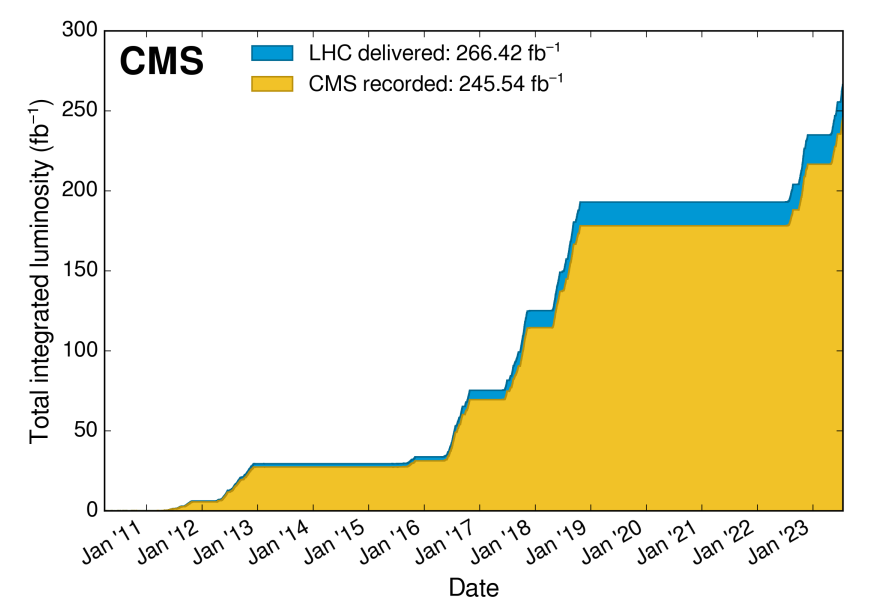
EXOTIC SEARCHES AT THE LHC

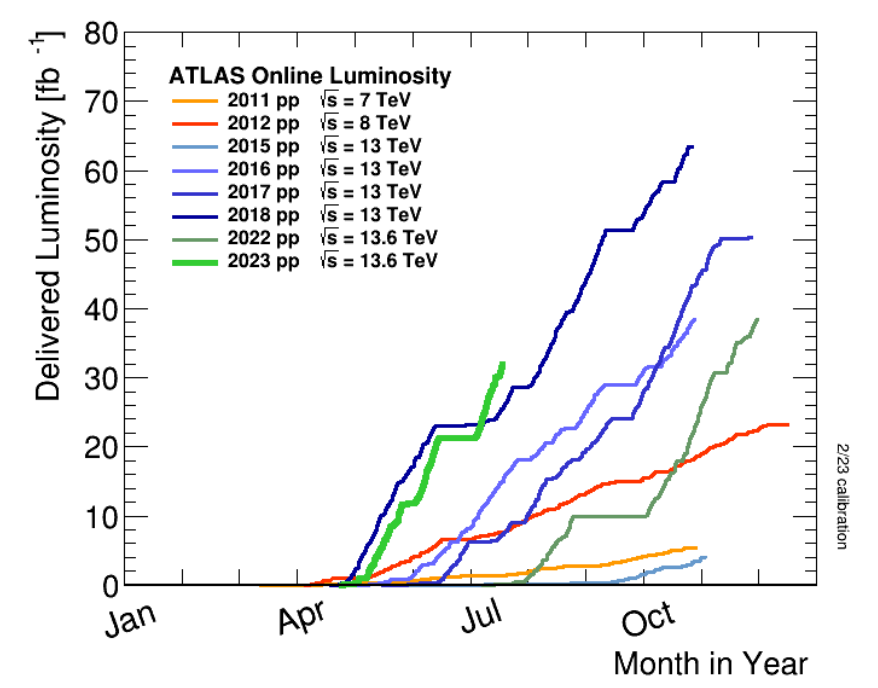
SHILPI JAIN

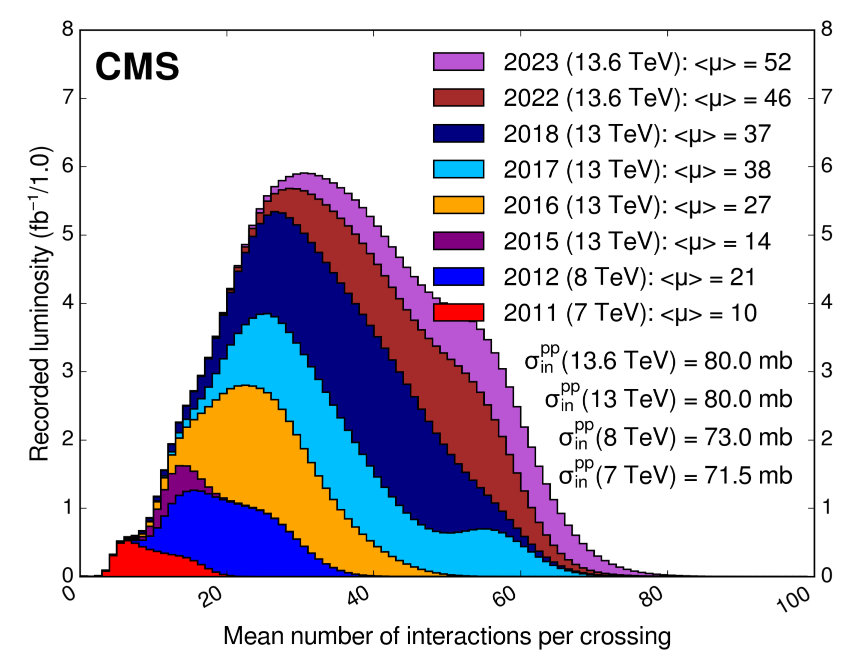
TATA INSTITUTE OF FUNDAMENTAL RESEARCH, MUMBAI

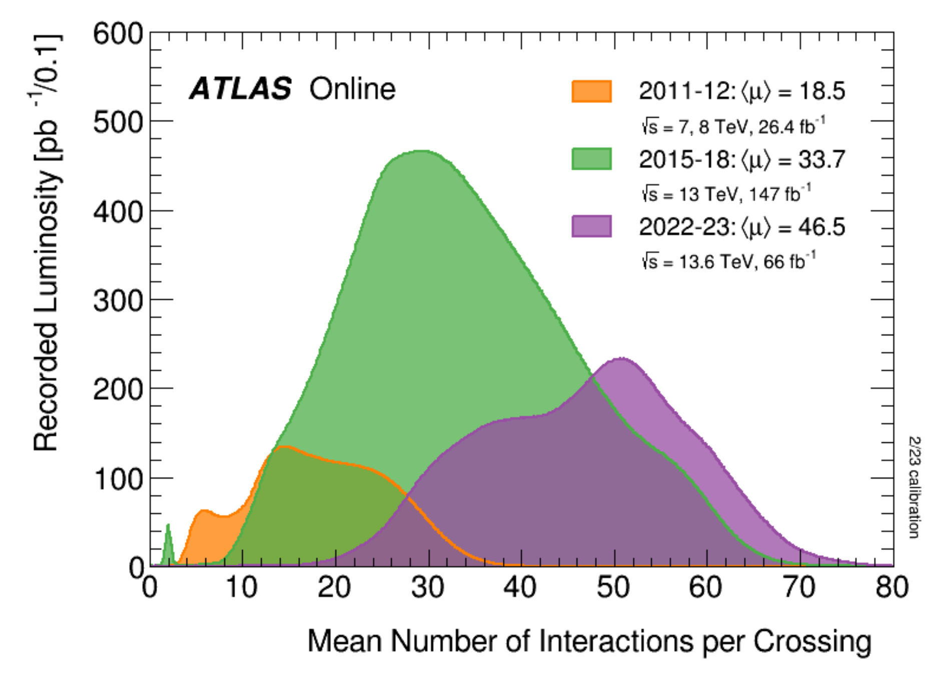
11th Dec - 15th Dec, 2023 International Conference on High Energy Particle & Astroparticle Physics

LHC so far



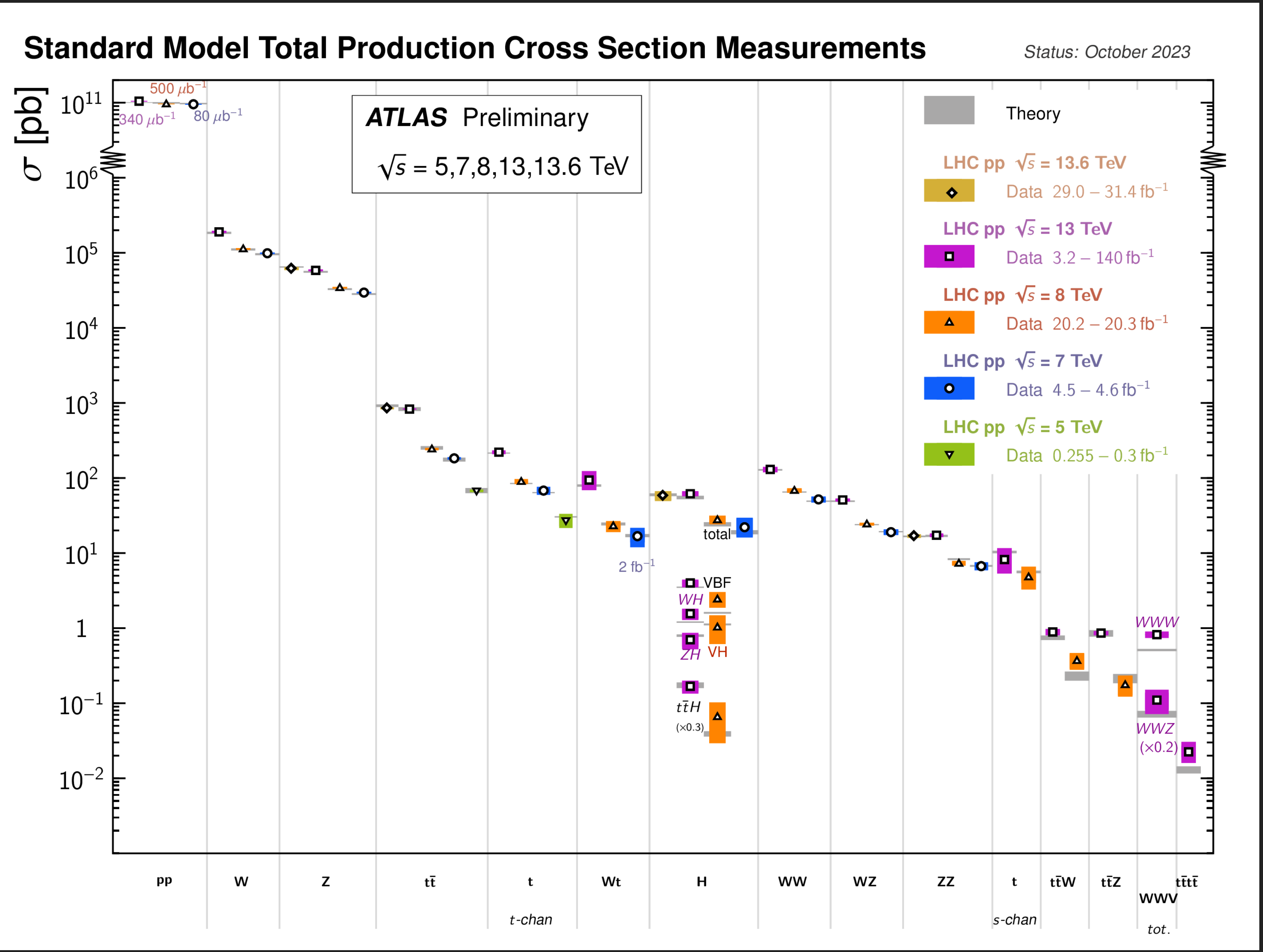






- 73 fb^{-1} delivered in Run 3(2022+2023)
- Many measurements and searches done by all the experiments at LHC
  - With the discovery of Higgs boson 11 years back, SM seems complete

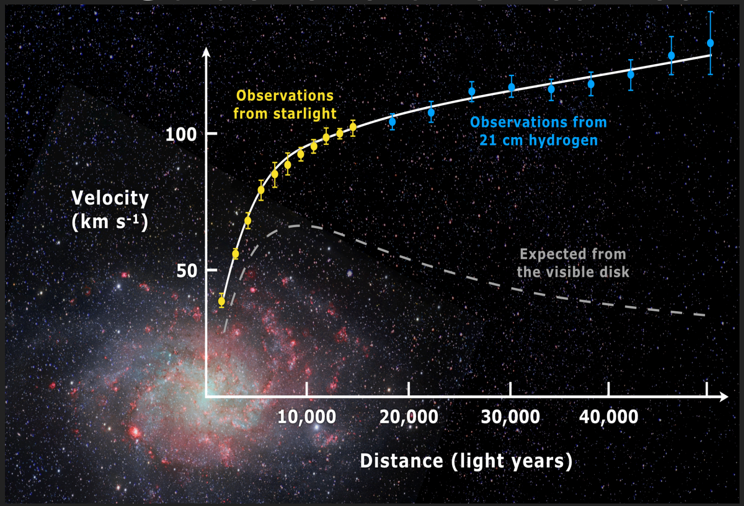
The Standard Model till now



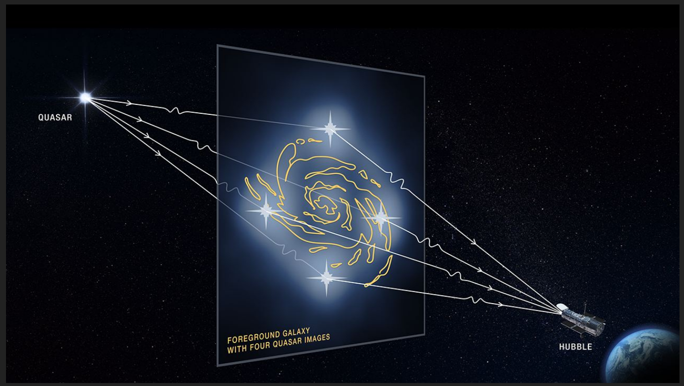
- Similar plot exists for CMS as well
- Excellent agreement with the SM across various energies
- However, SM is not the complete model because …

