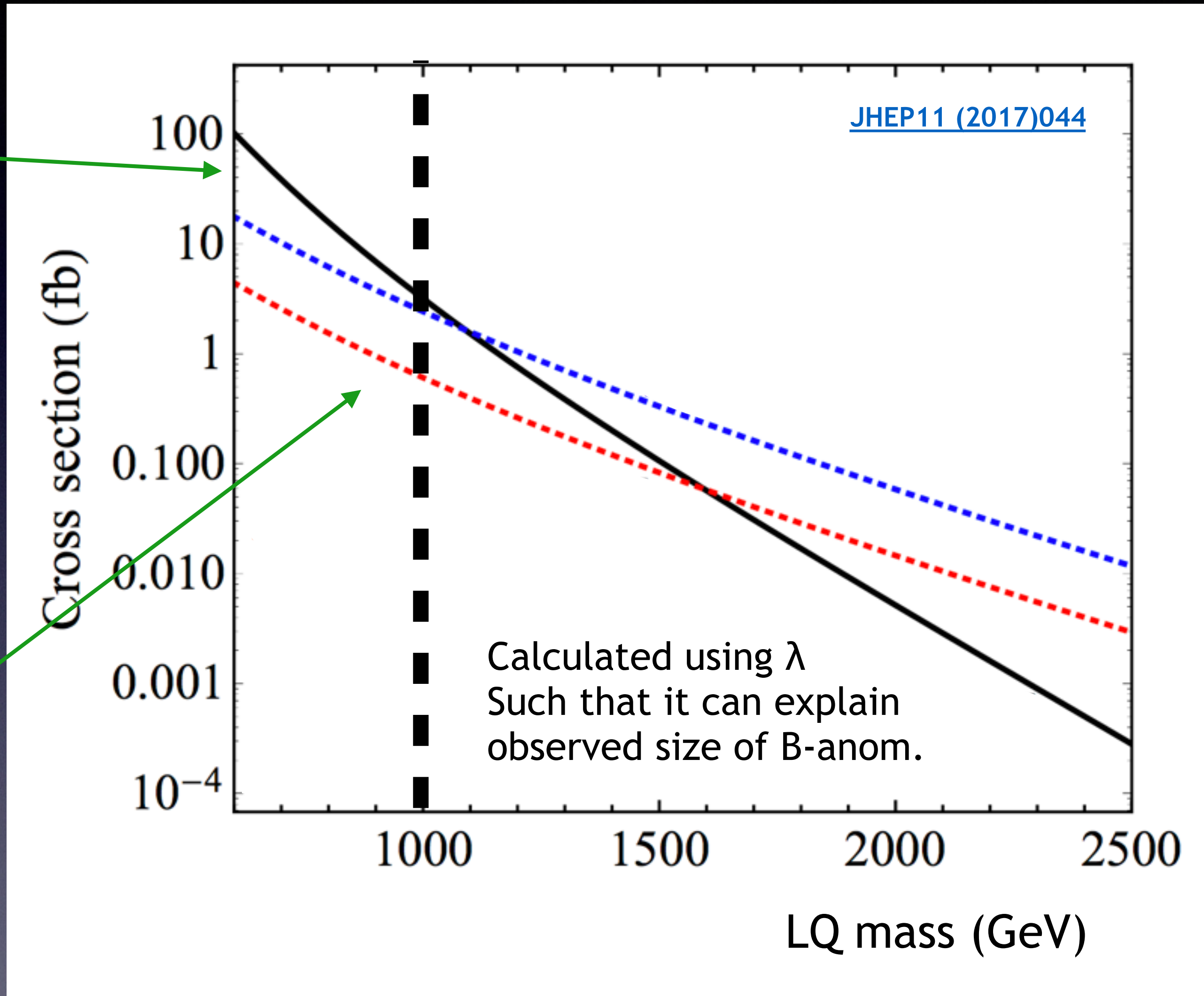
Single LQ production

Pair prod.



Single prod.





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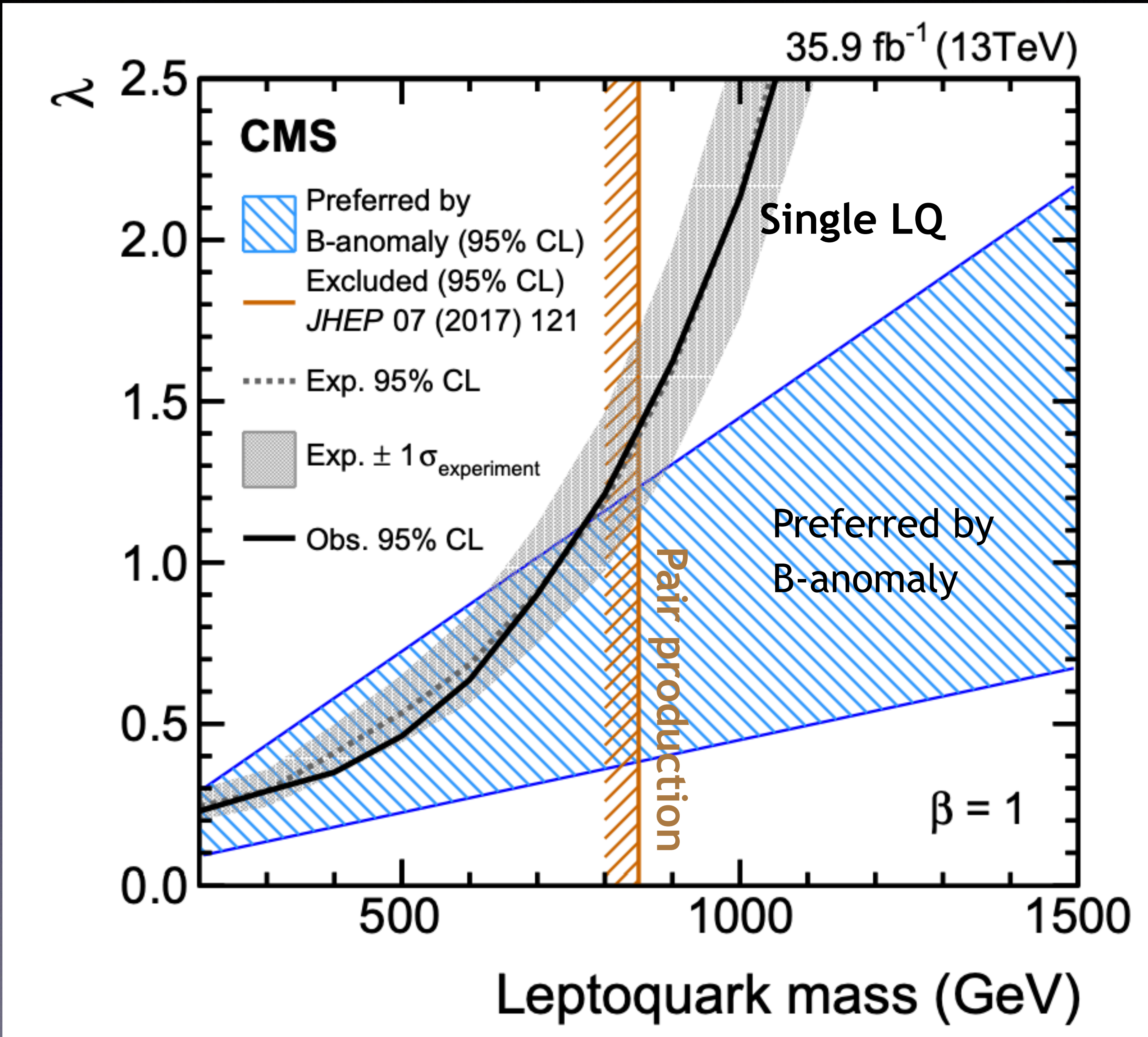
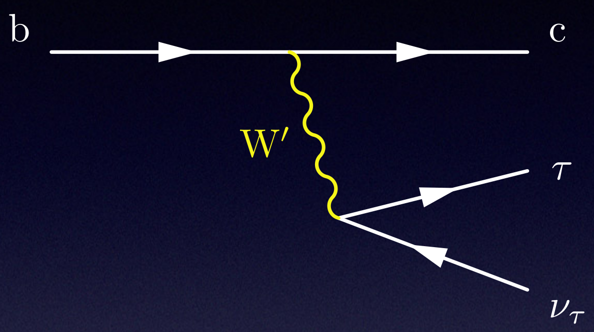
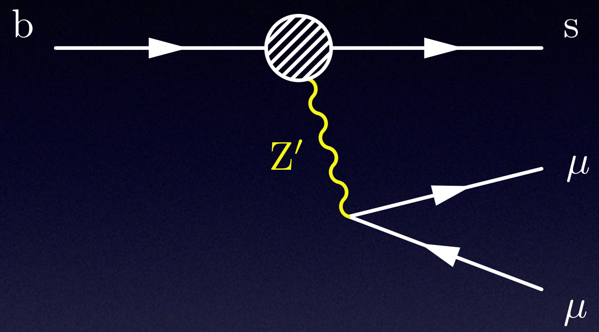

35.9 fb^{-1} (13TeV)
CMS
Preferred by B-anomaly (95% CL)
Excluded (95% CL) JHEP 07 (2017) 121
Exp. 95% CL
Exp. ± 1 $\sigma_{experiment}$
Obs. 95% CL
Single LQ
Preferred by B-anomaly
Pair production
β = 1
λ
2.5
2.0
1.5
1.0
0.5
0.0
500
1000
1500
Leptoquark mass (GeV)

W’ and/or Z’

At first sight, extra $SU(2)_L$ doublet seems to be a good solution





- This does not work, because W’ and Z’ couplings are related by SU(2) symmetry → lead to $M^{NP}(b \to s\mu\mu) \sim M^{NP}(b \to c\tau\nu)$

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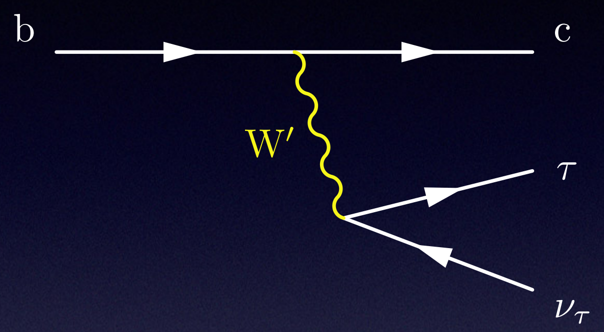