Unexpected observation/open standing questions not explained in the SM

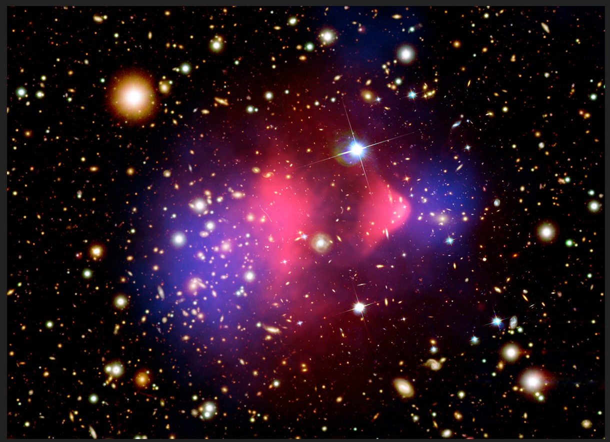
Galactic rotation curves

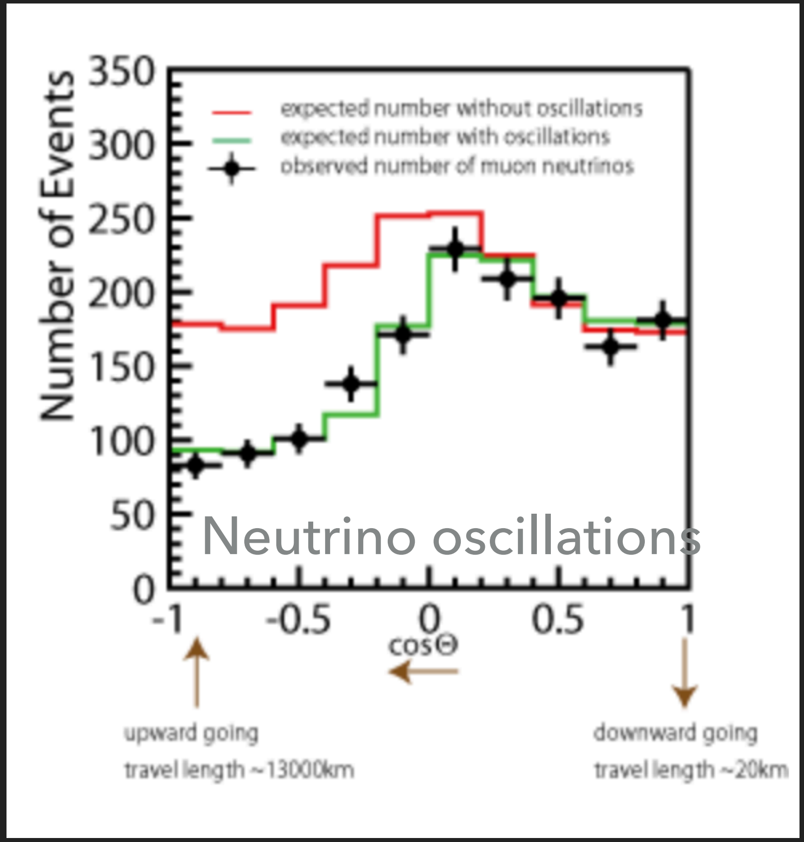


Gravitational lensing



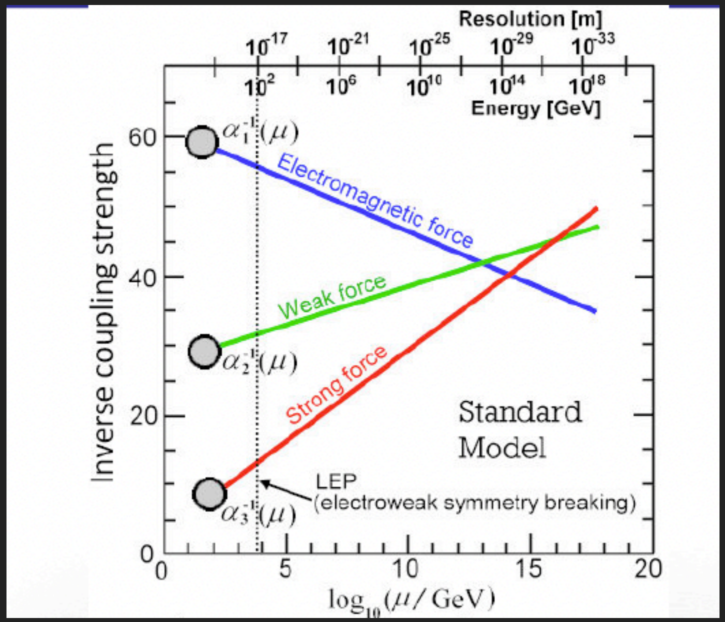
Bullet cluster





Neutrino oscillations

- Questions not answered by the SM
  - Unification of the gauge couplings: Why are gauge couplings different at the energies that we probe? Do they unify at higher scale?
  - No treatment for gravity
  - Hierarchy problem, origins of generations etc



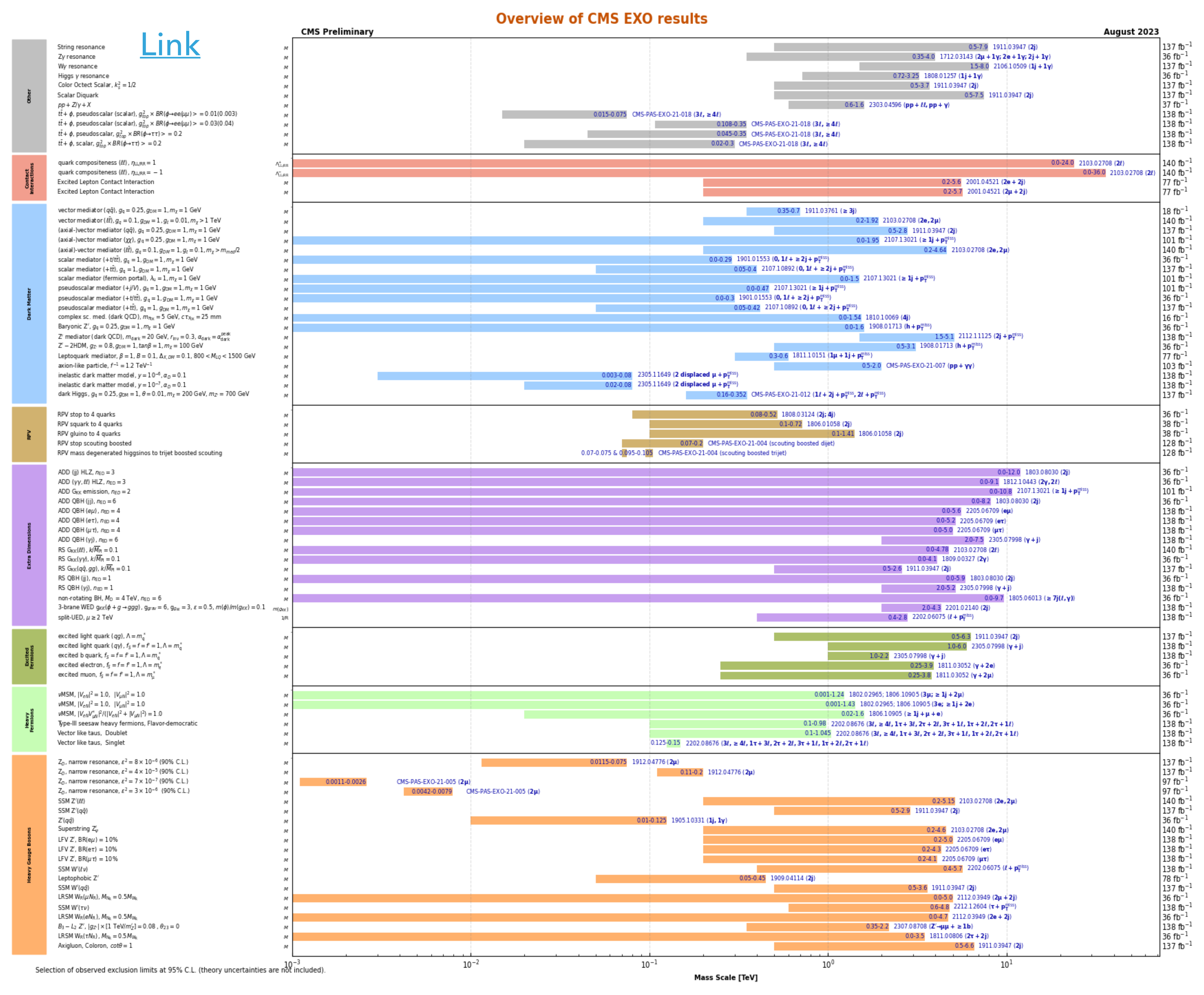
- Observations from non-collider experiments on new physics

- Many questions to be answered

- SM cannot be the ultimate fundamental theory

Look for Beyond the Standard Model Physics

- We do not know which direction to take and hence plethora of searches

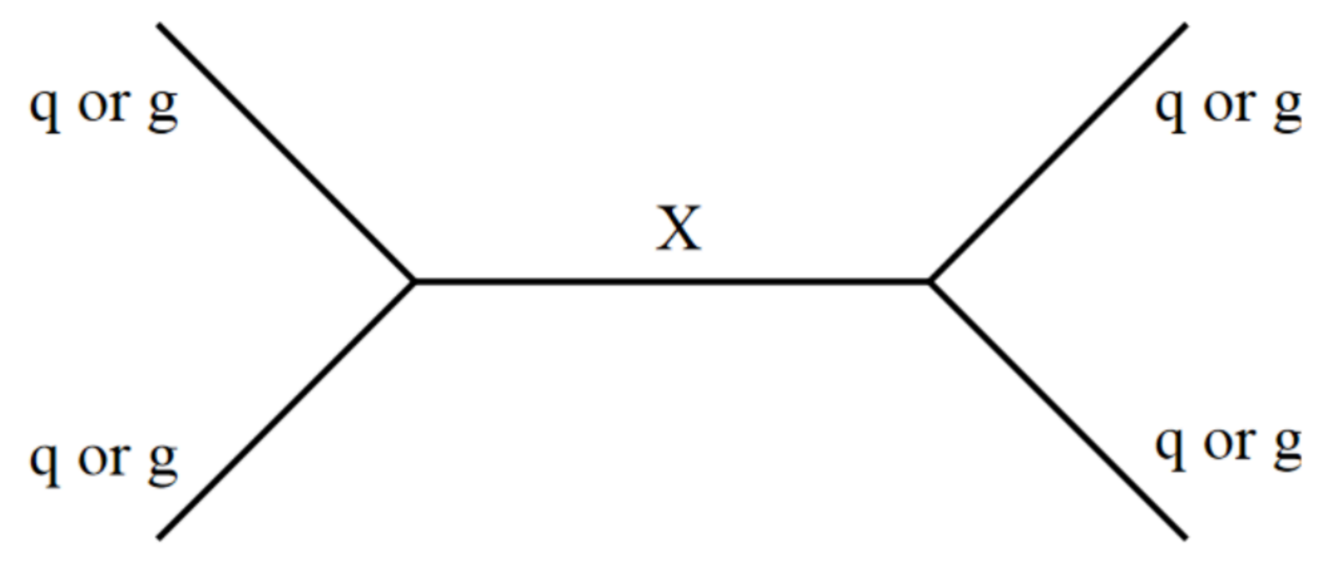


- Similar plot exists for ATLAS as well

Which direction to go?

- In the absence of strong presence of new physics signature in any sector, we do not know which direction to take
- In the recent years, an increasing number of hints, anomalies or excesses for BSM physics have been reported
- They span over a huge energy range
  - precision measurements of muon properties (g-2)
  - Semi-leptonic B meson decays
  - Measurement of W boson mass
  - **Direct LHC searches**
- We can filter out searches which have shown some anomalies or excesses above 3σ and check what CMS and ATLAS see
  - Helps us set some direction
  - **Main theme of today's talk**

Dijet Resonances

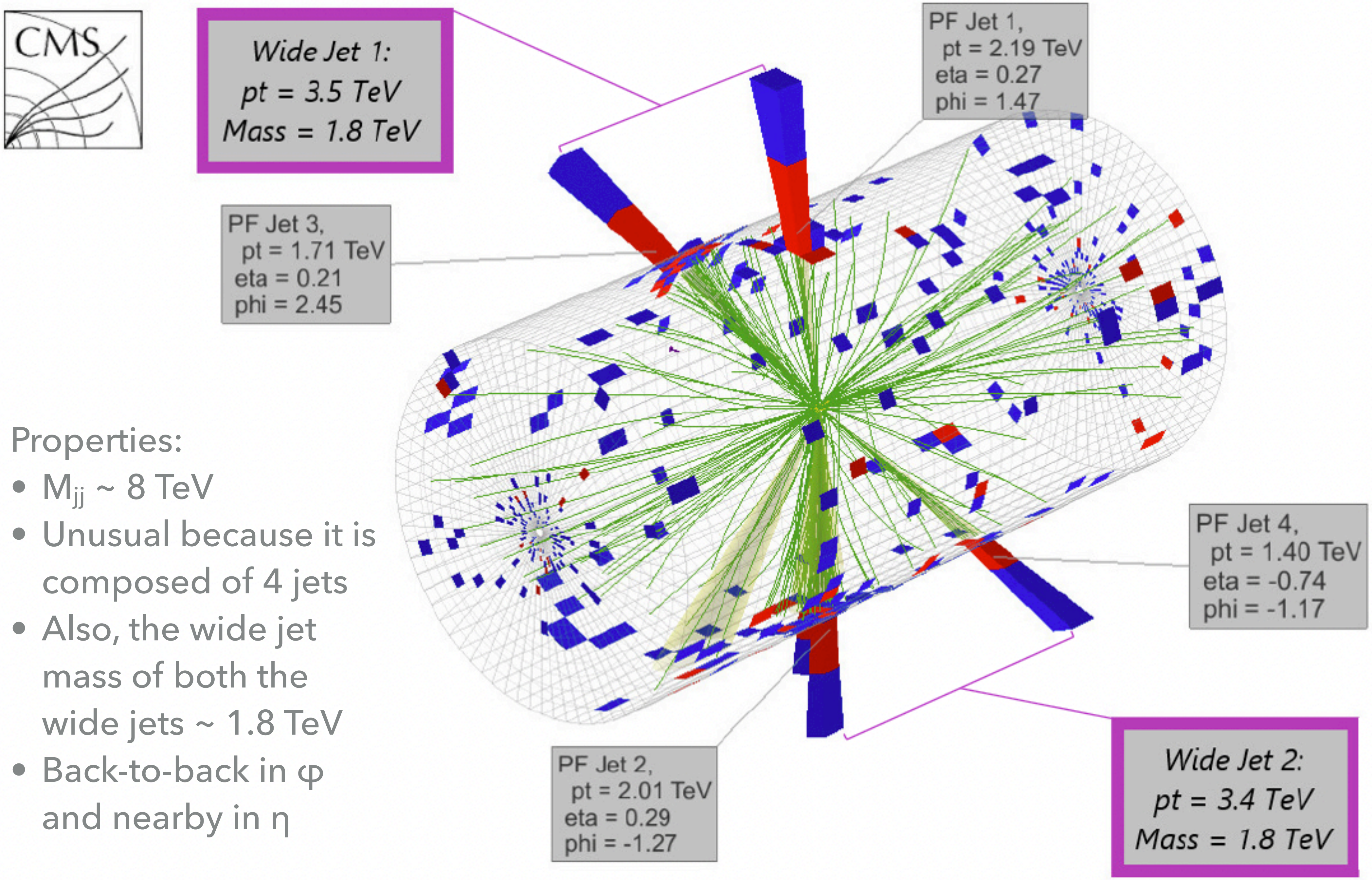


- Model independent search for a narrow or broad resonance
  - Produced in s-channel by gluon-gluon fusion or quark-antiquark annihilation, or quark-gluon scattering, further decaying to two jets
- Benchmark models: New gauge bosons (W′, Z′), dark matter mediators, RS graviton etc
- Have been done in CMS and ATLAS since Run I

Di-jet searches

- Main background: QCD multijet production
  - Estimated by fitting the the m_{jj} distribution with an empirical functional form
- Strategy:
  - Combine R = 0.4 jets into wide jets if they have dR < 1.1
    - collect final state radiation to improve the mass resolution
- 2 events were seen with m_{jj} ~8 TeV in 2017 in CMS
- Checked for detector and reconstruction pathologies

Characteristics of one of the unusual event



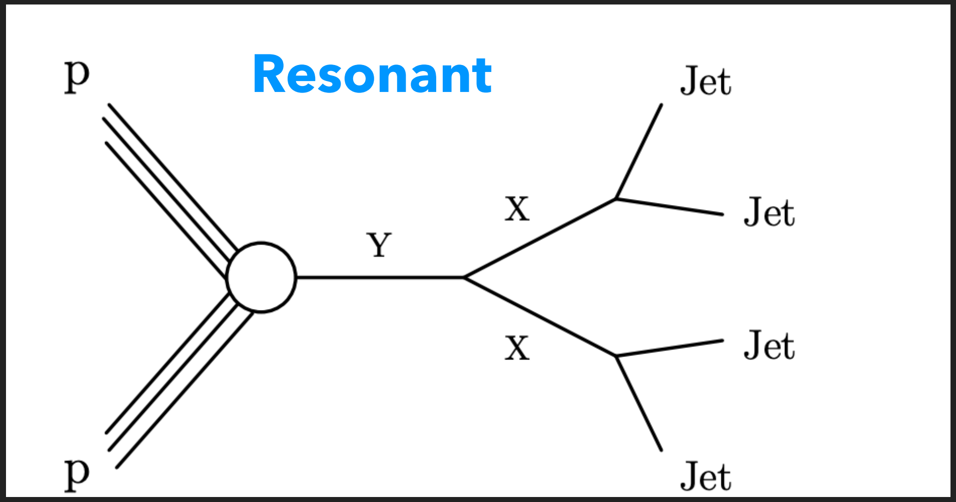
Properties:

- M_{jj} ~ 8 TeV
- Unusual because it is composed of 4 jets
- Also, the wide jet mass of both the wide jets ~ 1.8 TeV
- Back-to-back in φ and nearby in η

- Probability of getting such an event from QCD ~ 10^{-4}.
- This led to the start of dedicated paired jet search in CMS

Paired Dijet resonant searches

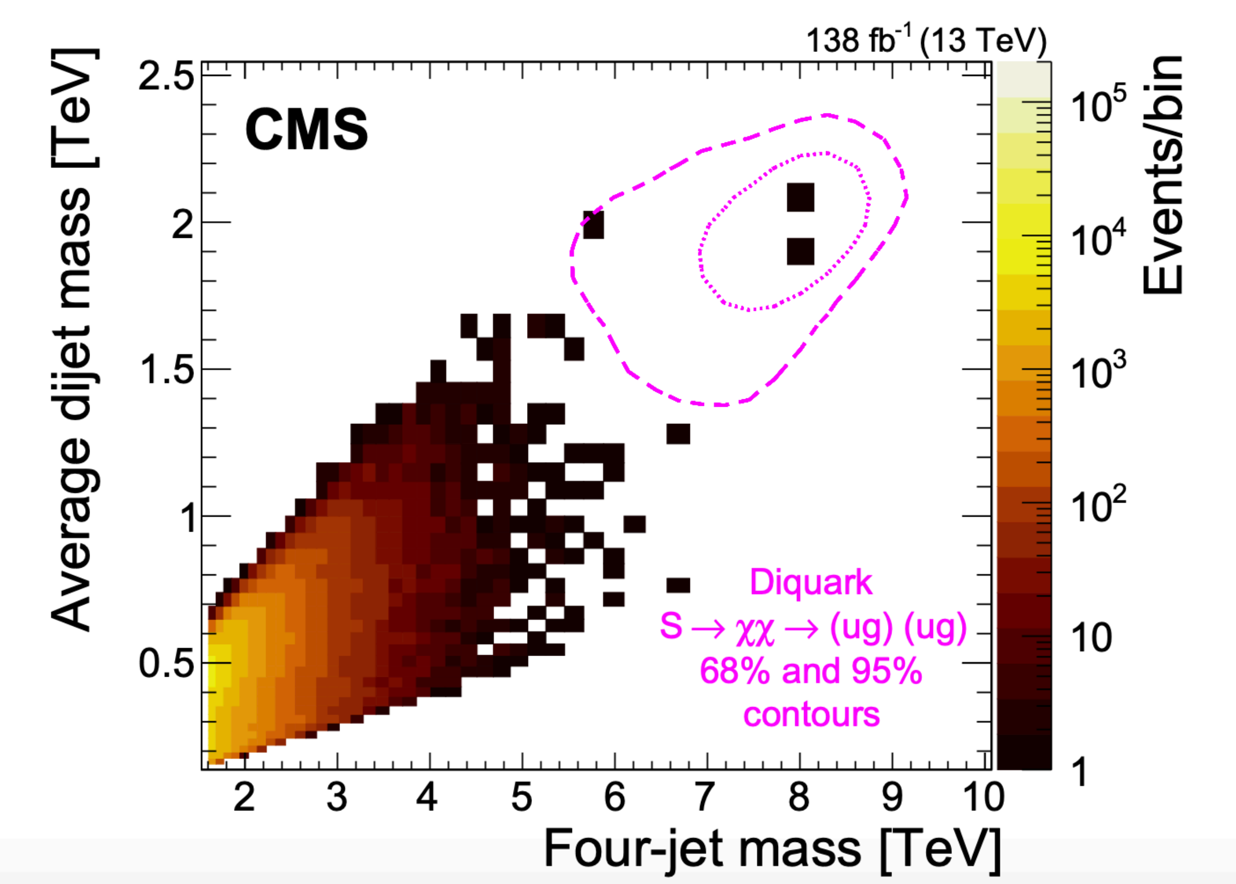
JHEP07(2023)161



- New physics models: Diquark (S_{uu}) decaying to vector-like quarks (which further decay to a quark (u) and a gluon)

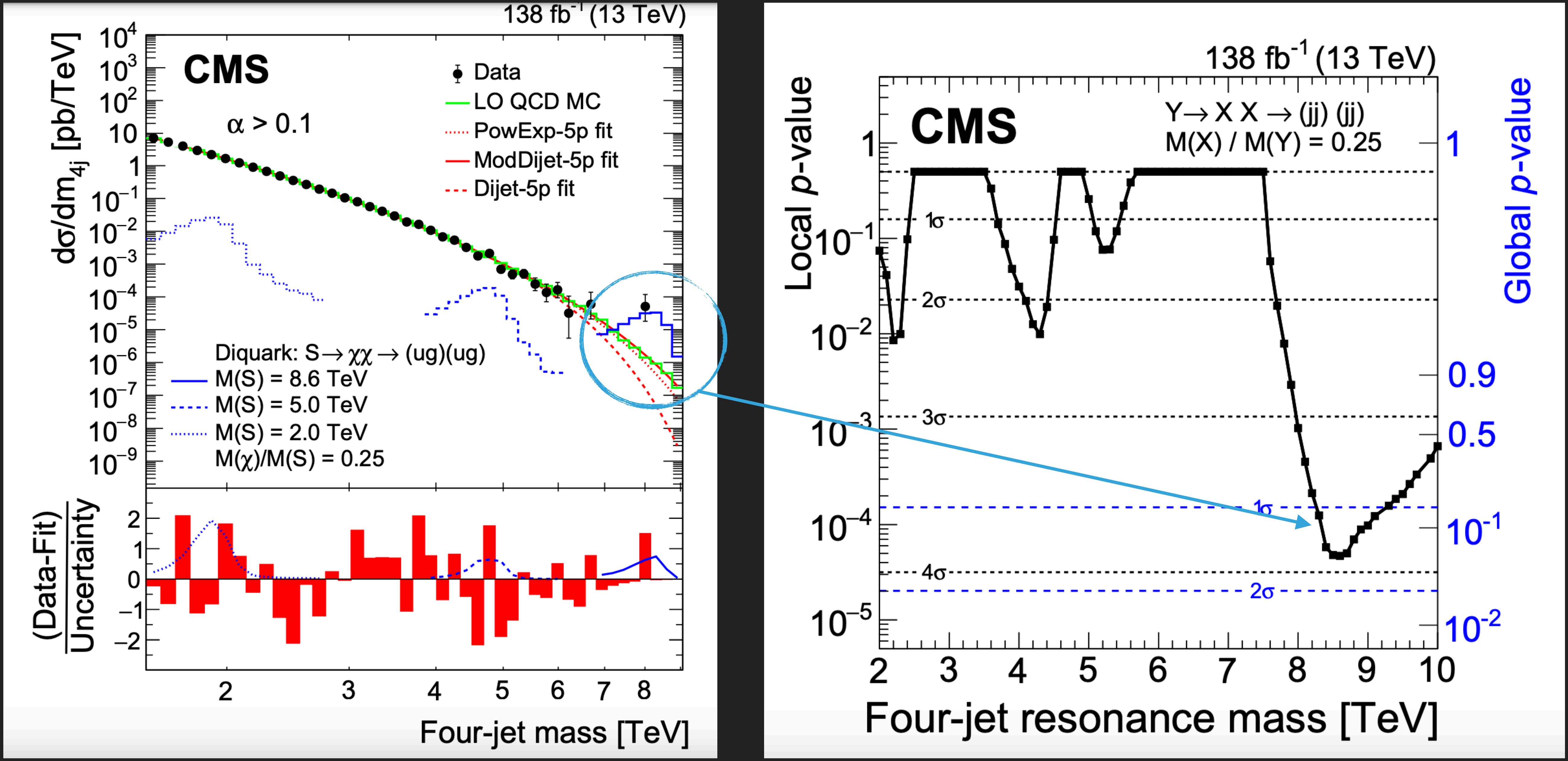
$$\Delta R = |(\Delta R_1 - 0.8)| + |(\Delta R_2 - 0.8)|.$$

Determines which jets to be paired



- To reduce background and wrong combinations:
  - After pairing, each pair of jets should satisfy dR < 2.0 to reject QCD background
  - $|\Delta\eta| < 1.1$ (between the two dijet pairs)
  - Asymmetry in dijet mass (property of pairs of identical resonances) = $\frac{m_1 - m_2}{m_1 + m_2} < 0.1$
  - Bin in $\alpha = m_{jj}/m_{4j}$ (avoid correlations), fit m_{4j} for resonant search