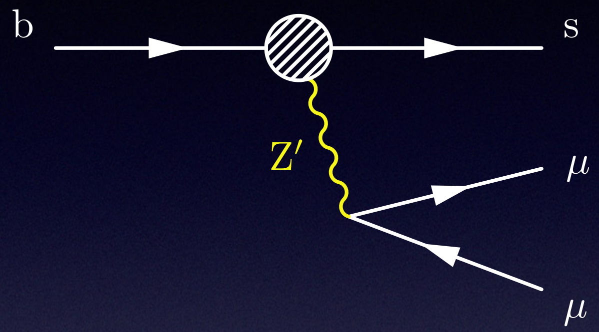

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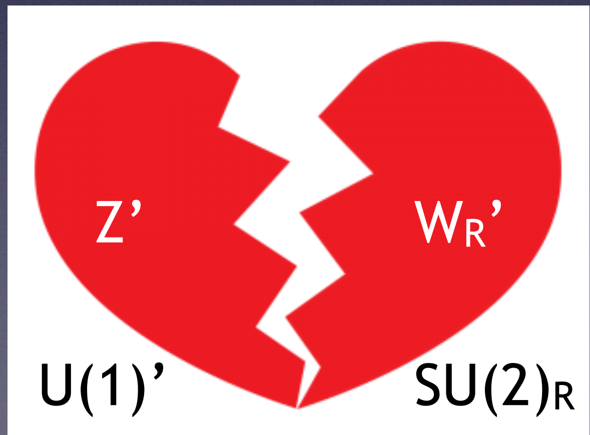
e.g.) solution



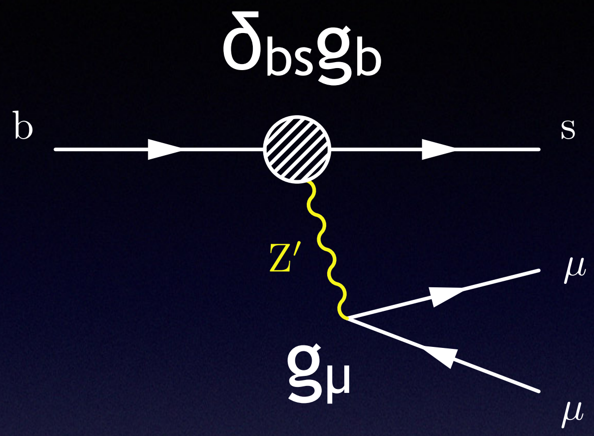
Need to give-up combined explanation

(we might have false alarm for one of the anomalies!)

Search for Z'

Q: What would be the (mass, coupling) favoured by B-physics anomalies ?

A: Z' contribution to B-anomaly = $\delta_{bs} g_b g_\mu / m_{Z'}^2$
→ any combination that gives right size of anomaly is allowed (δ_{bs} should be kept small not to conflict with Bs mixing through bs → Z' → bs)



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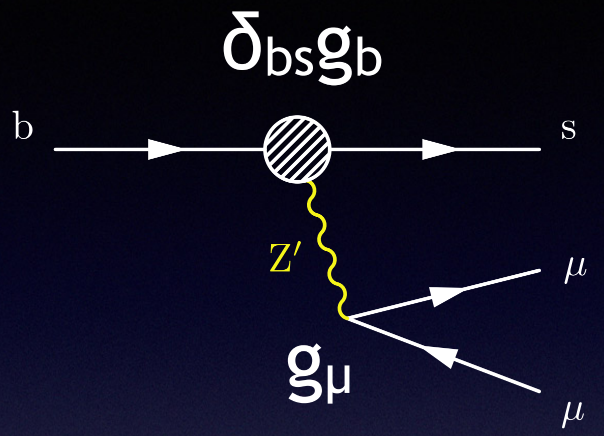
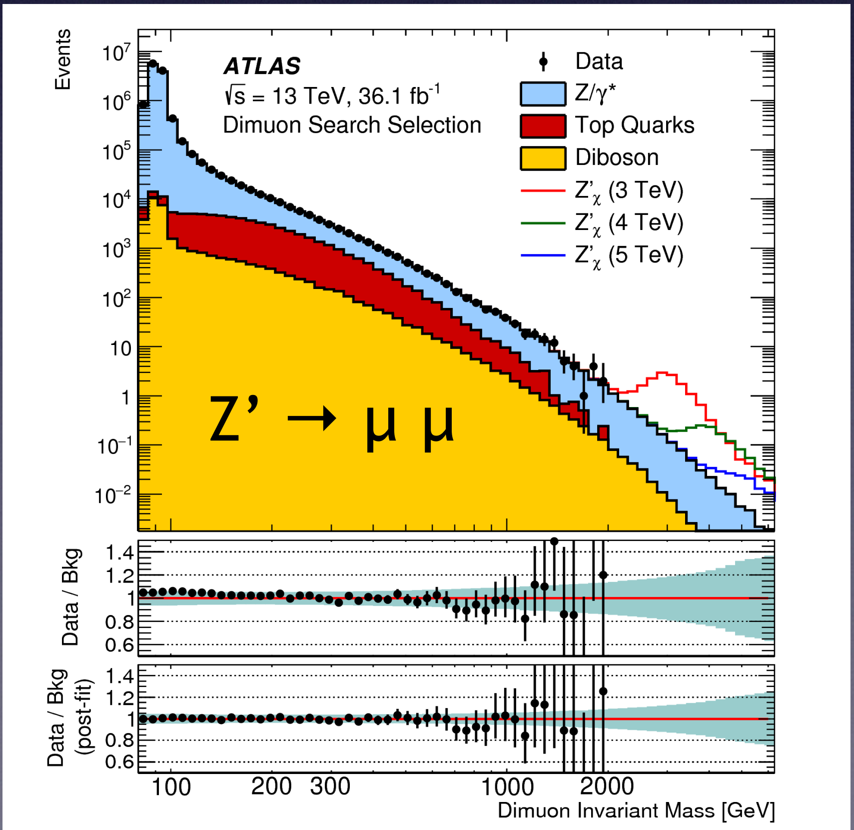


(Although it is not necessary),
if Z' is flavour-universal (SSM)

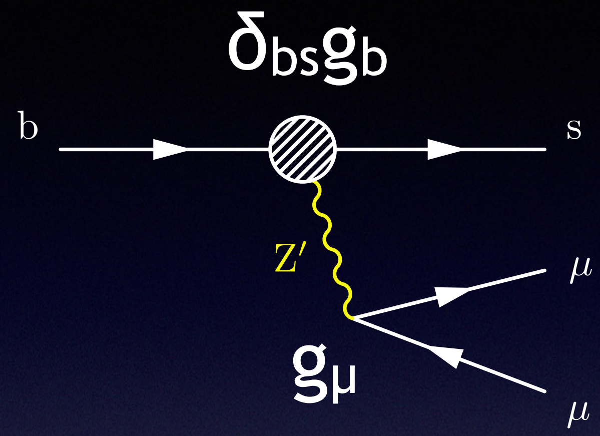


SSM Z' excluded up to 4.0 TeV

→ most of the (mass, coupling), favoured by B-anom. is excluded

This looks to be a bad news, but it is not

- It is not necessary to assume SSM
  - Couplings to light-quarks are not necessary
- Minimum Lagrangian is …



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

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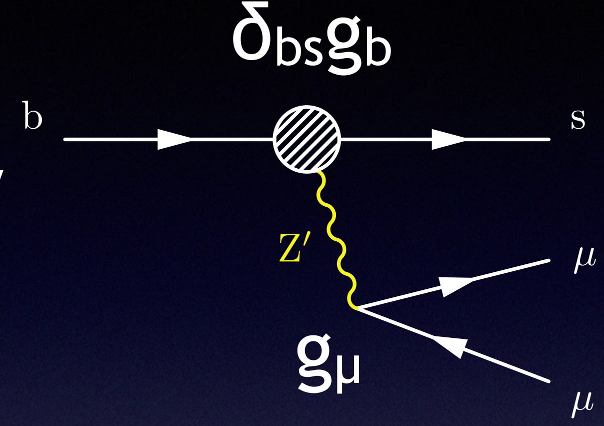

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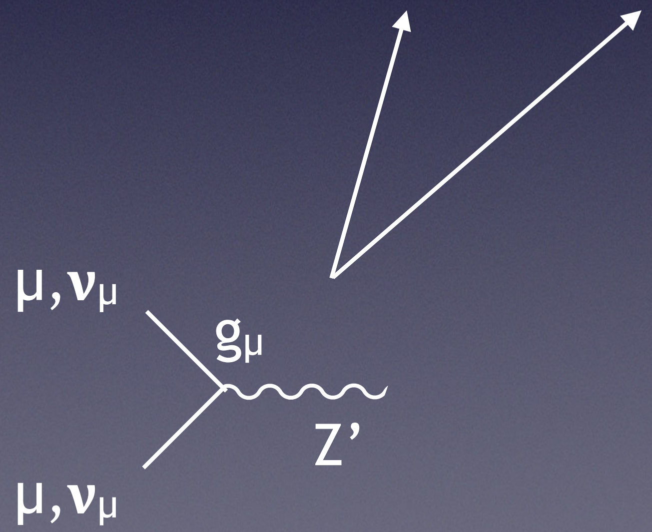

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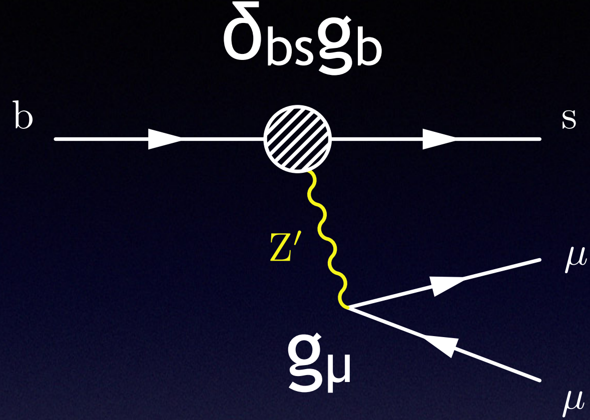

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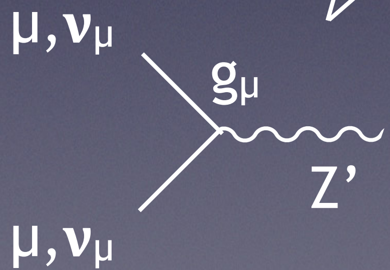