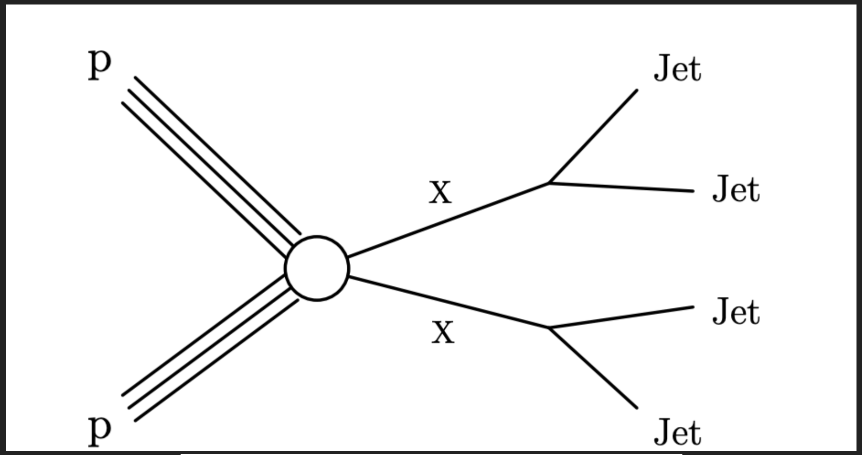
Paired Dijet resonant searches



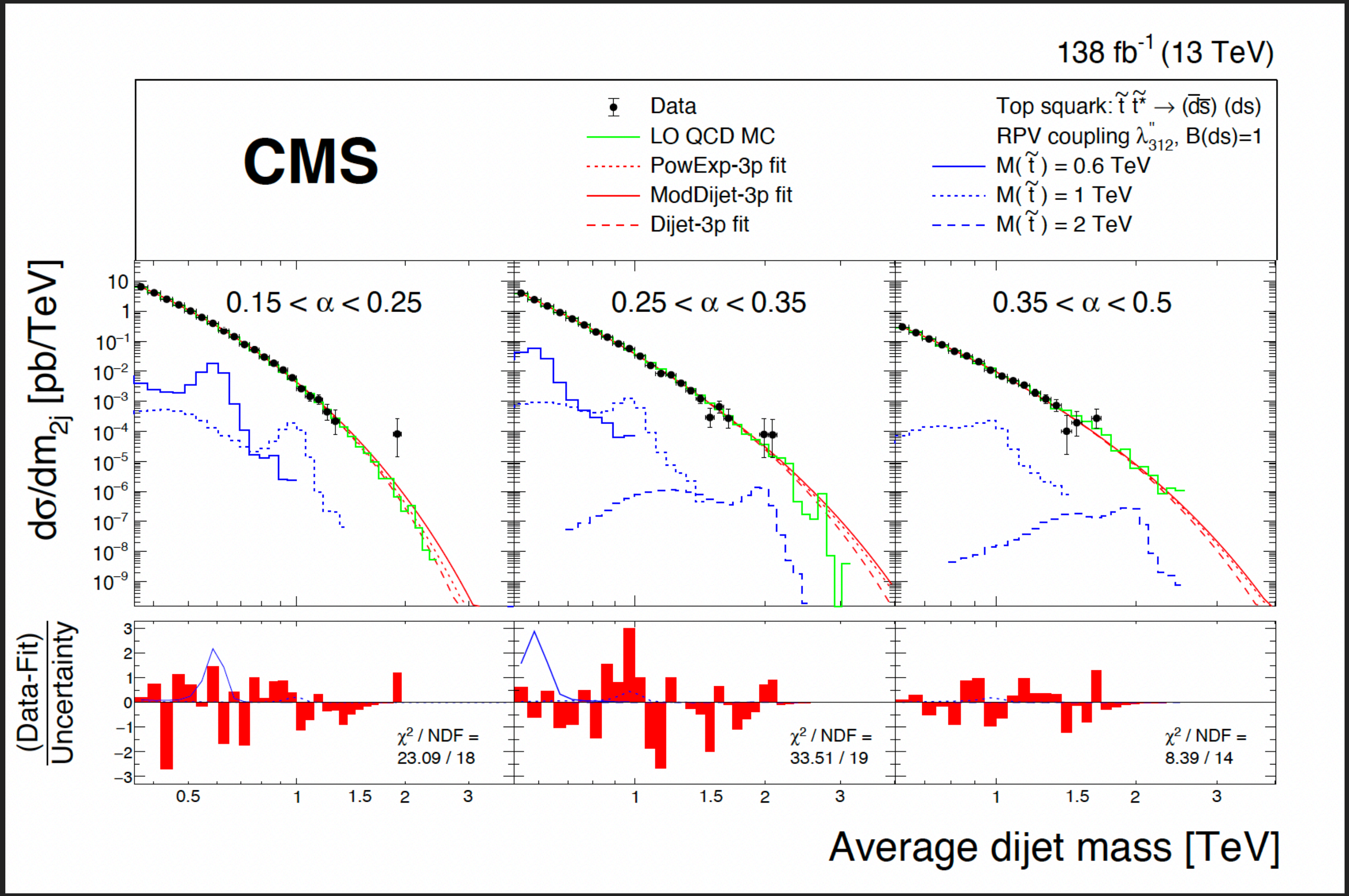
- Two candidate events found with m_Y ~ 8 TeV and 8.6 TeV and m_x ~ 1.8 TeV and 2 TeV
- Local significance ~3.9σ with global significance of 1.6σ considering resonant

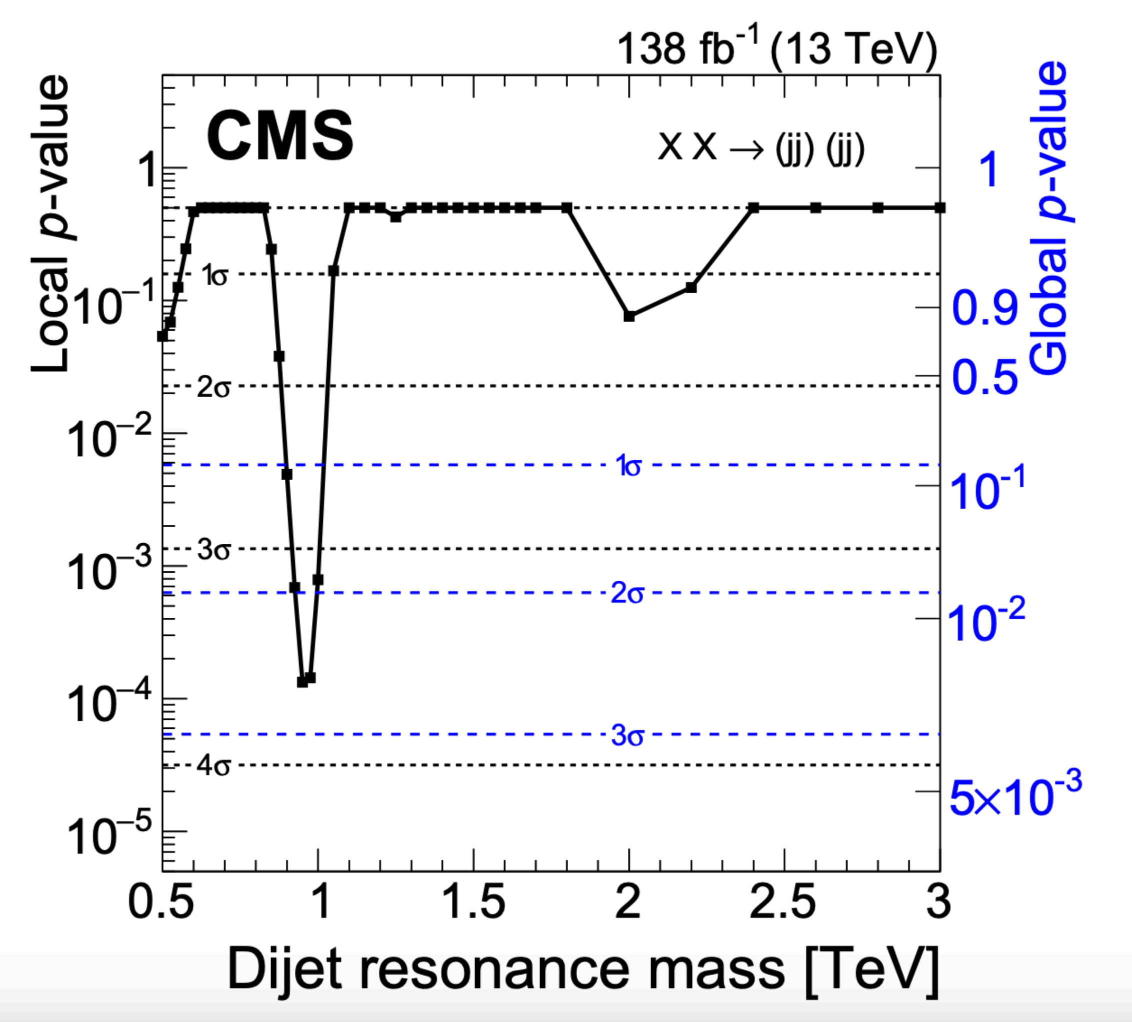
Paired dijet non-resonant searches

Non-Resonant



$pp \to \tilde{t}\tilde{t}^* \to (\bar{d}\bar{s})(ds).$



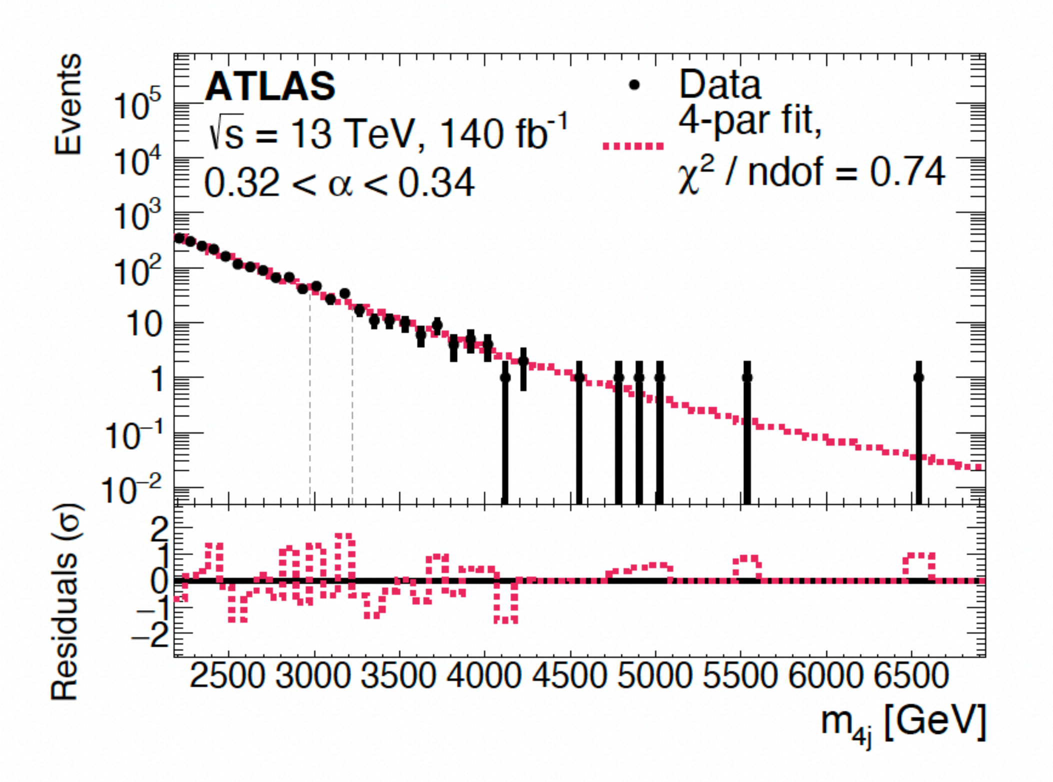


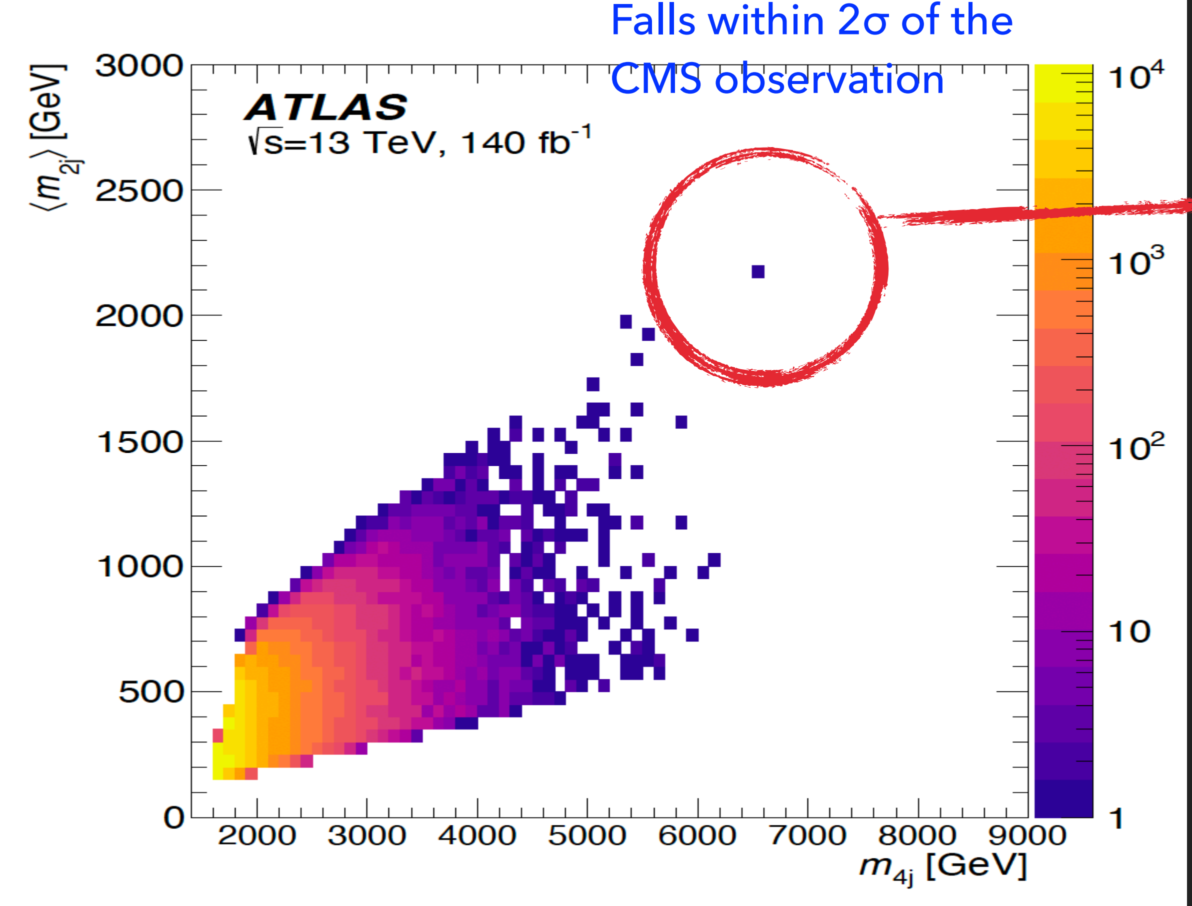
- New physics models: R-parity violating SUSY.
- Same strategy as in the resonant search but fit m_{jj} for the search
- One candidate events found with $m_X \sim 0.95$ TeV
- Local significance ~ 3.6σ with global significance of 2.5σ considering non-resonant searches

What about ATLAS - paired dijet searches?

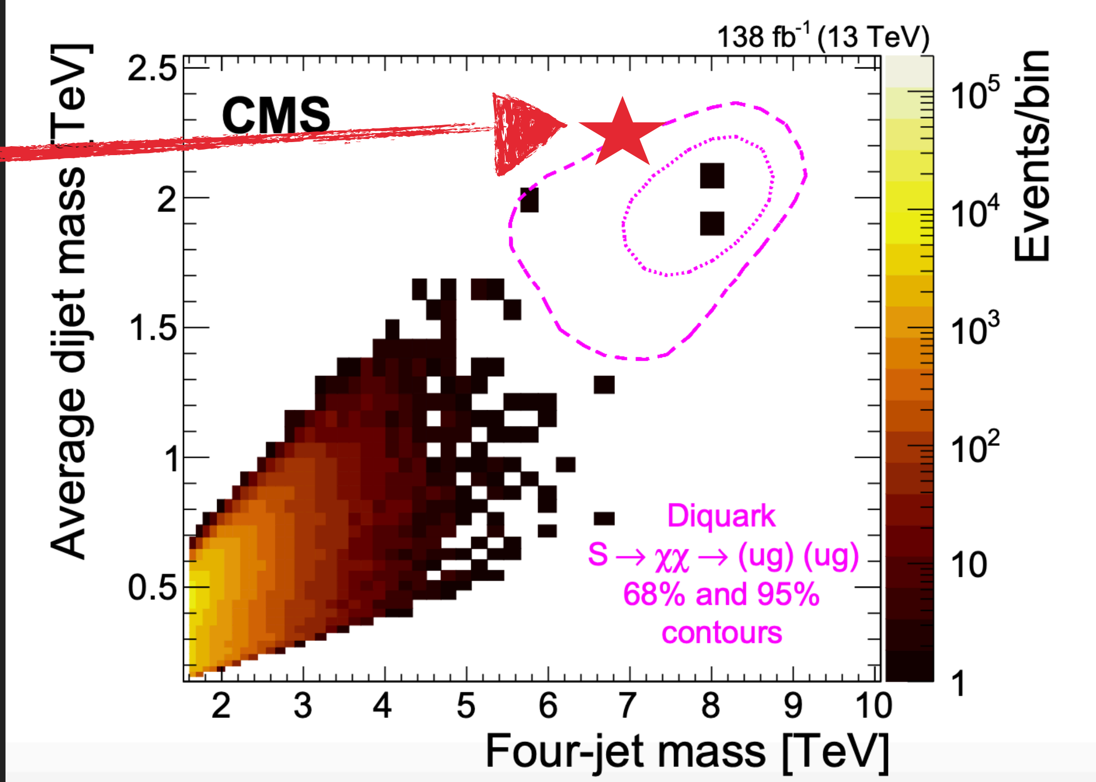
arXiv: 2307.14944

- Prompted by the slight excess seen by CMS in paired dijet searches, ATLAS has very recently investigated the paired dijet final state as well
- Similar search strategy as in CMS
- Highest observed 4 jet mass = 6.6 TeV corresponding to dijet mass = 2.2 TeV

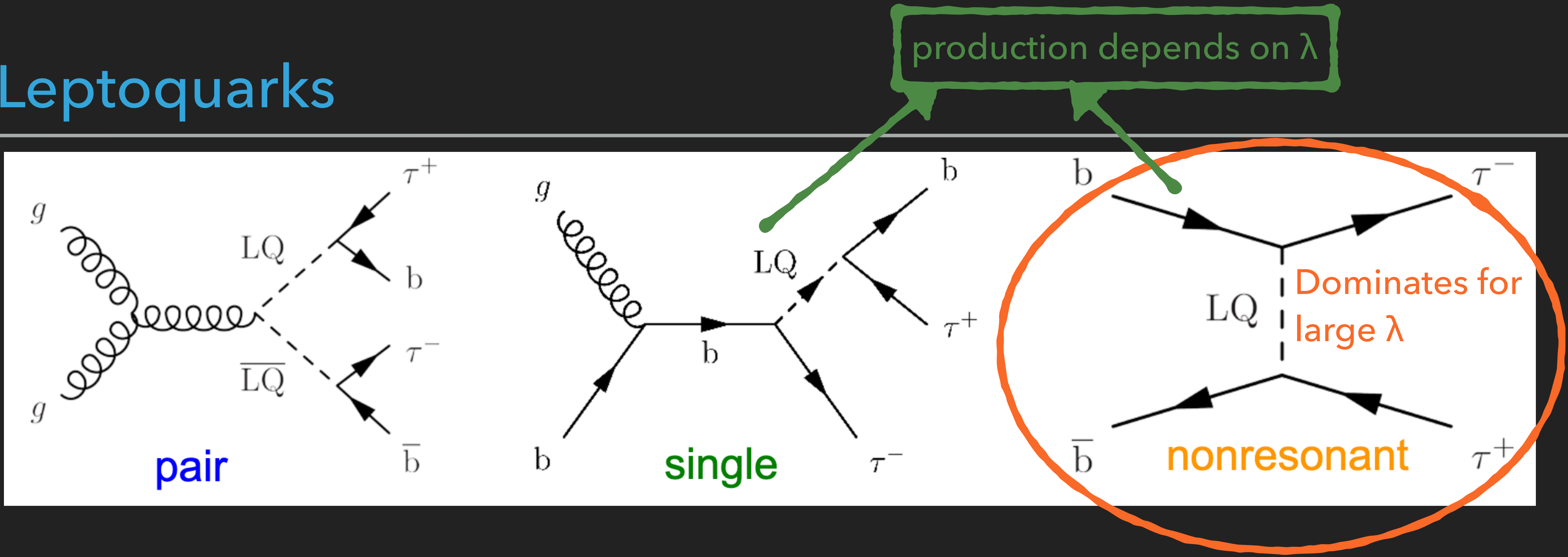




Falls within 2σ of the CMS observation

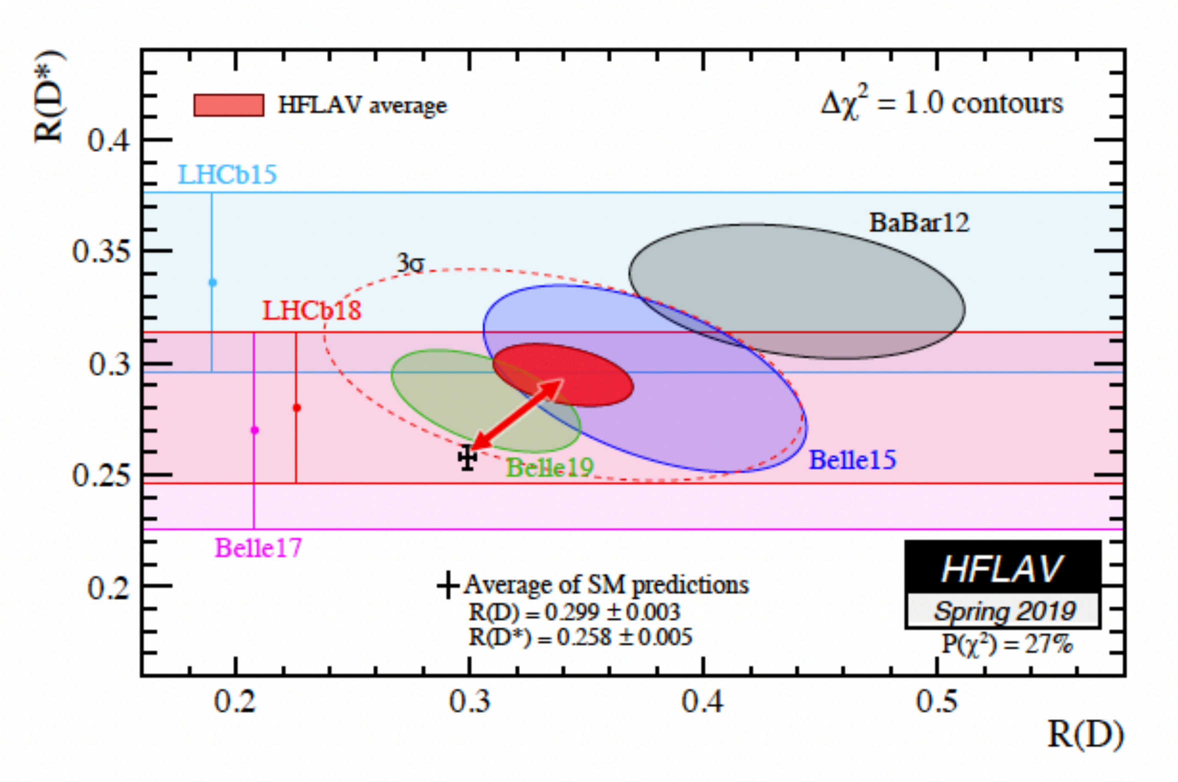


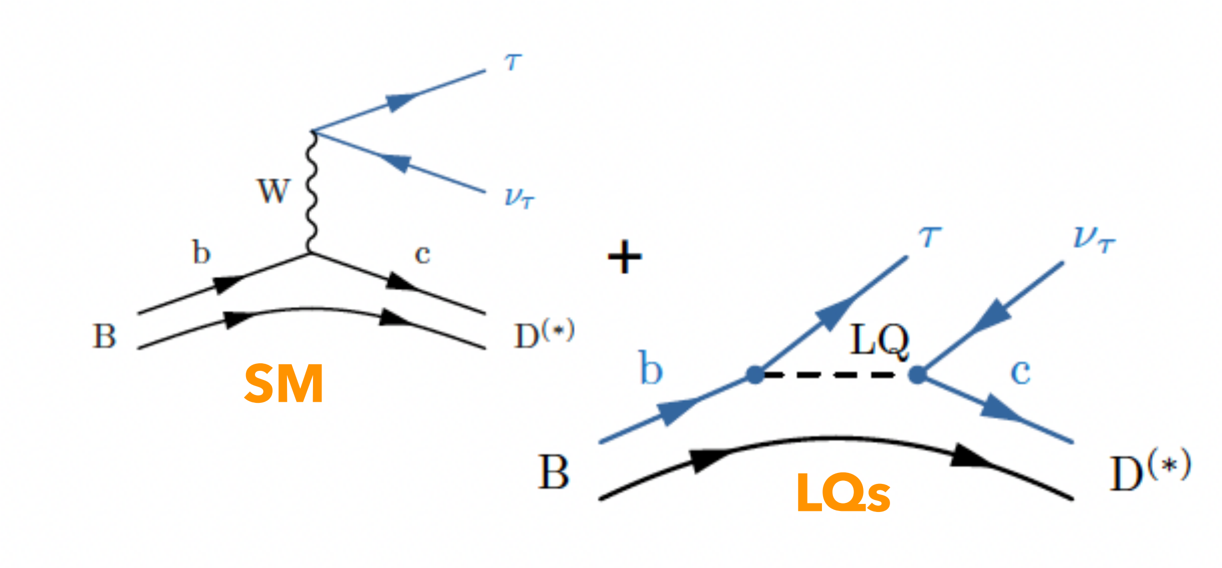
Leptoquarks



- Leptoquarks are hypothetical particles that couple to both a quark and a lepton of a given generation
  - Carry both baryon and lepton quantum numbers and have fractional electric charge
  - Predicted by many theories: grand unification, technicolor frameworks, compositeness etc
- LQs can be produced
  - In pairs via gluon-gluon fusion, quark-antiquark annihilation
  - Singly via quark-gluon fusion
- Production and decay determined by:
  - LQ mass m_{LQ}
  - Yukawa couplings λ to lepton and quark
  - Branching fractions β to a given lepton and quark flavors
  - coupling parameter κ in case of vector LQs (coupling with the SM gauge fields)

Why look at lepto-quarks?





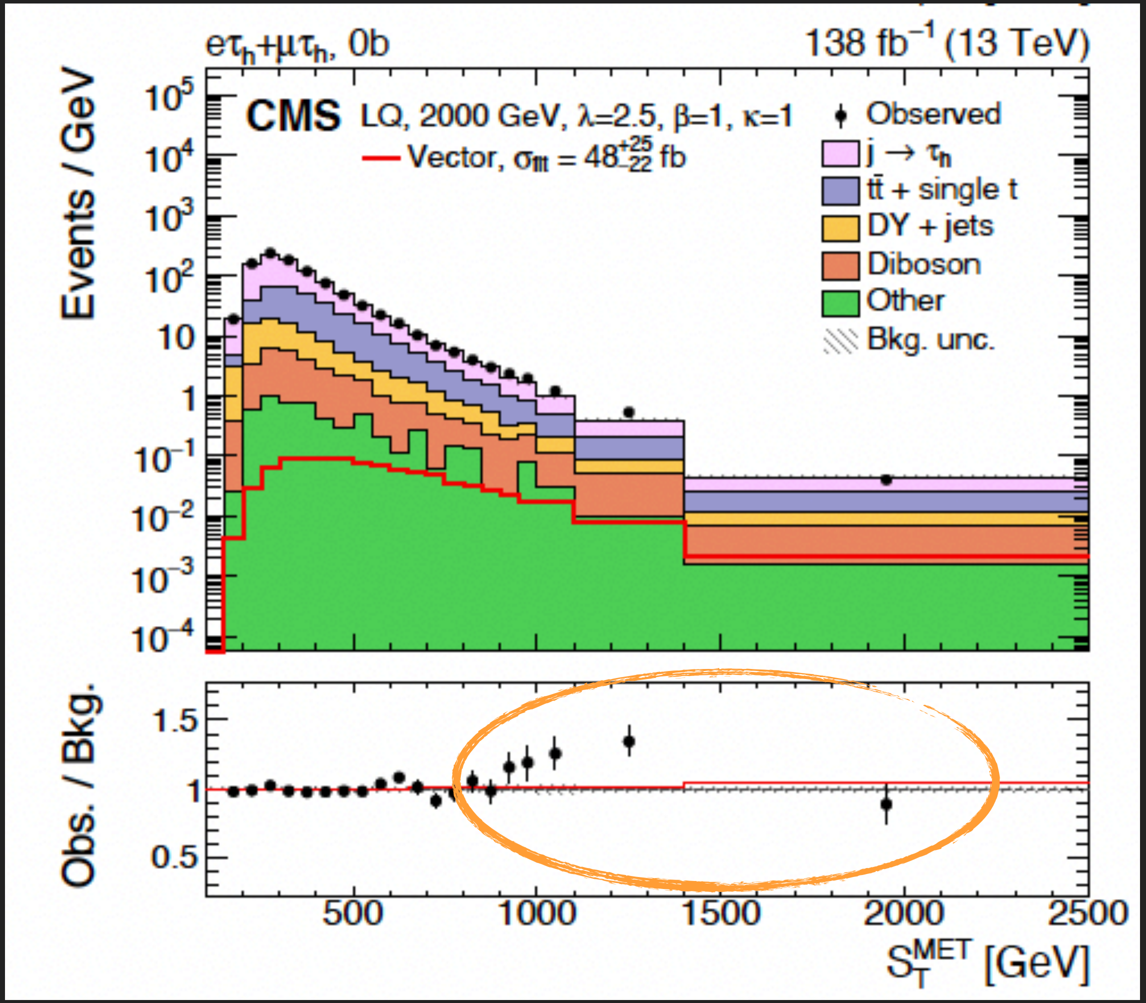
G.Isidori et. al.: 1, 2

- R(D*) combined is 3.1σ deviation (B–>D*τb)
- LQ models can explain the Lepton Flavour Universality Violation: a LQ that couples most strongly to third-generation fermions could explain
  - second and third generation LQs are especially important in the above context