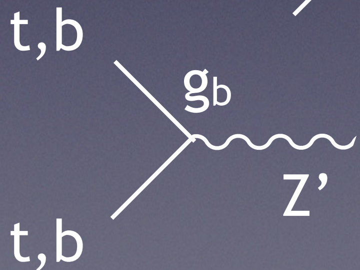

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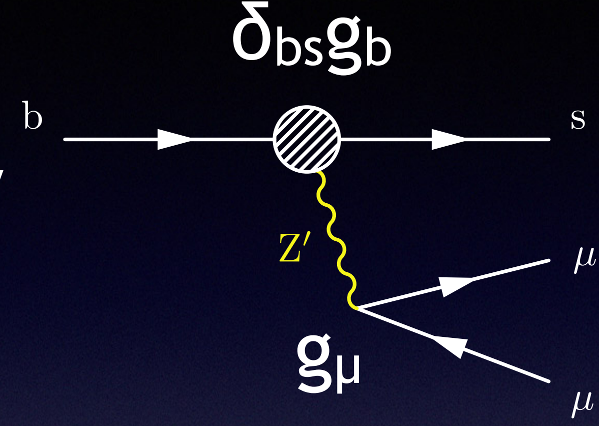

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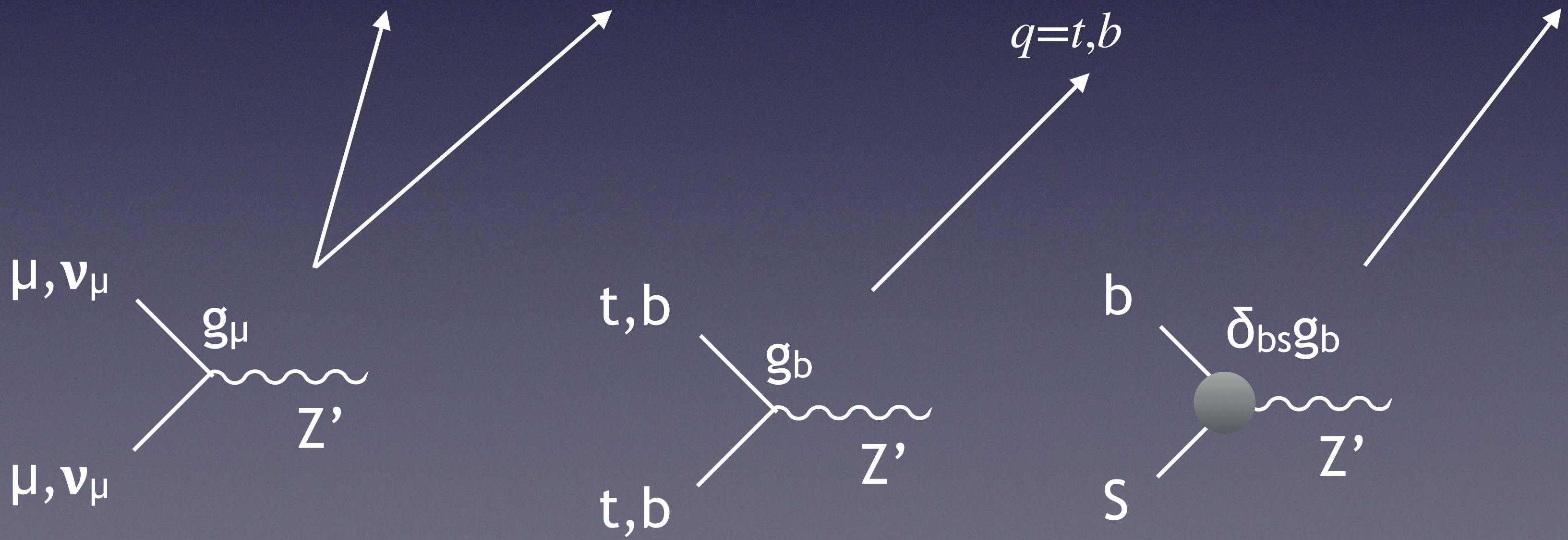

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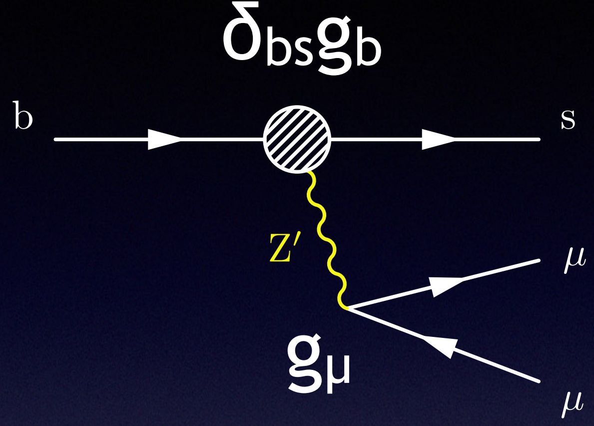

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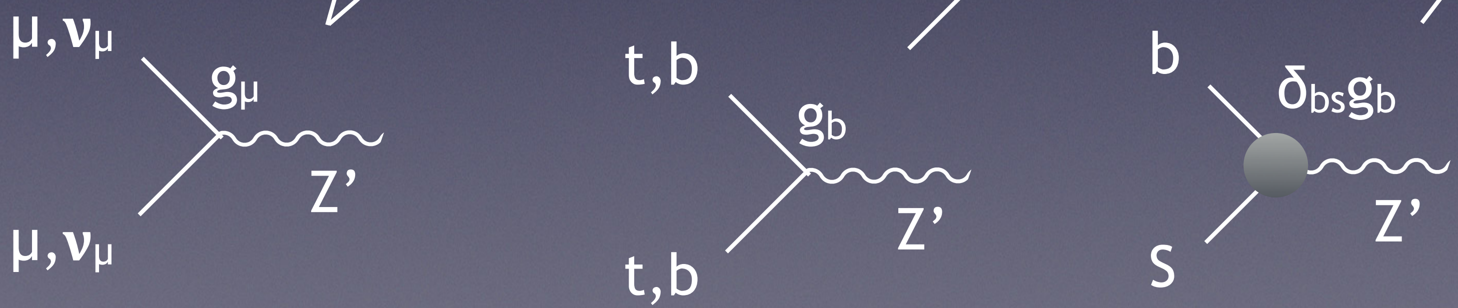
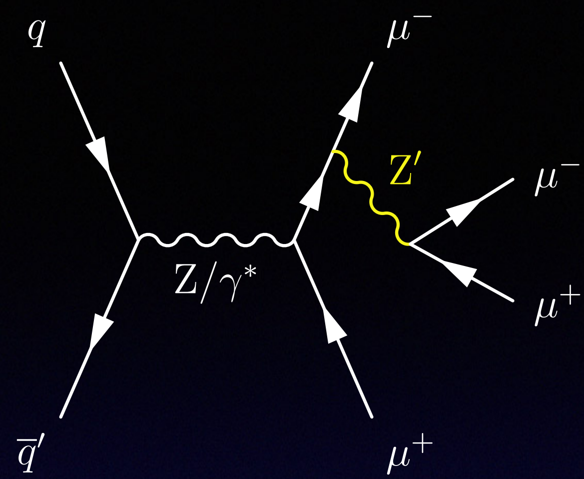


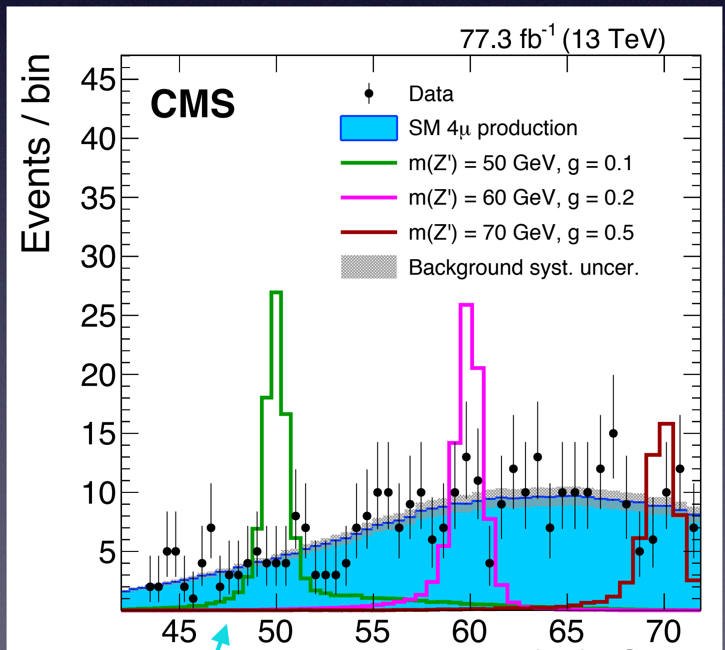
minimum:
Z’ couplings to
$\mu\bar{\mu}$, $b\bar{b}$, $t\bar{t}$, (bs)

Flavoured Z'

Search for Z' that only couples to μ

- Select events with 4 muons
- m(4μ) ~ m_Z
- Choose 2 muons, that, most probably come from Z'

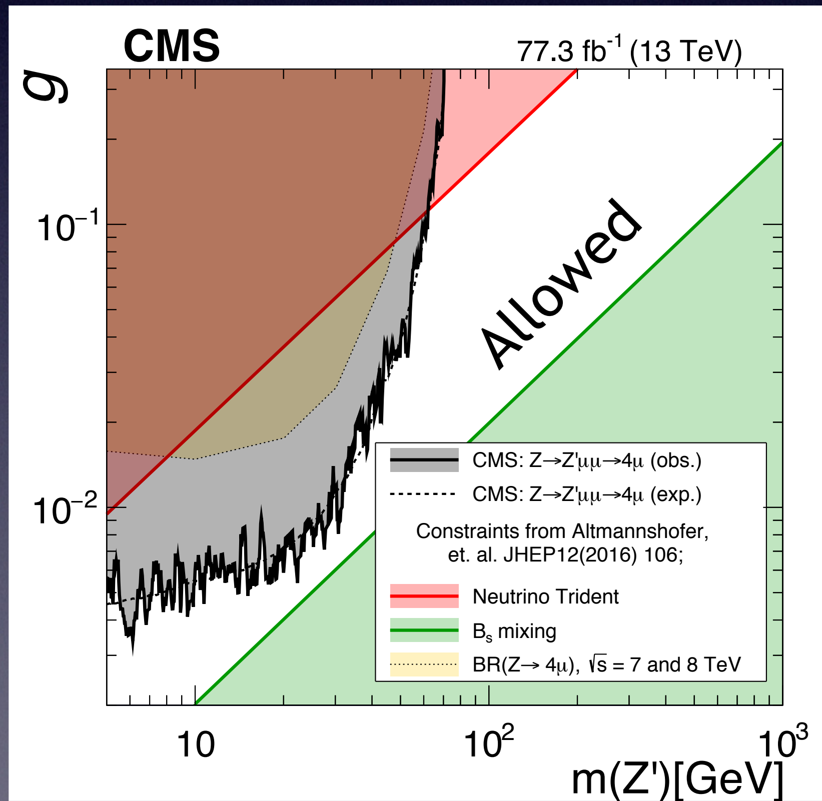




m(μμ) GeV

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

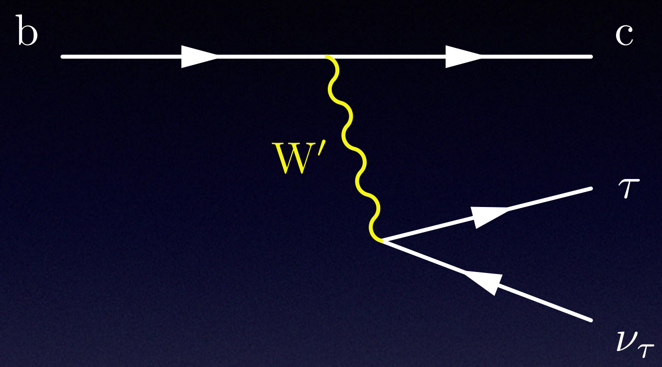
Coupling strength to muon



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

Search for W_R'