2308.07826

CMS: Leptoquark coupling to a τ lepton and a b quark

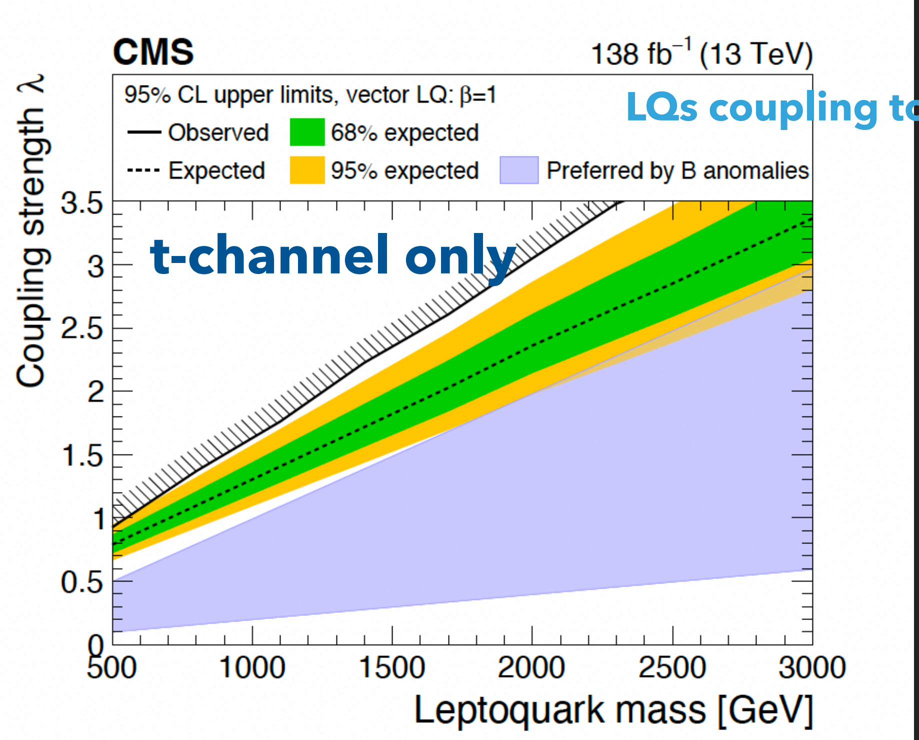
- Single and pair production of scalar and vector LQs decaying to two τ leptons and at least a b quark
- Non-resonant production of τ lepton pair
- Several decay channels of τ lepton pair: (τ_h τ_h), ($e\tau_h$, $\mu\tau_h$) and ($e\mu$, $\mu\mu$)
    - ($e\mu$, $\mu\mu$) is primarily to constrain the SM background
- Sort search variables by sensitivity
- **Resonant channels (single and pair):** Two high-pT τ leptons + one or two high-pT b quarks. **Sensitive variable:**
    - $S_T^{MET} = P_T(\tau_1) + P_T(\tau_2) + P_T(j_{leading}) + P_T^{miss}$
    - Further categorized: 0bjet and >=1bjet
- **Non-resonant channels:** Two high-pT τ leptons in the final state. No jets above pT > 50 GeV required in this category. **Sensitive variable:**
    - $\chi = \exp(|\eta(\tau_1) - \eta(\tau_2)|)$ –> angular separation between the two τ lepton candidates
        - New physics process lies at low χ values (background has flat distribution)
- Driven by non-resonant signal



- Main backgrounds: $t\bar{t}$, single t, DY+jets, W+jets, diboson and QCD

Further categorization in bins of m_{vis}

Leptoquark coupling to a τ lepton and a b quark



t-channel only

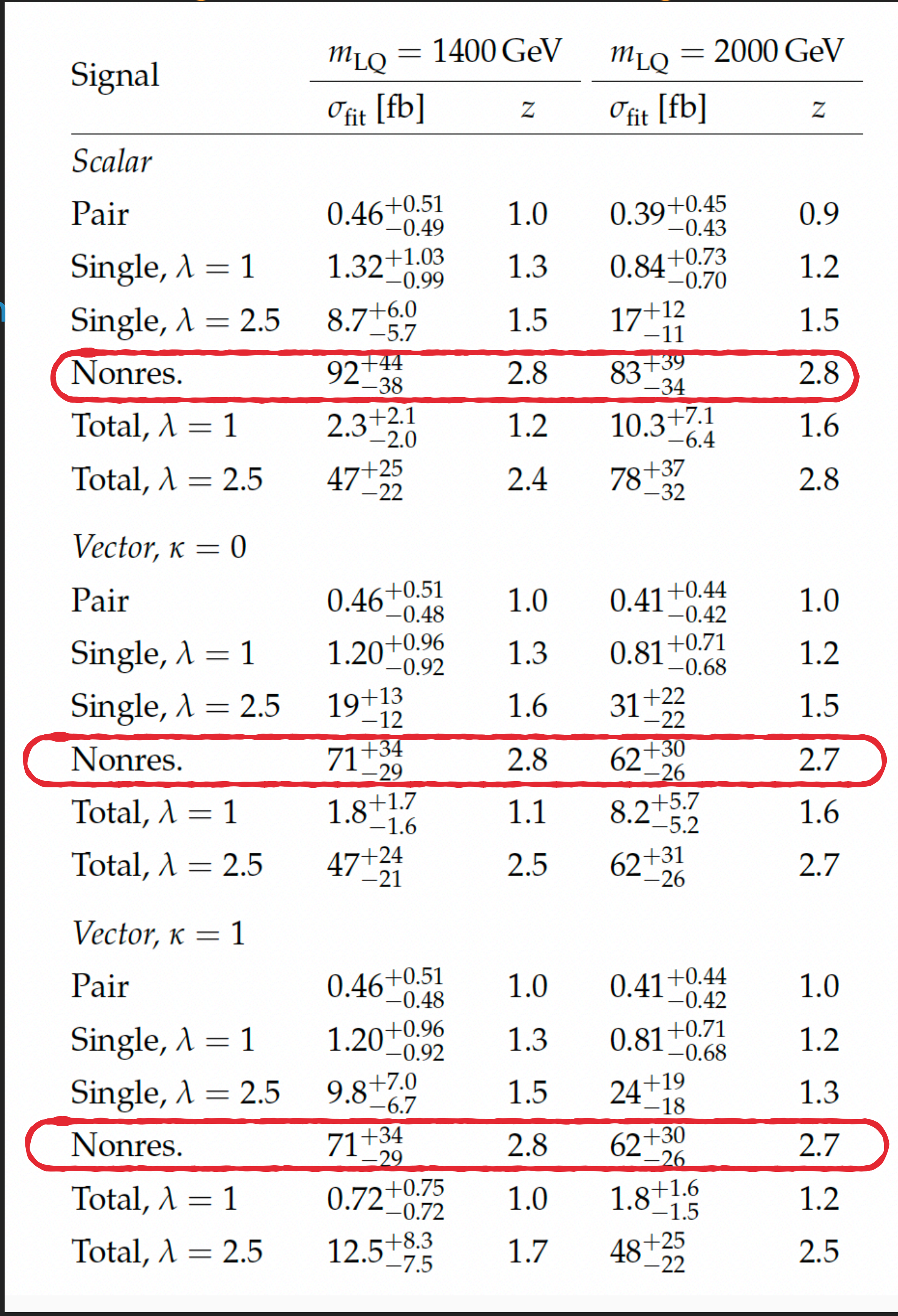
LQs coupling to bτ exclusively

This excess is observed in all the channels in both the STMET and χ distributions

LQ masses below 1.50 (1.82) TeV for the vector model λ=1 and a coupling parameter κ = 0 (1)

- Binned maximum likelihood of S_T^{MET} and χ
  - UL on the $\sigma^{\text{tot}} \equiv \sigma^{\text{single}} + \sigma^{\text{pair}} + \sigma^{\text{nonres}}.$
- Excess seen in the non-resonant channel
- Further studies showed that it is coming from 0b jet category
- Local significance ~ 2.8. This excess is consistent with LQ model of mass 2 TeV and λ=2.5
  - Similar with the global significance
- Limits on mass (for vector-like): For λ=1.0 masses below 1.50 TeV and λ = 2.5 masses below 1.73 TeV are excluded

Best-fit signal xsec to all the categories



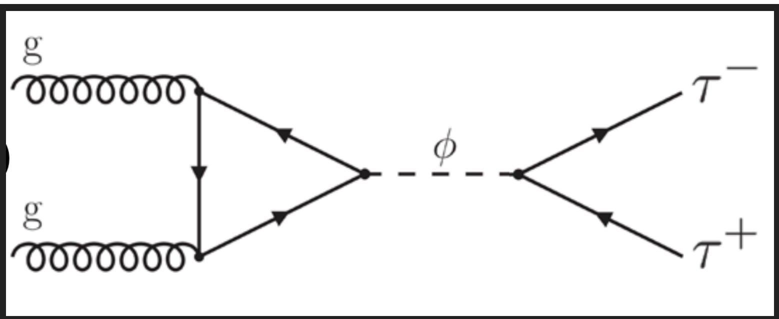
Signal	$m_{\text{LQ}} = 1400\,\text{GeV}$		$m_{\text{LQ}} = 2000\,\text{GeV}$	
	σ_{fit} [fb]	z	σ_{fit} [fb]	z
Scalar				
Pair	$0.46^{+0.51}_{-0.49}$	1.0	$0.39^{+0.45}_{-0.43}$	0.9
Single, $\lambda = 1$	$1.32^{+1.03}_{-0.99}$	1.3	$0.84^{+0.73}_{-0.70}$	1.2
Single, $\lambda = 2.5$	$8.7^{+6.0}_{-5.7}$	1.5	17^{+12}_{-11}	1.5
Nonres.	92^{+44}_{-38}	2.8	83^{+39}_{-34}	2.8
Total, $\lambda = 1$	$2.3^{+2.1}_{-2.0}$	1.2	$10.3^{+7.1}_{-6.4}$	1.6
Total, $\lambda = 2.5$	47^{+25}_{-22}	2.4	78^{+37}_{-32}	2.8
Vector, $\kappa = 0$				
Pair	$0.46^{+0.51}_{-0.48}$	1.0	$0.41^{+0.44}_{-0.42}$	1.0
Single, $\lambda = 1$	$1.20^{+0.96}_{-0.92}$	1.3	$0.81^{+0.71}_{-0.68}$	1.2
Single, $\lambda = 2.5$	19^{+13}_{-12}	1.6	31^{+22}_{-22}	1.5
Nonres.	71^{+34}_{-29}	2.8	62^{+30}_{-26}	2.7
Total, $\lambda = 1$	$1.8^{+1.7}_{-1.6}$	1.1	$8.2^{+5.7}_{-5.2}$	1.6
Total, $\lambda = 2.5$	47^{+24}_{-21}	2.5	62^{+31}_{-26}	2.7
Vector, $\kappa = 1$				
Pair	$0.46^{+0.51}_{-0.48}$	1.0	$0.41^{+0.44}_{-0.42}$	1.0
Single, $\lambda = 1$	$1.20^{+0.96}_{-0.92}$	1.3	$0.81^{+0.71}_{-0.68}$	1.2
Single, $\lambda = 2.5$	$9.8^{+7.0}_{-6.7}$	1.5	24^{+19}_{-18}	1.3
Nonres.	71^{+34}_{-29}	2.8	62^{+30}_{-26}	2.7
Total, $\lambda = 1$	$0.72^{+0.75}_{-0.72}$	1.0	$1.8^{+1.6}_{-1.5}$	1.2
Total, $\lambda = 2.5$	$12.5^{+8.3}_{-7.5}$	1.7	48^{+25}_{-22}	2.5

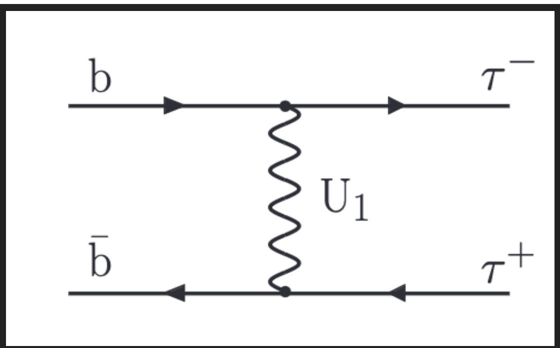
A related excess in the MSSM sector

arXiv:2208.02717

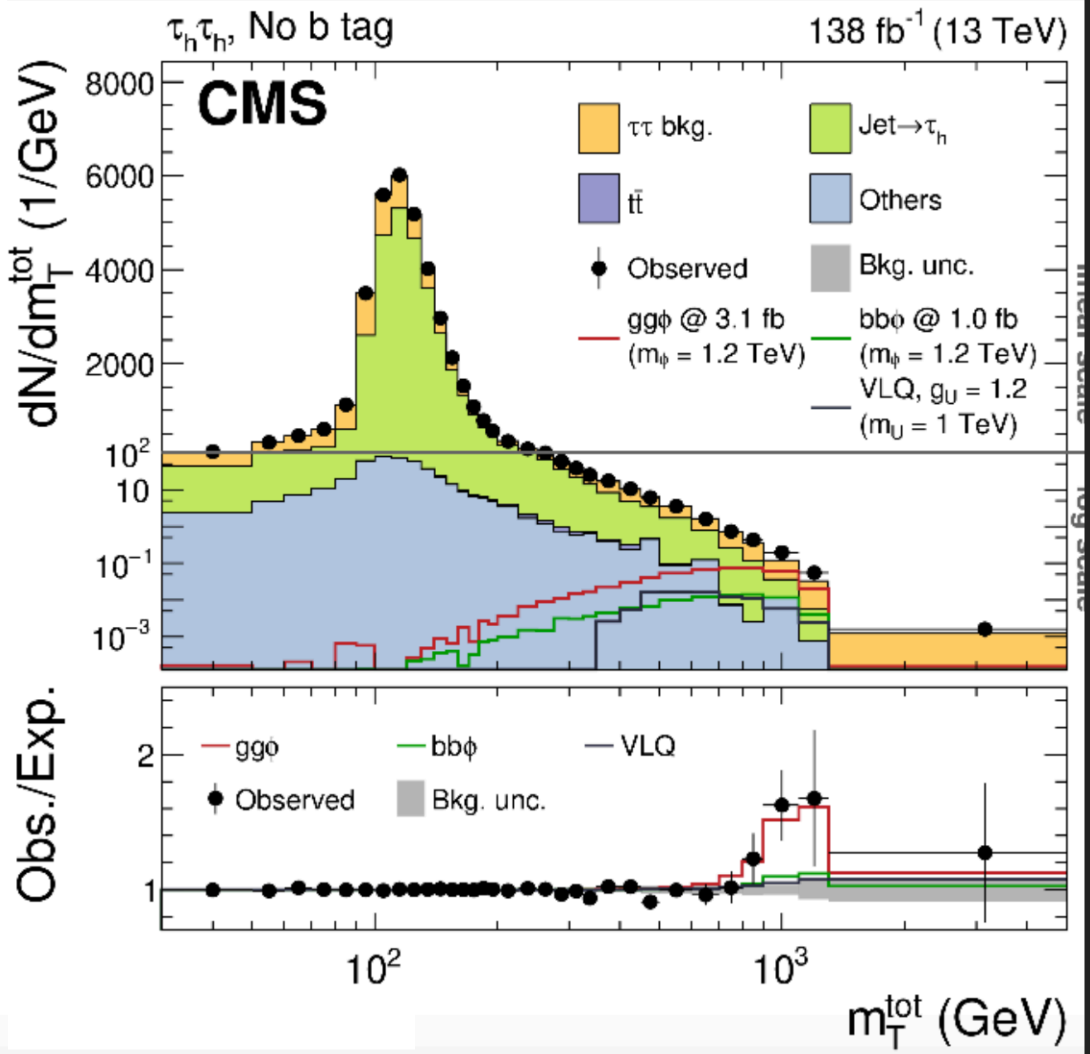
- Search for φ–>ττ using (additional spin 0 state)
    - Also provides a vector LQ interpretation
- 0 bjet category with S$^{\mathrm{MET}}$ > 800 GeV
- m_φ = 1200 GeV: 2.8σ local, 2.4σ global
- Driven by “no b tag region” (no jet requirement)
- Seemingly quite compatible - something to keep eyes on!