- If W_R' is responsible for $b \to c\tau\nu$ anomaly, couplings of W'bc, W'$\tau\nu$ is necessary
  - In this case, ν should be RH and $m(\nu_R) < 5$ GeV
- Under this consideration, W' $\to \tau\nu$ is the most promising search channel



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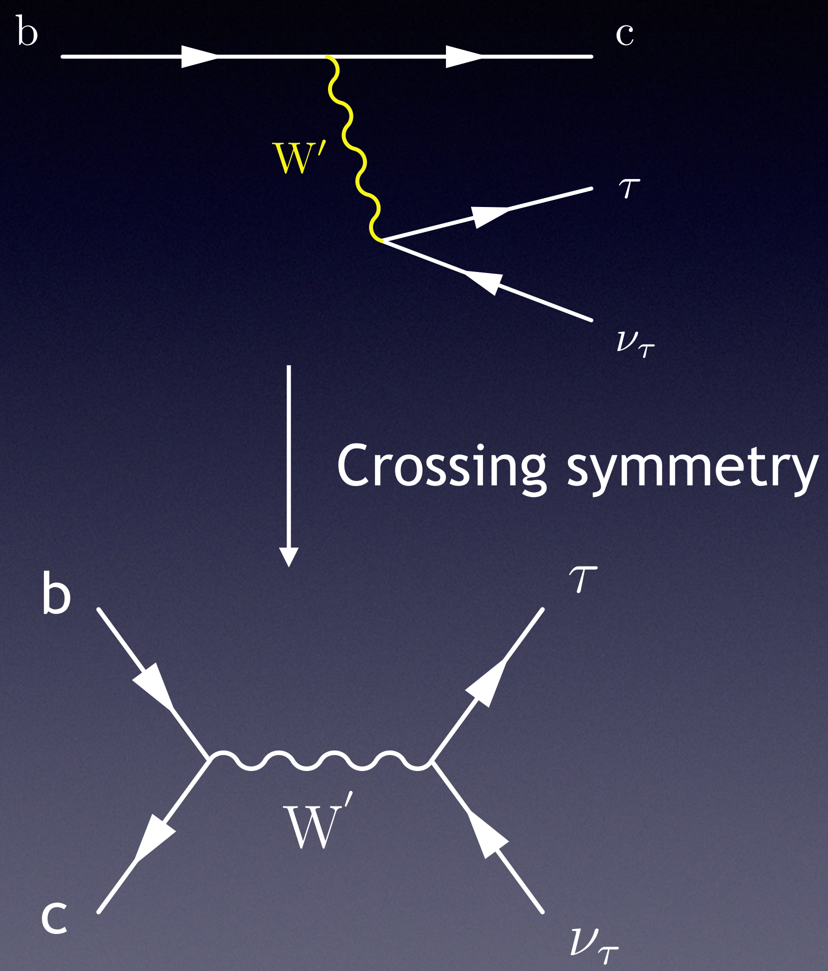

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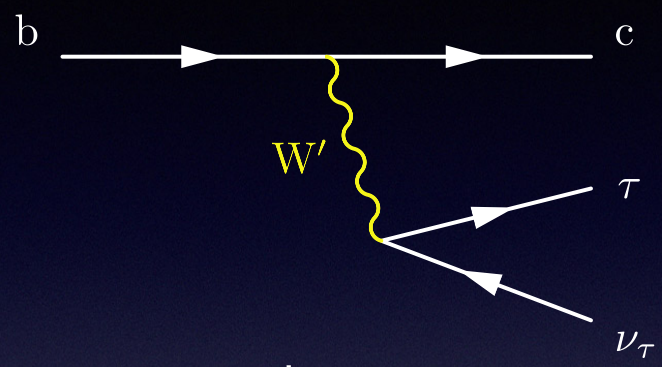
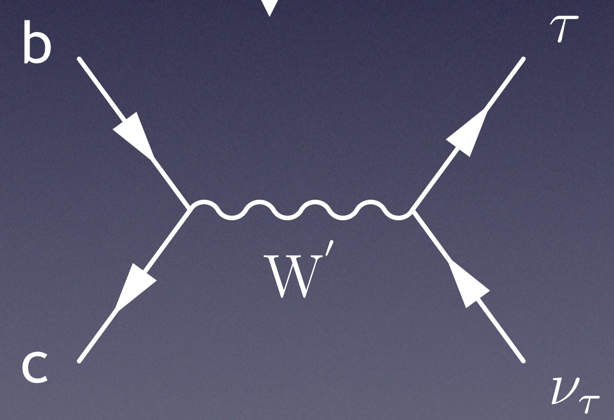


Crossing symmetry

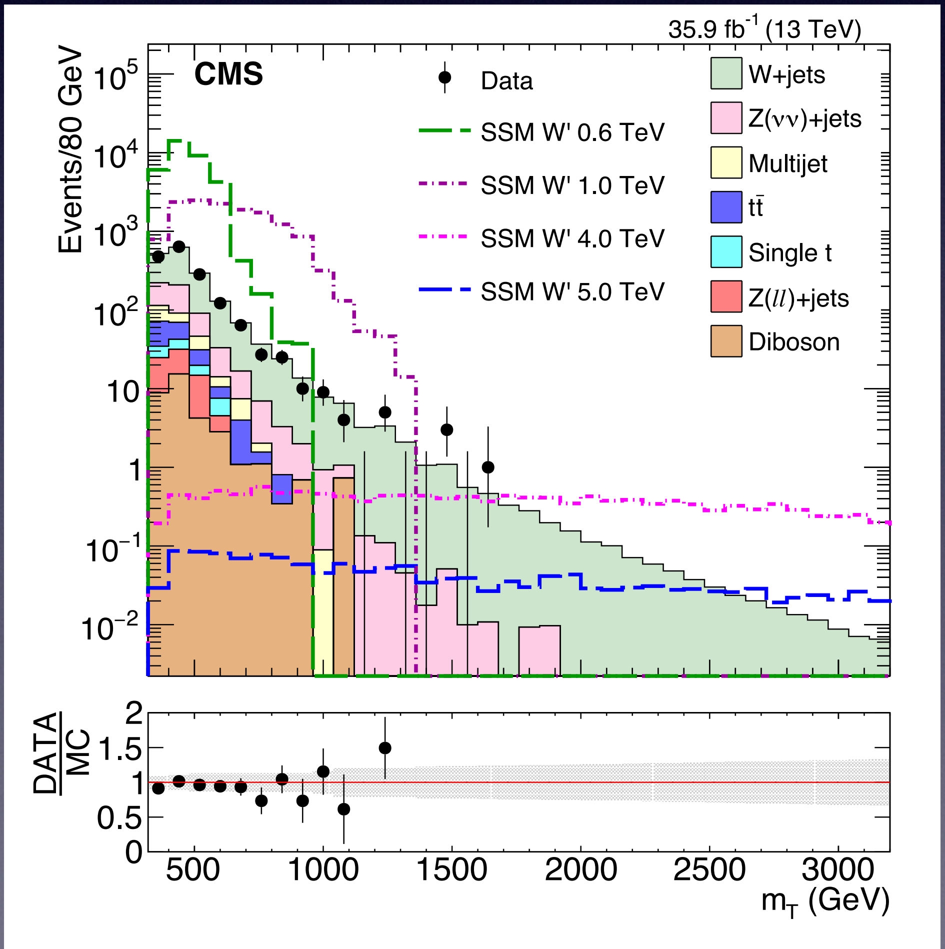


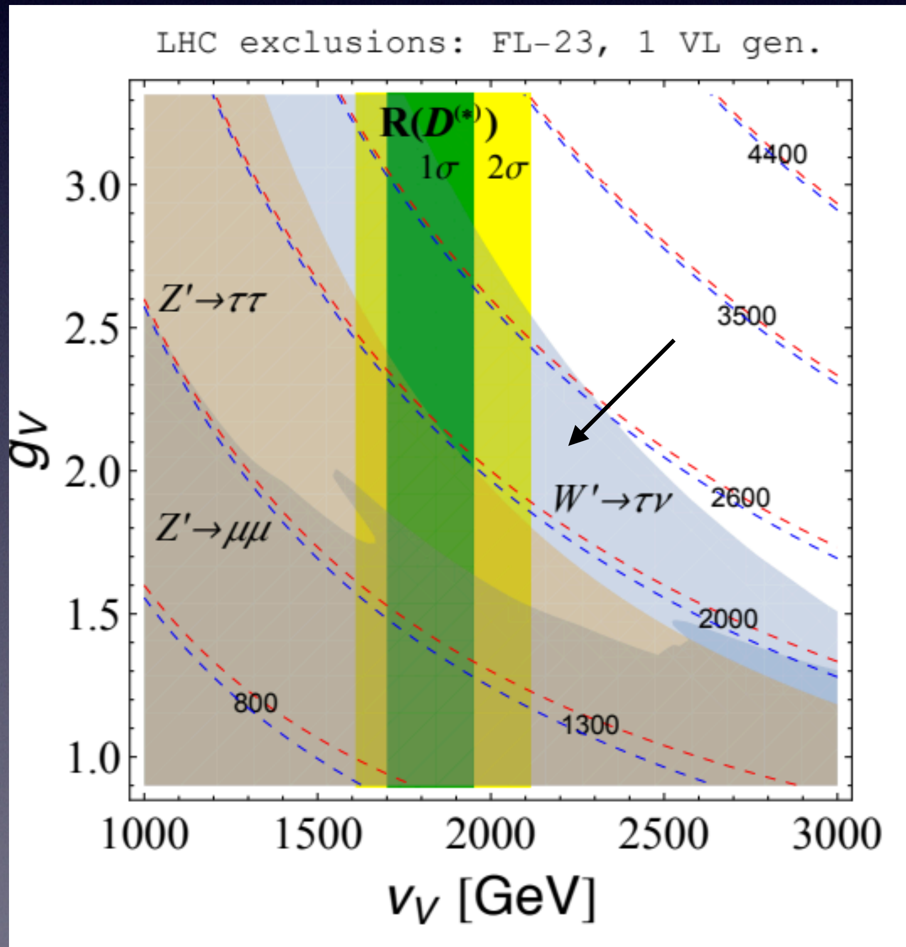
Note: W' does *not* necessarily couple *all* types of fermions (at least b and c !)

1 τ_h + missing E_T (due to ν) with back-to-back topology ($\Delta\phi$ > 2.4 rad)

Assume only minimum couplings (W_R'$b_R c_R$)

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





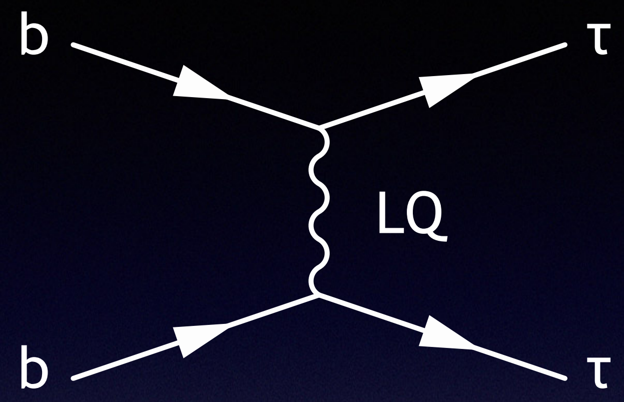
What's next ?

- Wide ττ resonance search
- Development of boosted top/bottom tagging
- Cross-checking B-anomalies at CMS

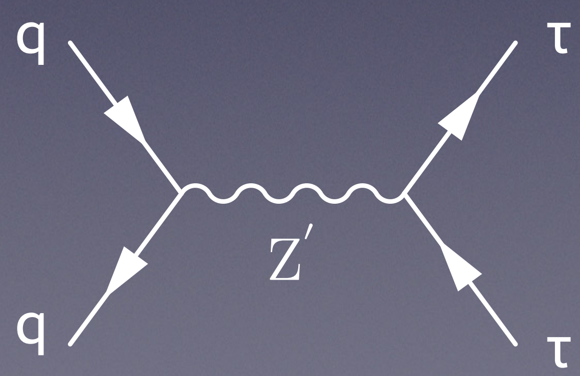
Wide ττ resonance search

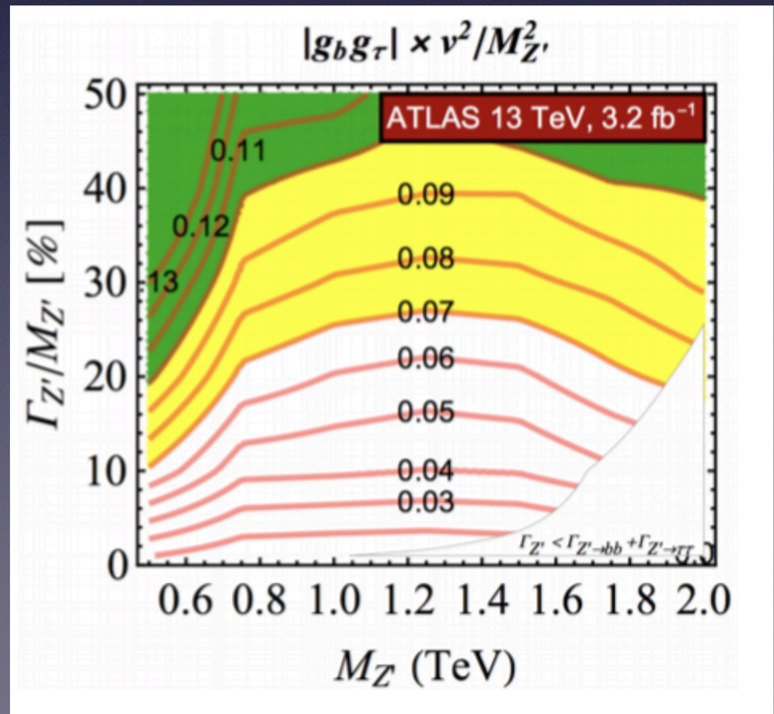
1. If LQ is beyond LHC energy reach, LQ is preferably produced via off-shell t-channel

→ make wide ττ resonance



2. Although I said ($W'^{\pm}$, Z') $SU(2)_L$ doublet is not a good solution for combined explanation, there are still allowed parameter space

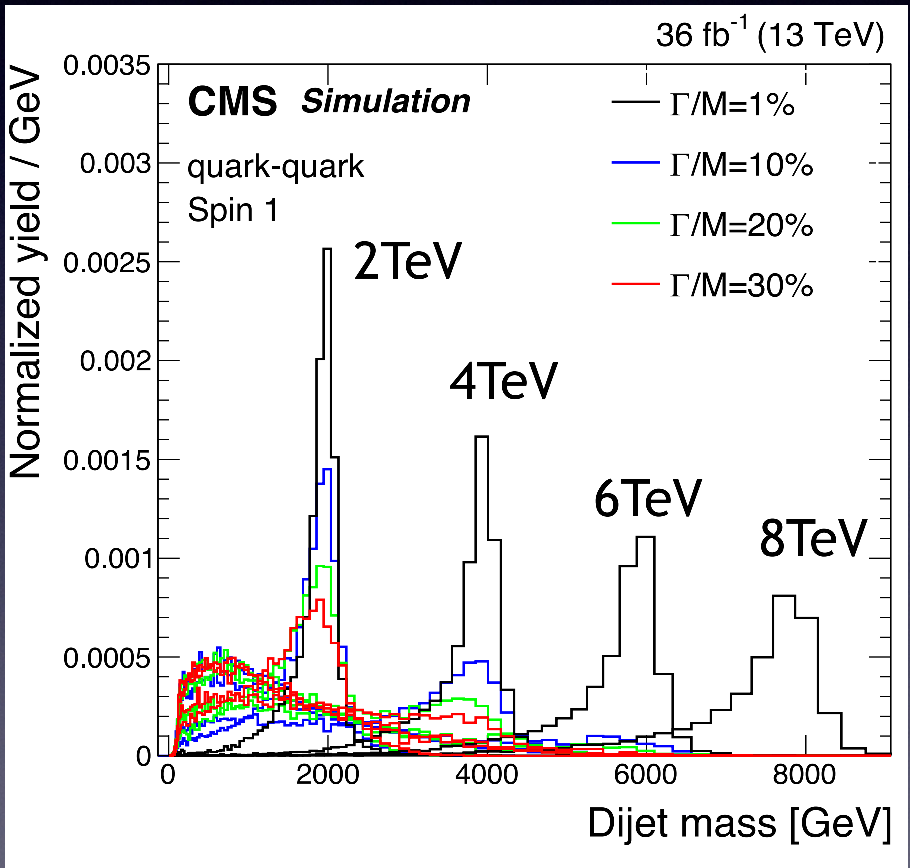


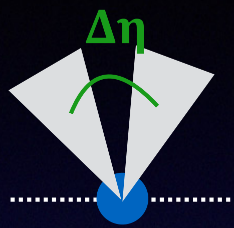


Wide resonance search is difficult

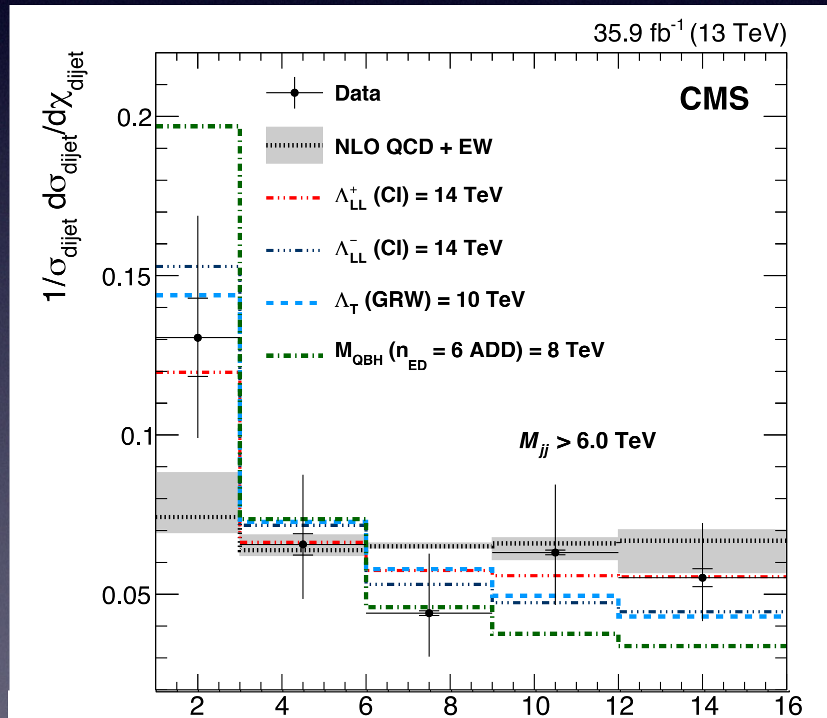
Instead, one can look at angular separation between jets (width independent)