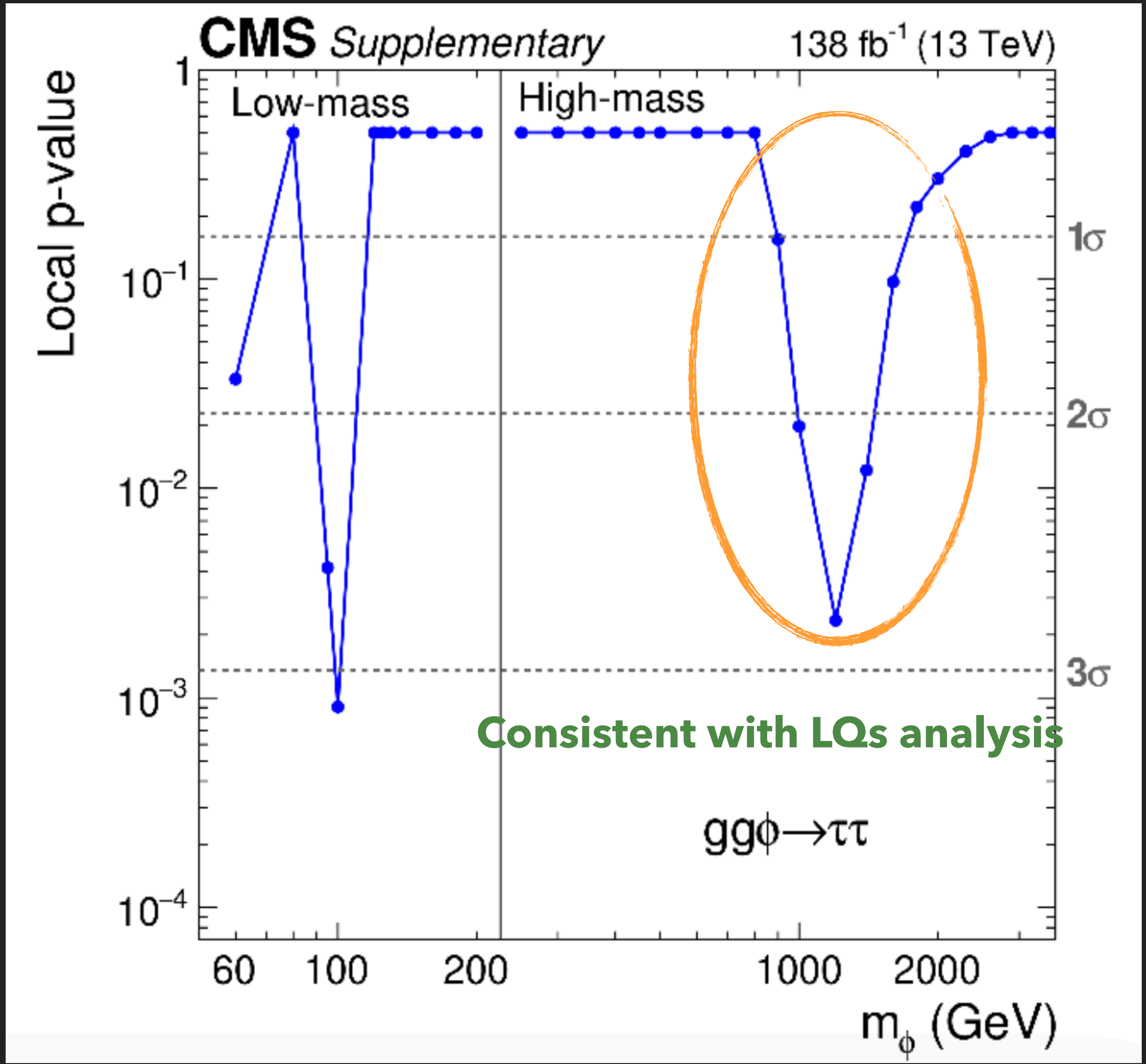
$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(\vec{p}_{\mathrm{T}}^{\,\tau_1}, \vec{p}_{\mathrm{T}}^{\,\tau_2}) + m_{\mathrm{T}}^2(\vec{p}_{\mathrm{T}}^{\,\tau_1}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) + m_{\mathrm{T}}^2(\vec{p}_{\mathrm{T}}^{\,\tau_2}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})}$$





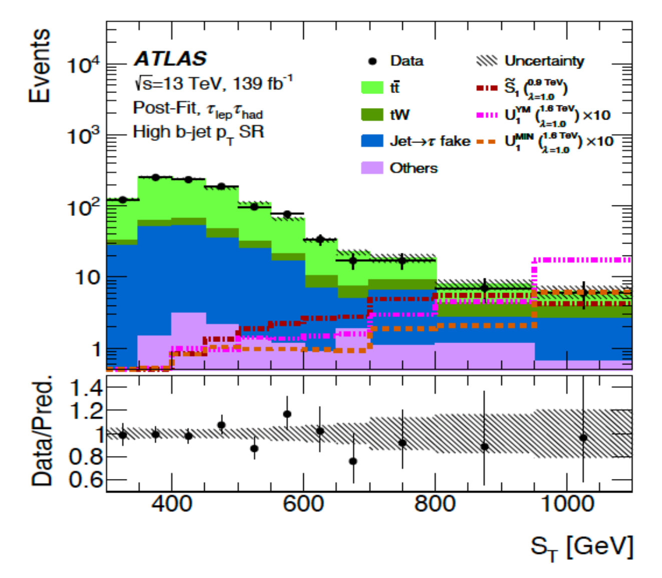
Leptoquark

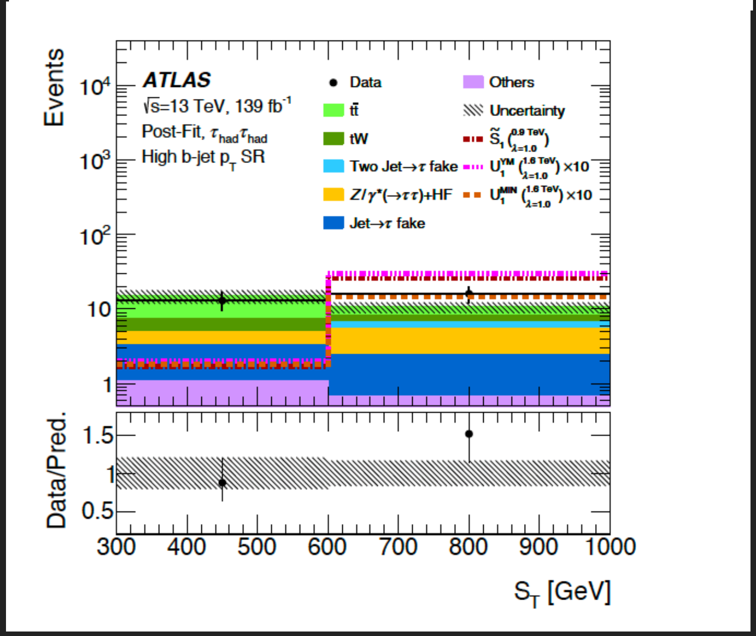


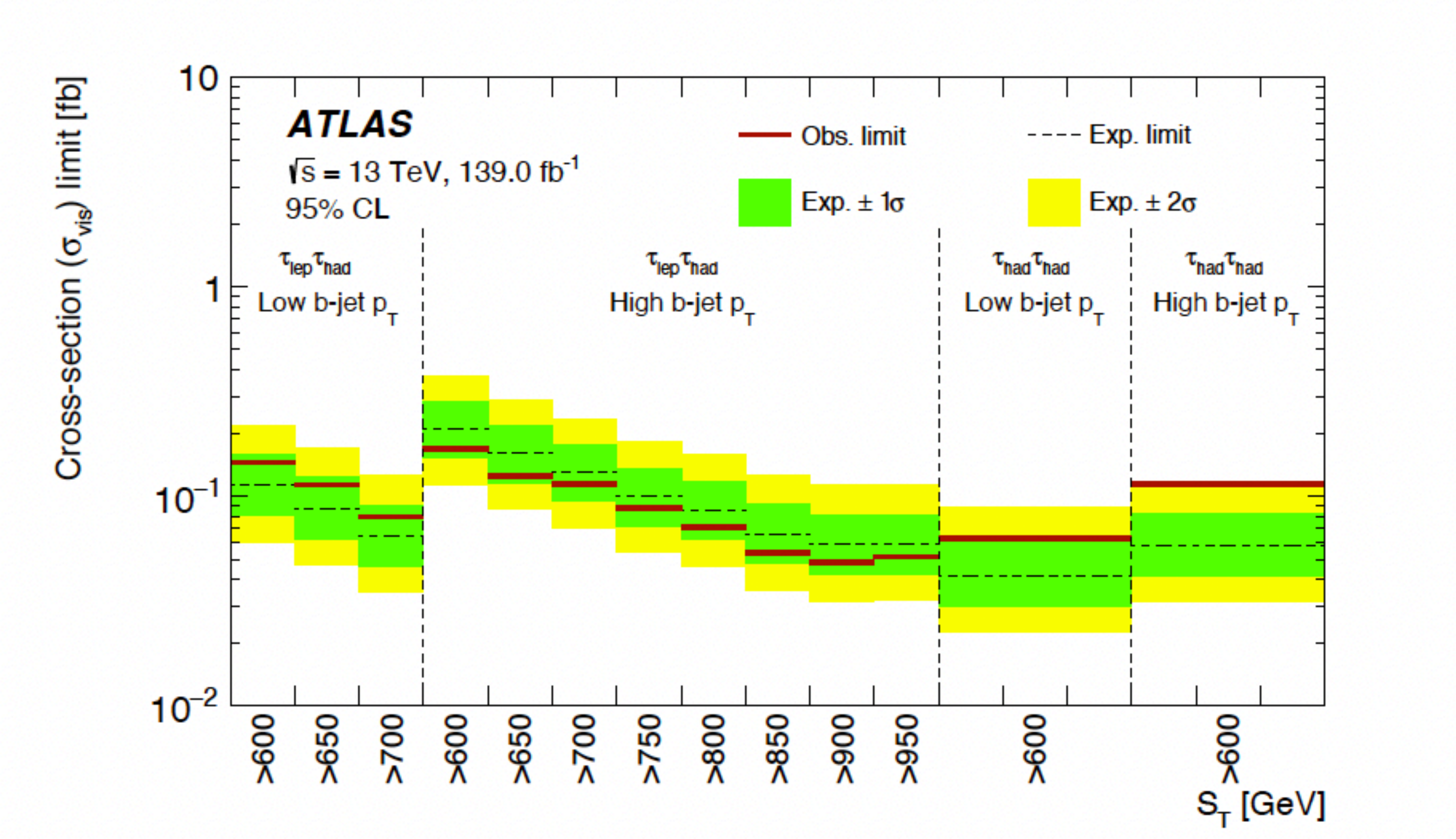


Consistent with LQs analysis

What about ATLAS?



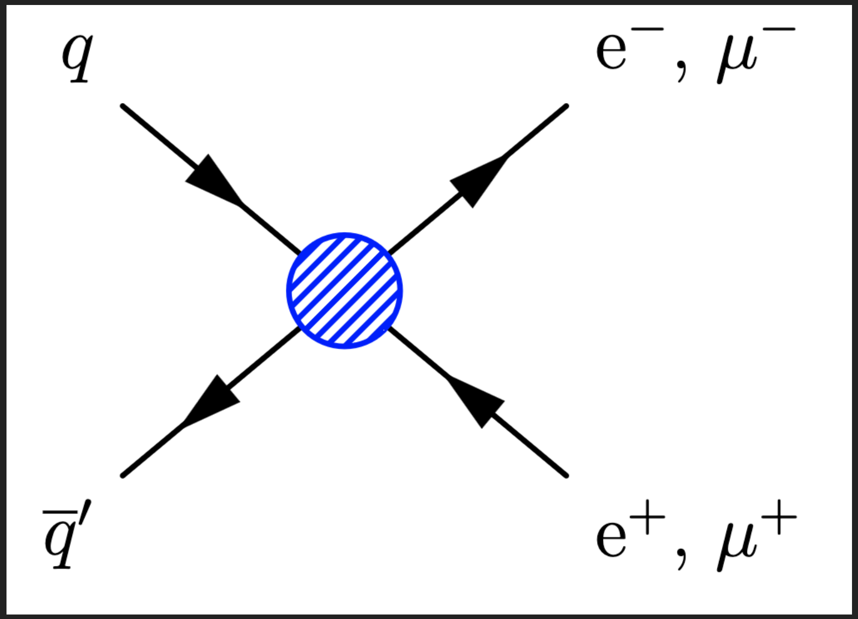




- Variable used: $S_T = P_T(\tau_1) + P_T(\tau_2) + P_T(j_{leading})$
- Upper limit on the cross-section of vector like leptoquarks produced via either single plus non-resonant production, or considering all production
  - For λ=1.0 masses below 1.58 TeV and λ = 2.5 masses below 2.05 TeV are excluded