e.g.) di-jet resonance





* New physics: flat in Δη
* QCD BG:peak at small Δη



$e^{2\Delta\eta}$

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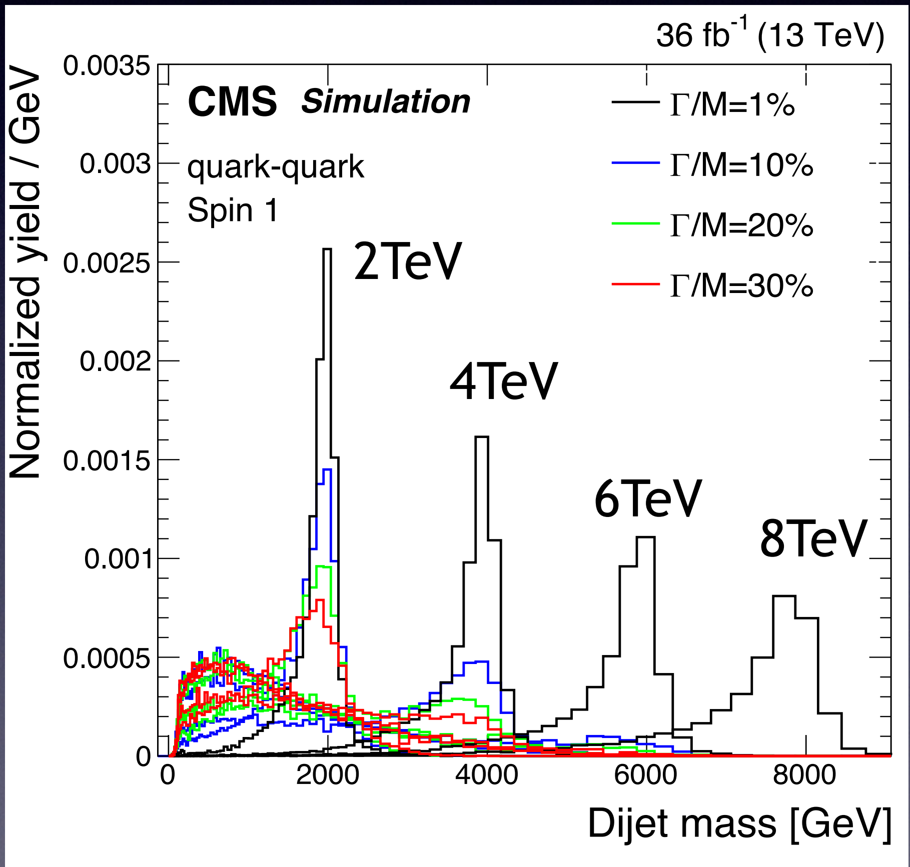

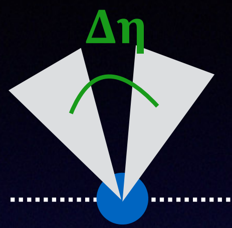

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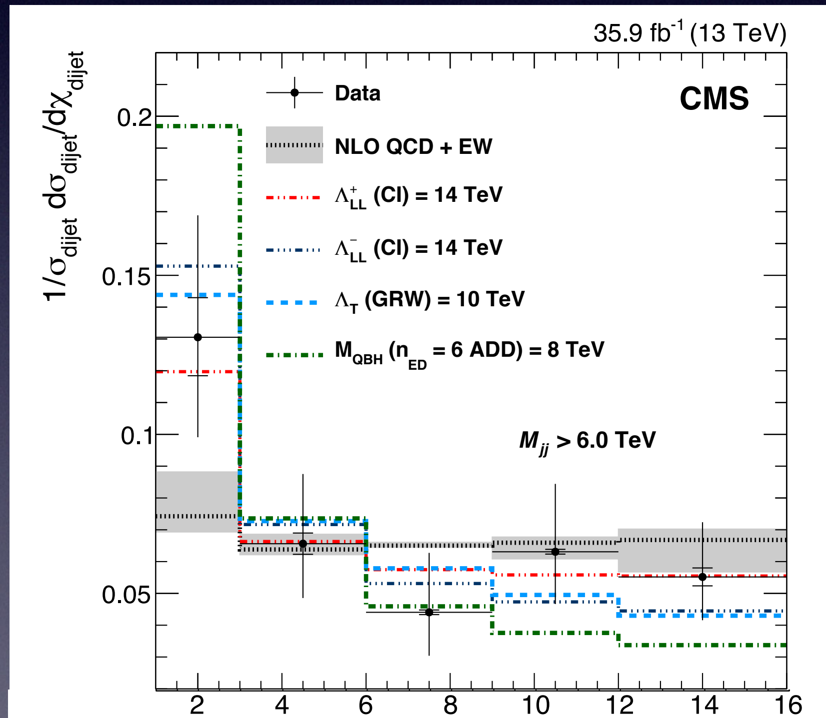

$e^{2\Delta\eta}$

Narrow resonance  

Wide resonance  

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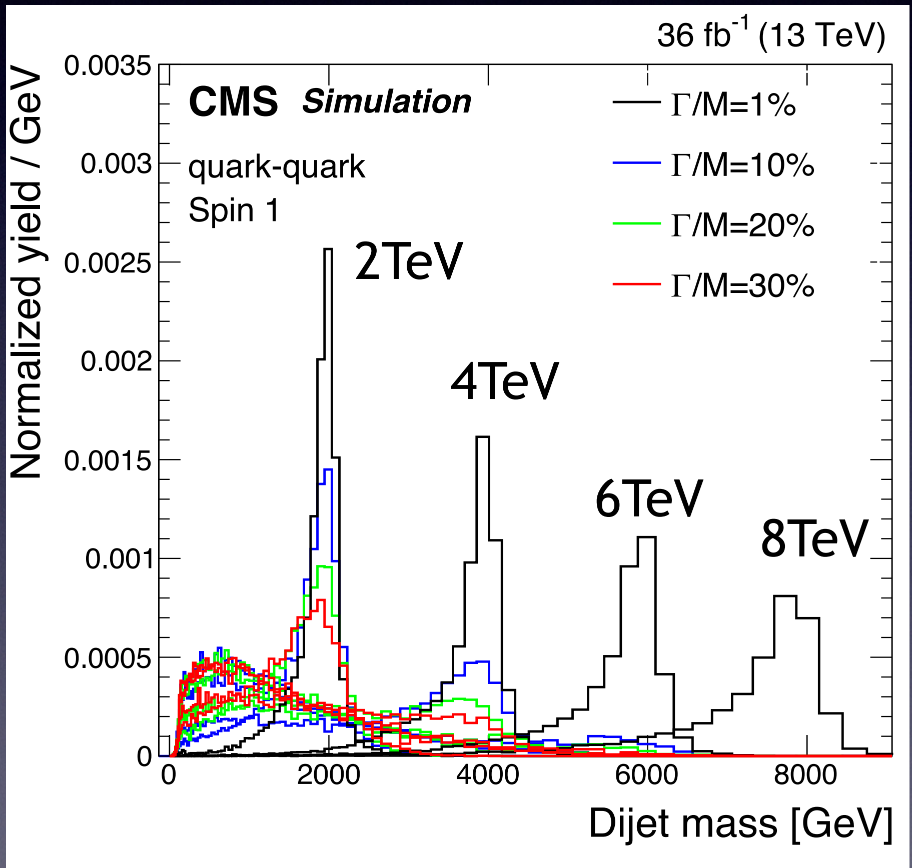

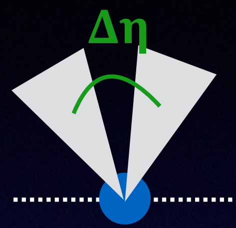

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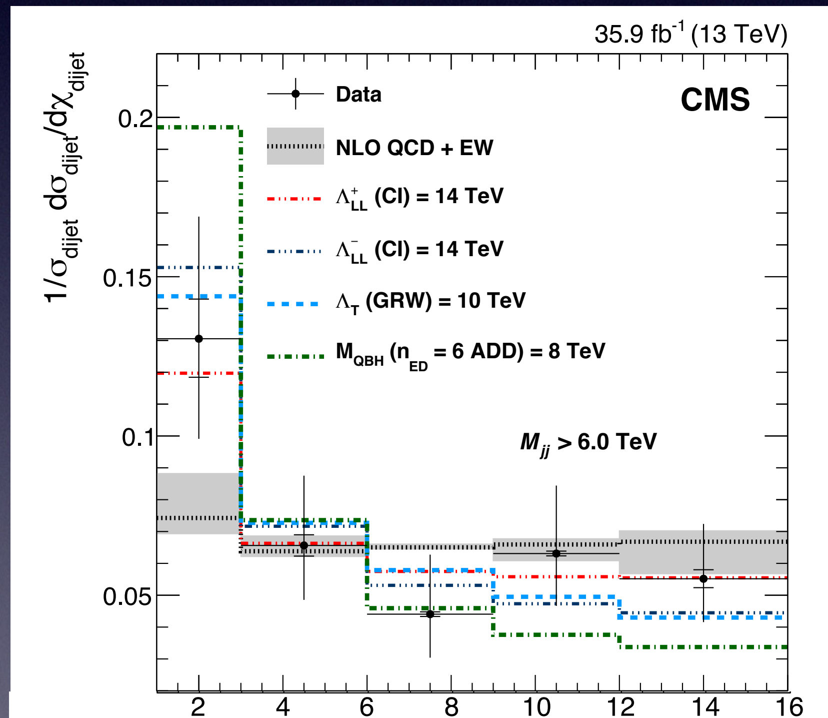


$$e^{2\Delta\eta}$$

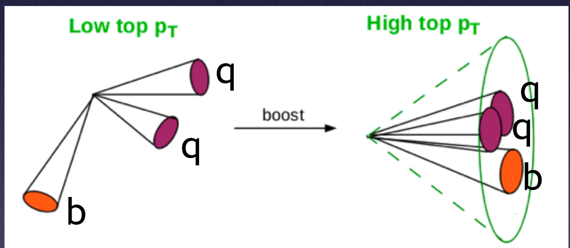
Narrow resonance  

Wide resonance   Do this using ττ final state

Boosted top/bottom tagging

- Search for high-mass Z' → $b\bar{b}$, $t\bar{t}$ is motivated
- However, as Z' becomes heavier, top/bottom quark carry more p_T, which makes them difficult to identify

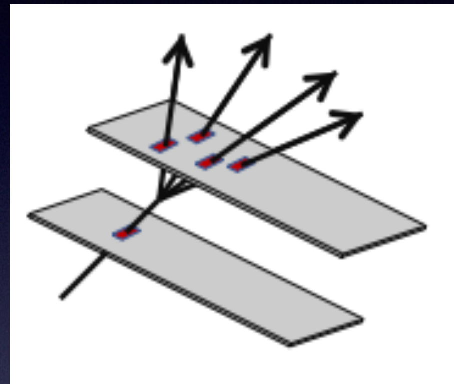
Top-quark



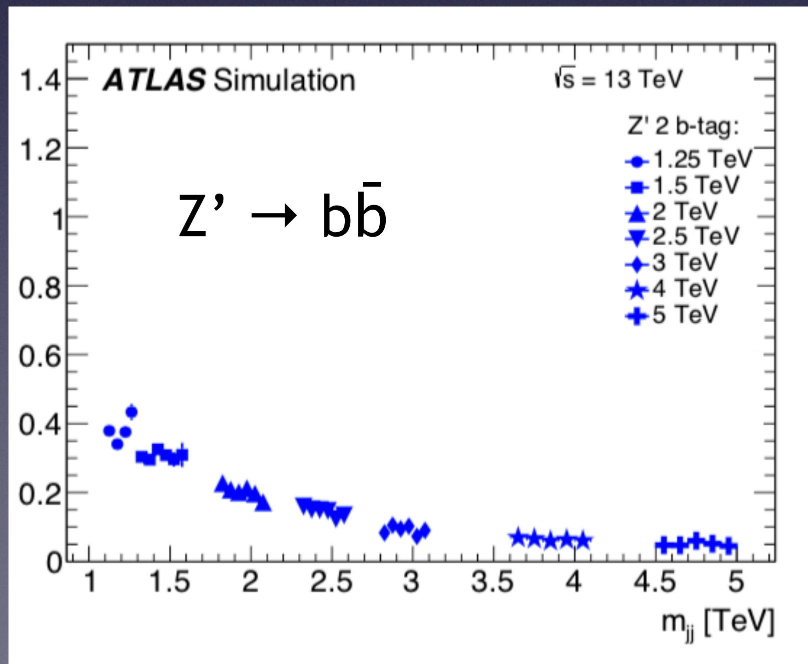
eff. ~ 50% @ fake rate ~ 3%

b-quark

For high p_T b-jets, one cannot reconstruct secondary vertex



Efficiency of tagging 2b



Cross-check B-anom. at CMS - R(K*)

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  Currently, ~15% of trigger budget allocated to B's and we cannot increase this fraction

New Idea

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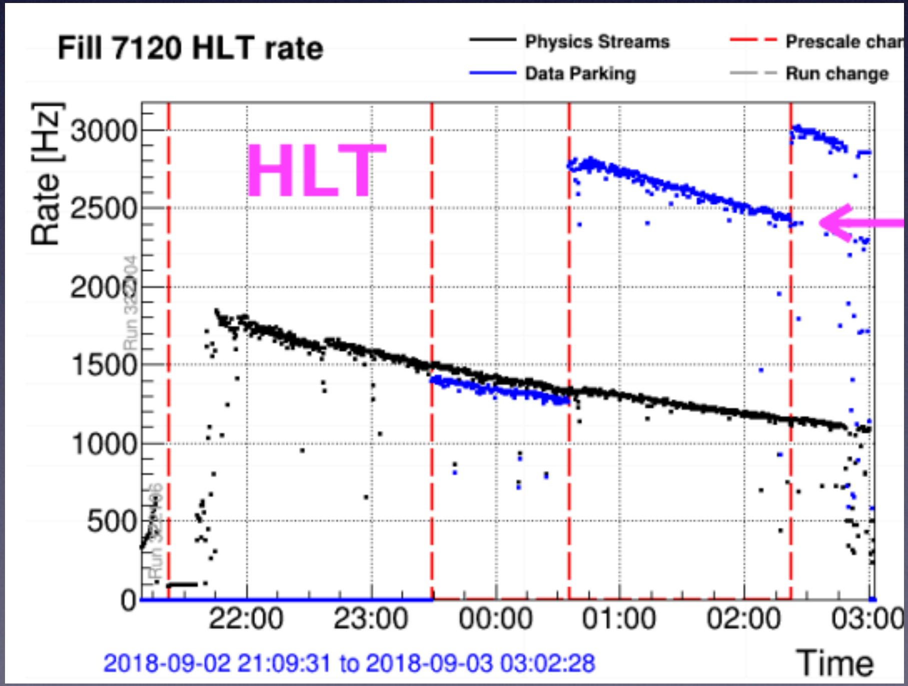

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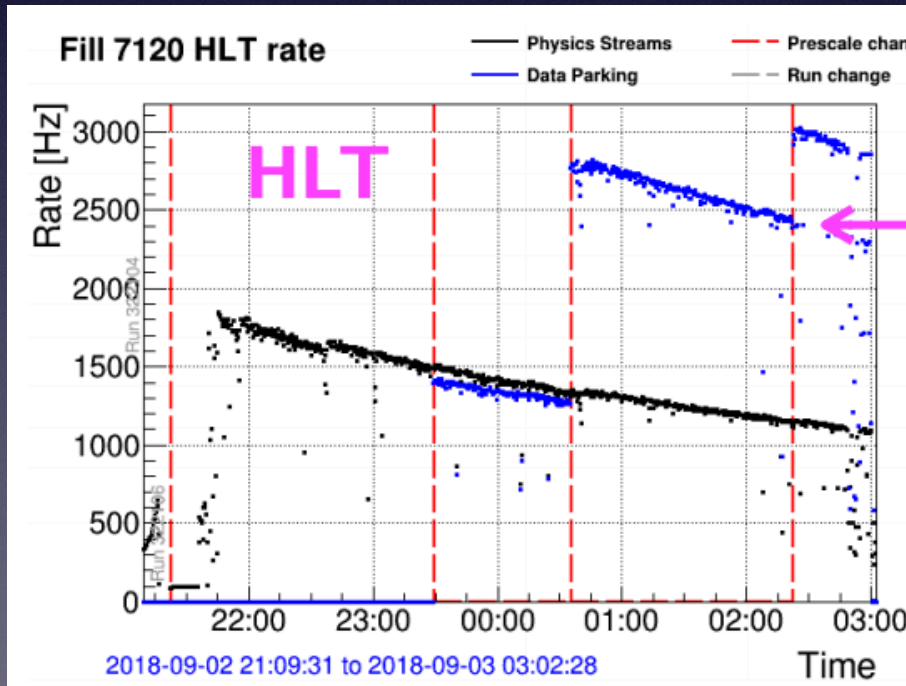

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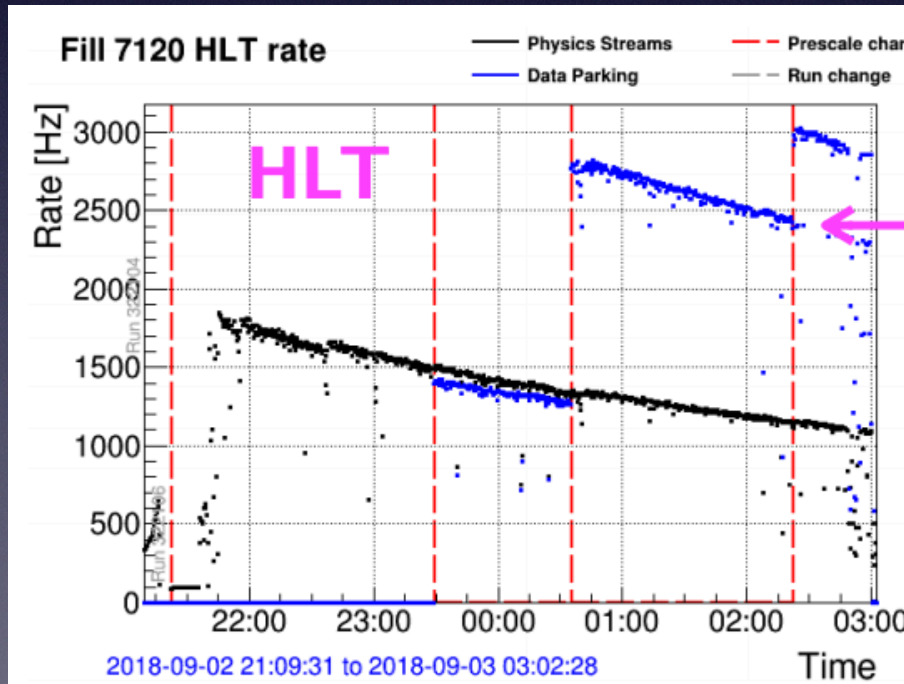

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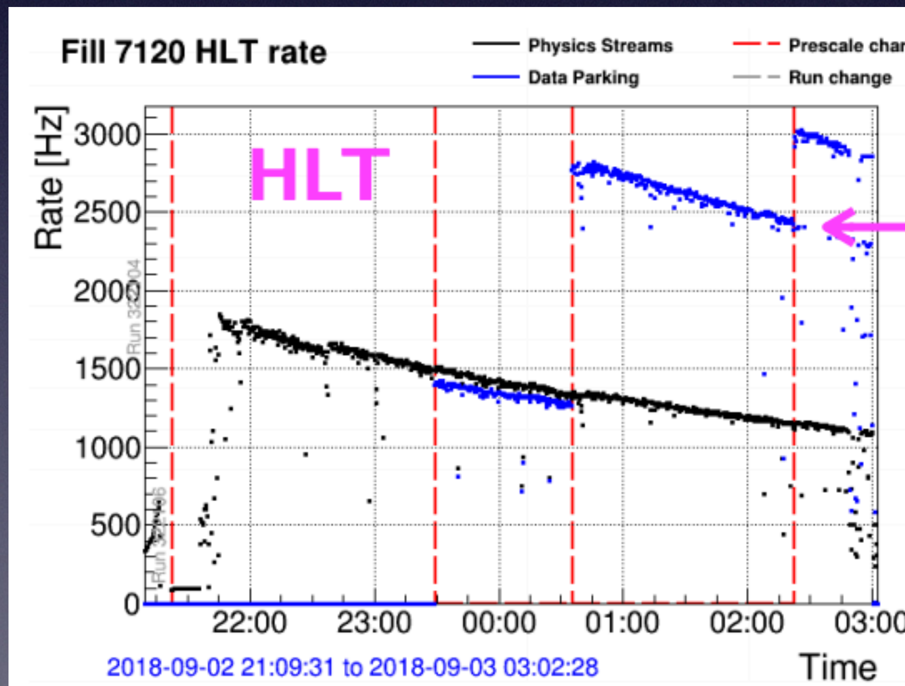


$\sigma / p_T \sim 1\,\%$ (ATLAS) $\sigma / p_T \sim 0.5\,\%$ (CMS)

Conclusions

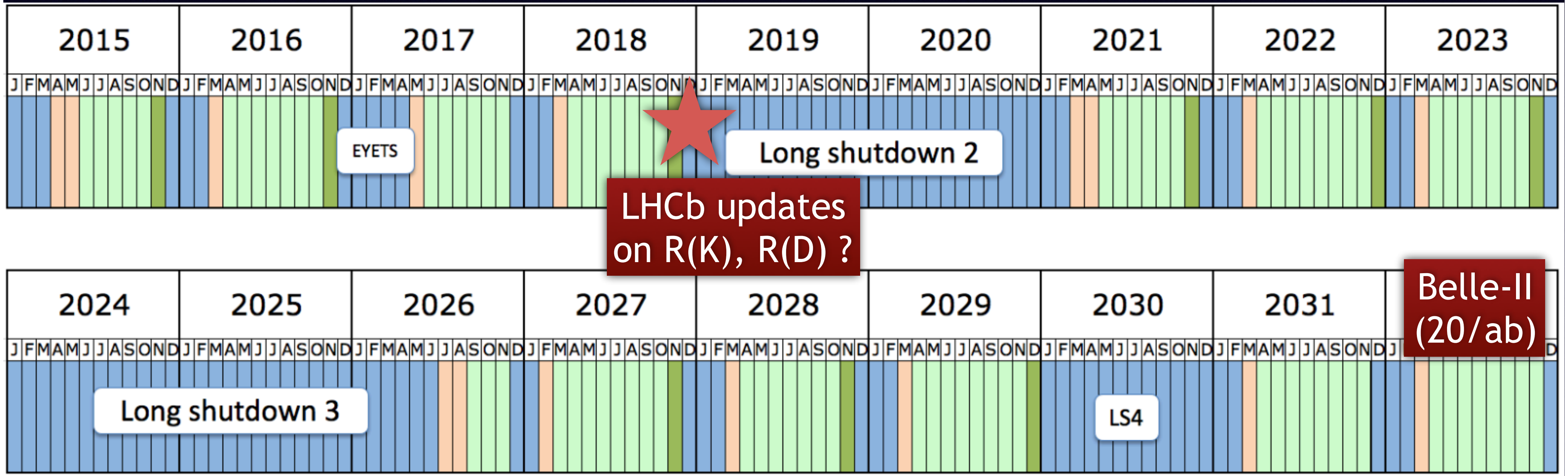
- B-anomalies are pointing to new physics, whose energy scale within reach at ATLAS & CMS
- Broad search programmes for LQ, W' and/or Z'
    - Interpretation performed in the context of B-anom.
- No new physics yet. In the next few years, (I think) we should focus on,
    - Wide $\tau\tau$ resonance search
    - Improve "Boosted object tagging" technique
    - Cross-checking B-anomalies at CMS

Run-2

13 TeV, **150/fb**

Run-3

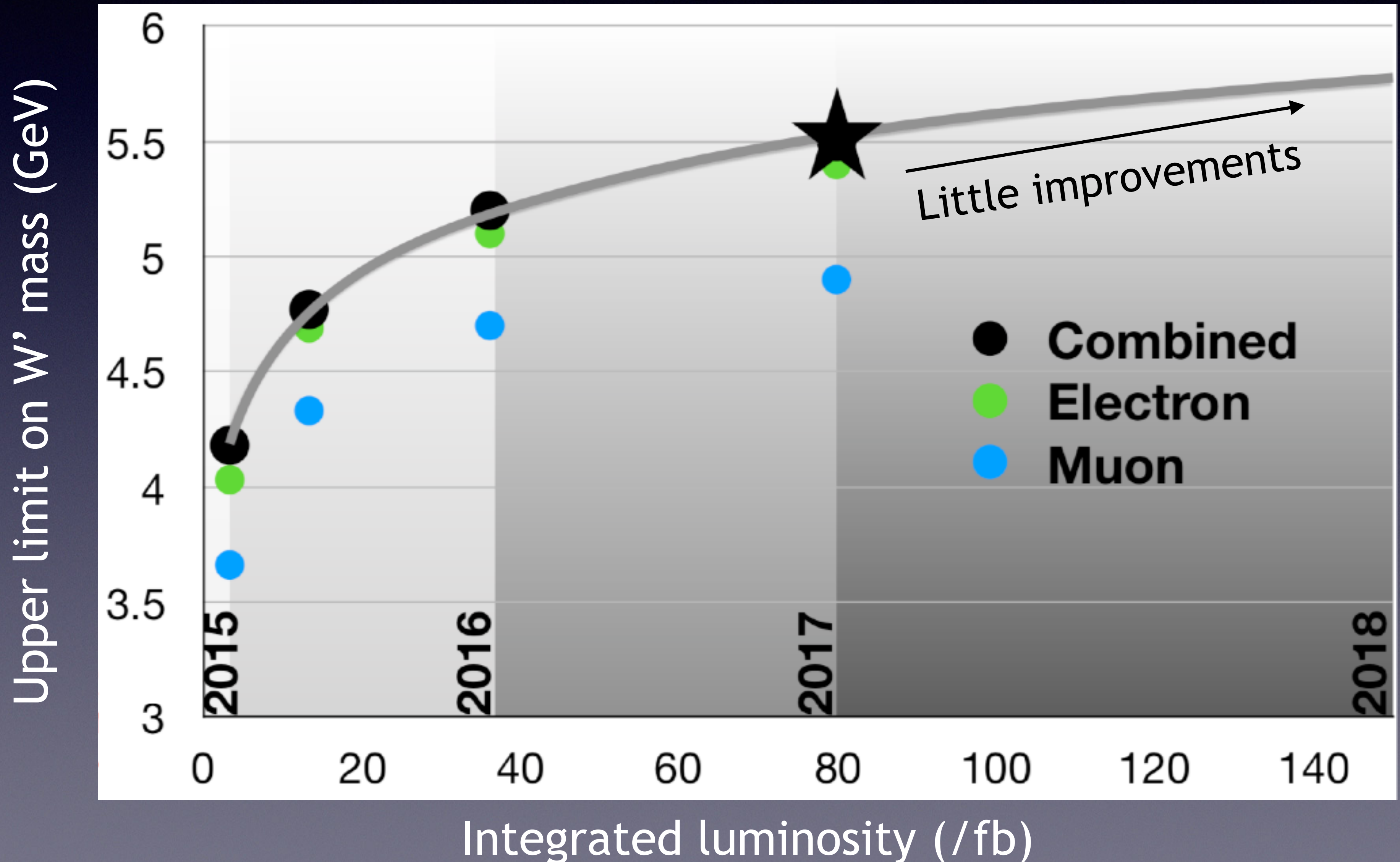
14 TeV, 300/fb

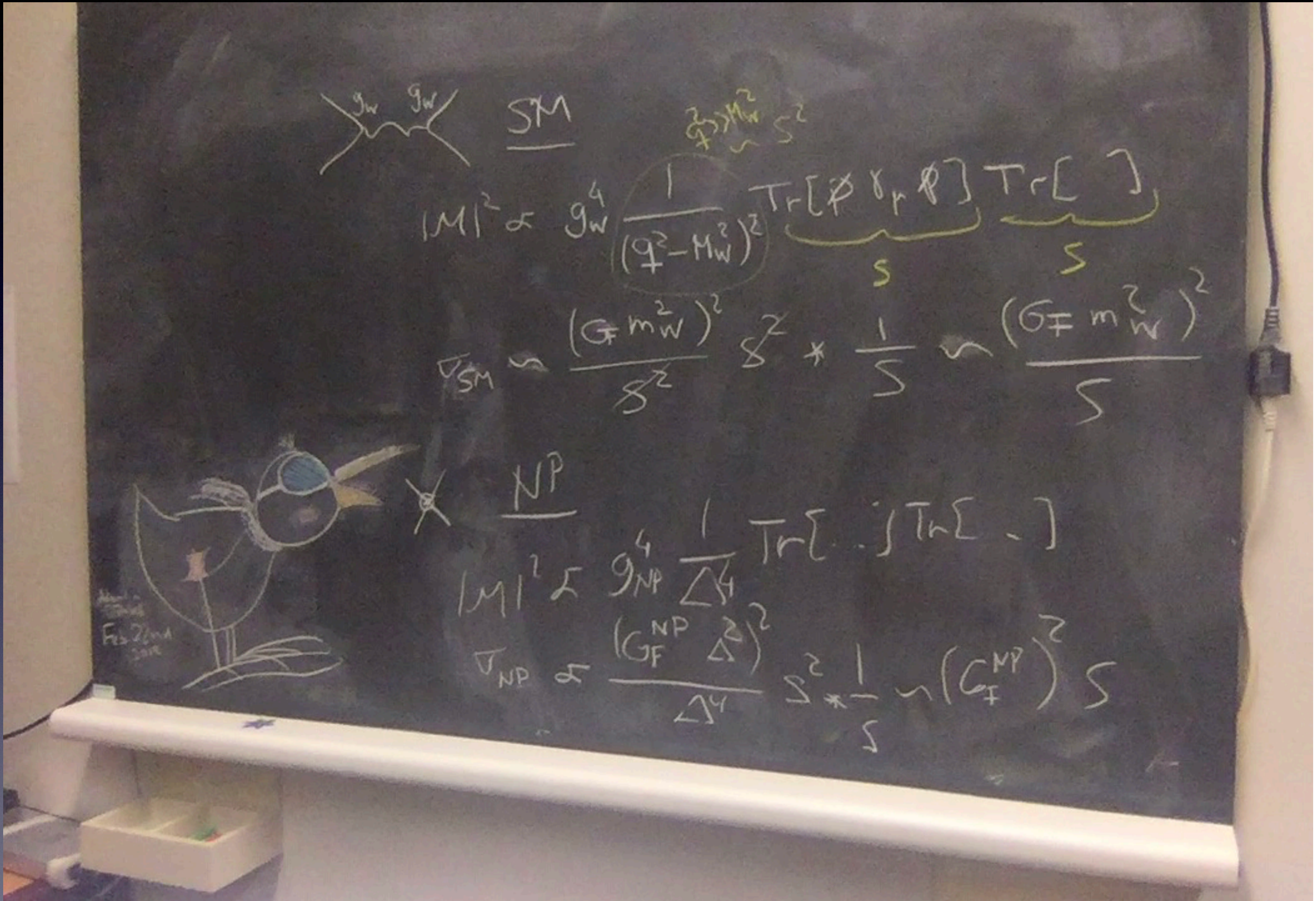


HL-LHC

14 TeV, 3000/fb

We should not "repeat" what we did so far ...




g_W g_W
SM
q² >> M_W² ~ s²
|M|² ∝ g_W⁴ 1/(q² − M_W²)² Tr[p̸ γ_μ p̸] Tr[ ]
s s
σ_SM ~ (G_F m_W²)²/s² s² * 1/s ~ (G_F m_W²)²/s
NP
|M|² ∝ g_NP⁴ 1/Δ⁴ Tr[ ] Tr[ ]
σ_NP ∝ (G_F^NP Δ²)²/Δ⁴ s² * 1/s ~ (G_F^NP)² s