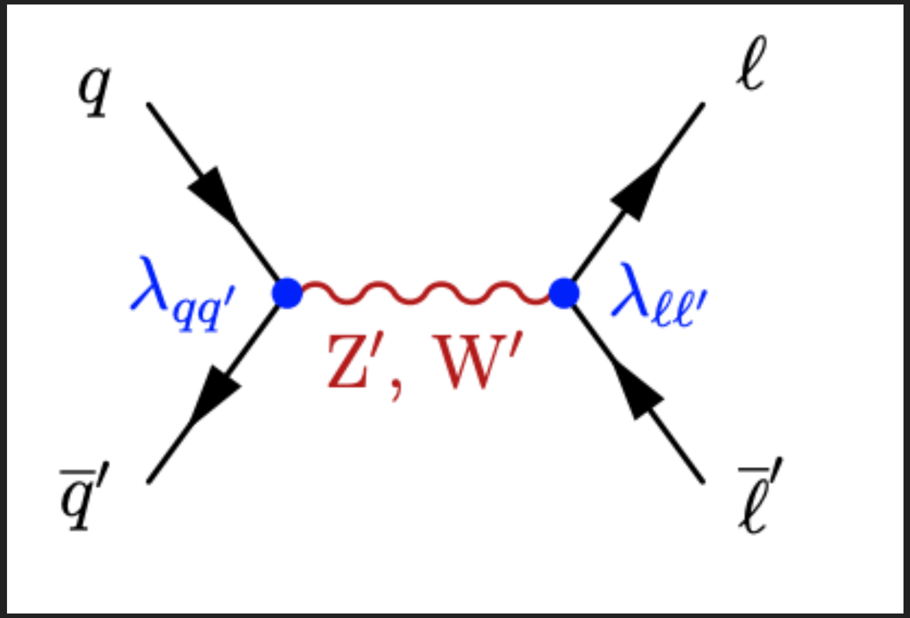
Excess in High pT dilepton tails in 1st and the 2nd generation leptons

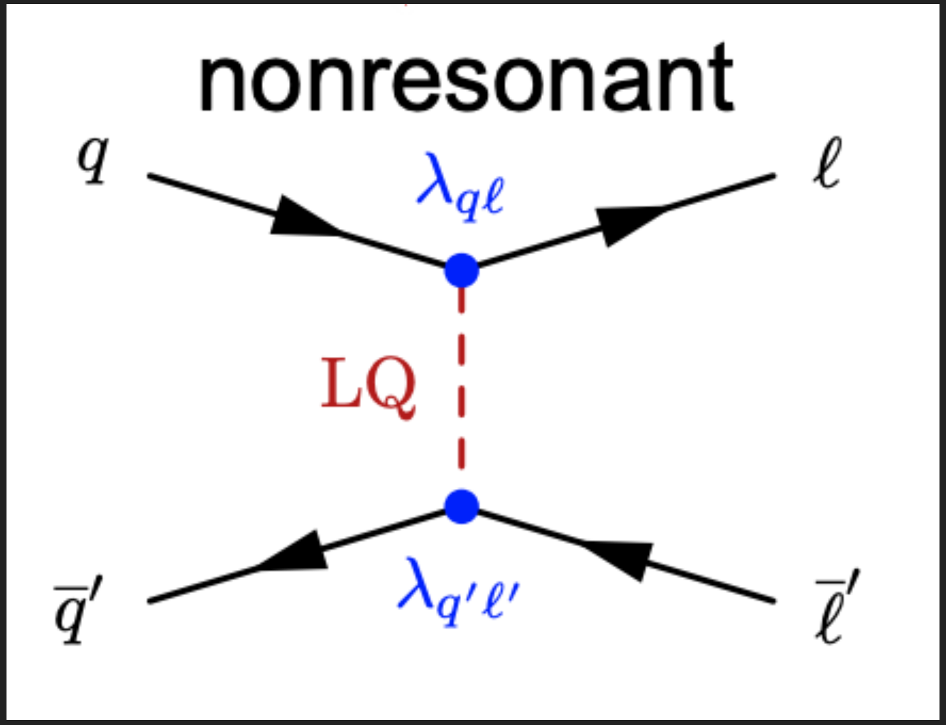
- Many models predict high pT di-lepton tails and may violate lepton flavour universality
- New neutral gauge bosons predicted by several models. E.g.:
  - Spin-1 mediators between SM and dark matter particles, spin-2 gravitons in RS model etc. LFUs can also be tested
    - Can result in resonance in RS model or overall nonresonant excess of events at high mass in ADD model
- Non-resonant: Four-fermion contact interaction, graviton



resonant

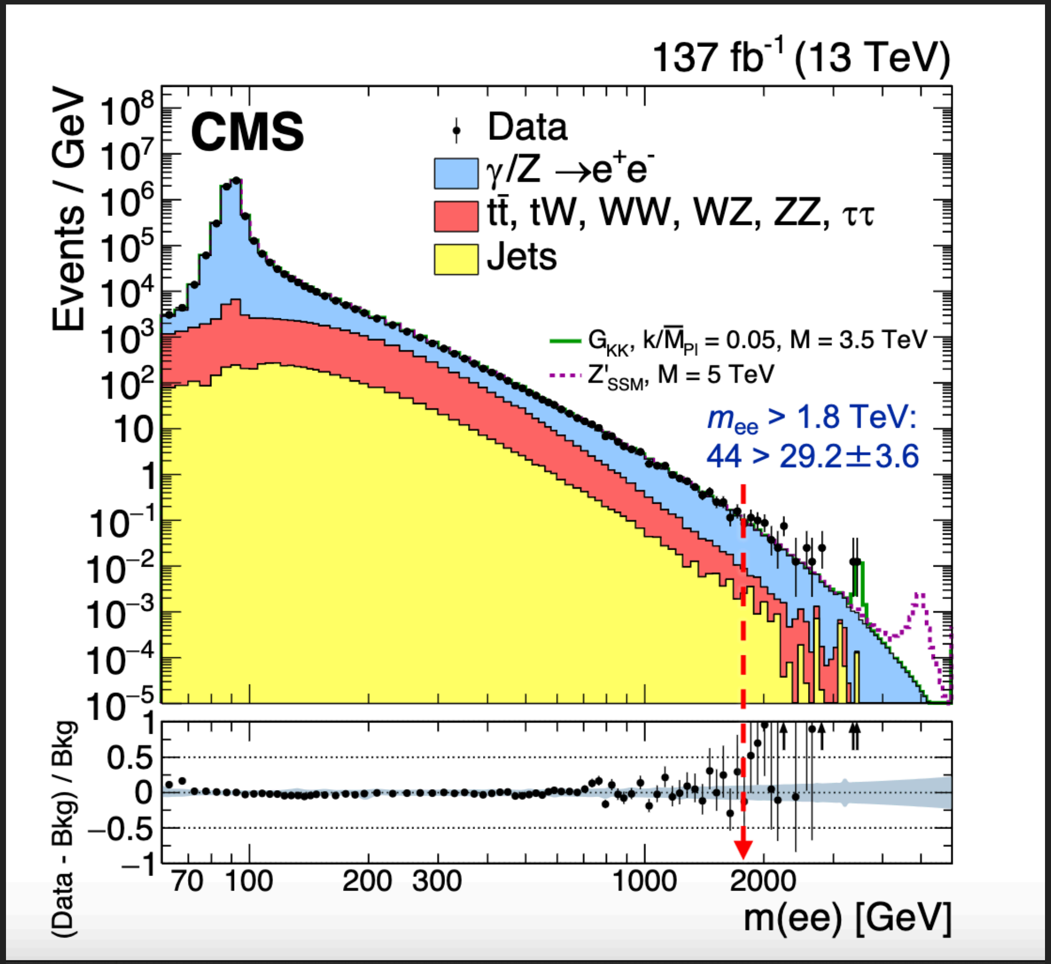
non-resonant

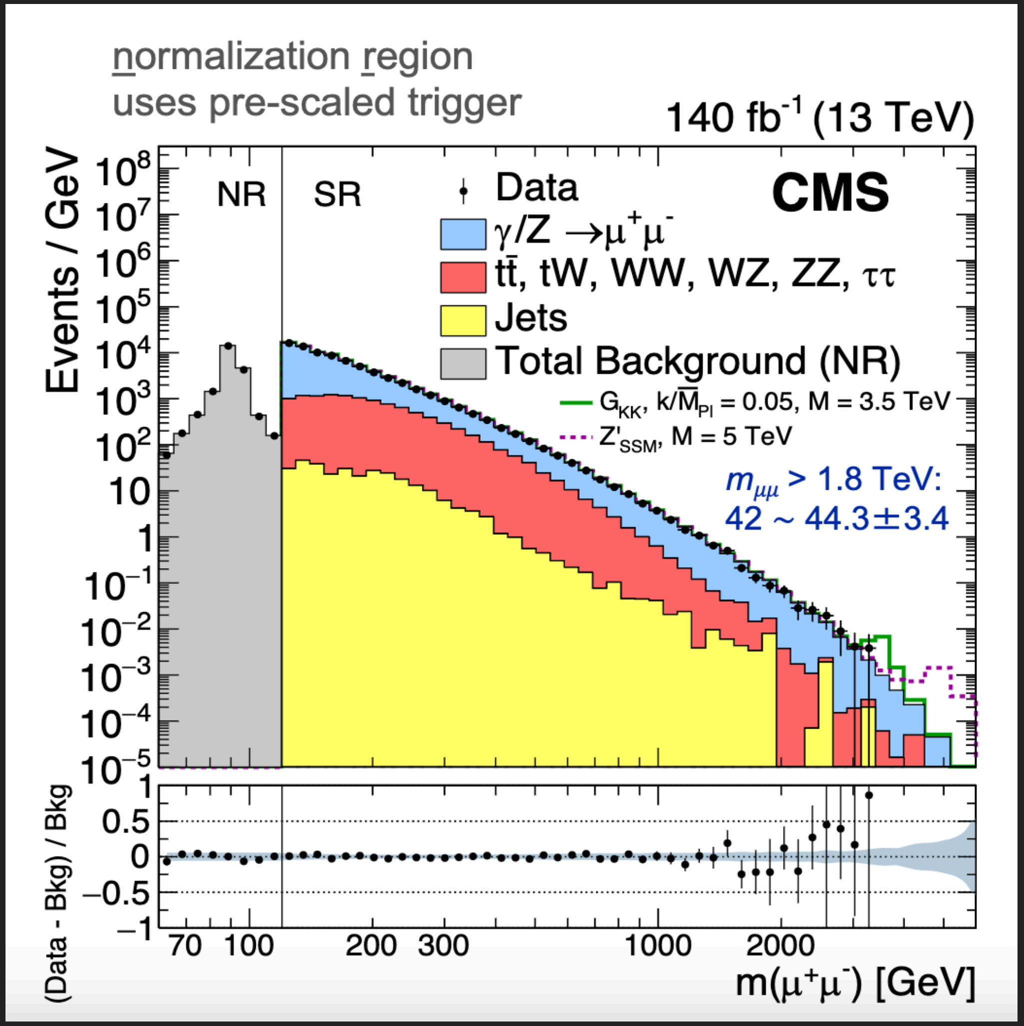




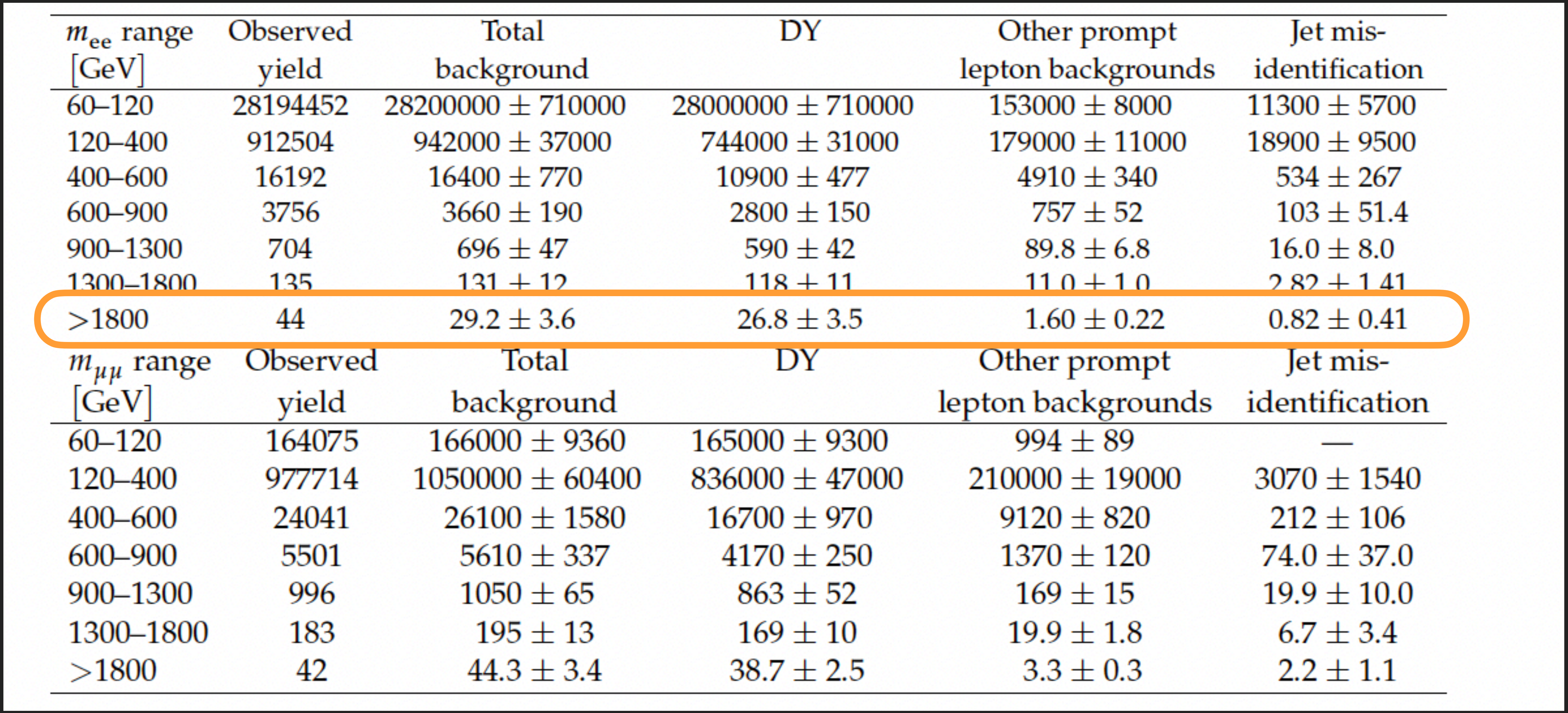
Resonant ee, μμ searches - CMS

- Models considered: Z′, spin-2 gravitons and spin 1 DM mediators (which mediates between SM and the DM particles)
  - Models like ADD can give excess of events in the tails (series of mass degenerate excitations) whereas RS can give rise to mass resonance
- Select high-pT ee, μμ
- Dominant sources of backgrounds: DY, $t\bar{t}$, QCD, W+jets, diboson etc
  - jet –> lepton estimated from data driven method (overall contribution is 1-3%)
- Good data-MC agreement over whole range, except small excess for M_{ee} > 1.8 GeV





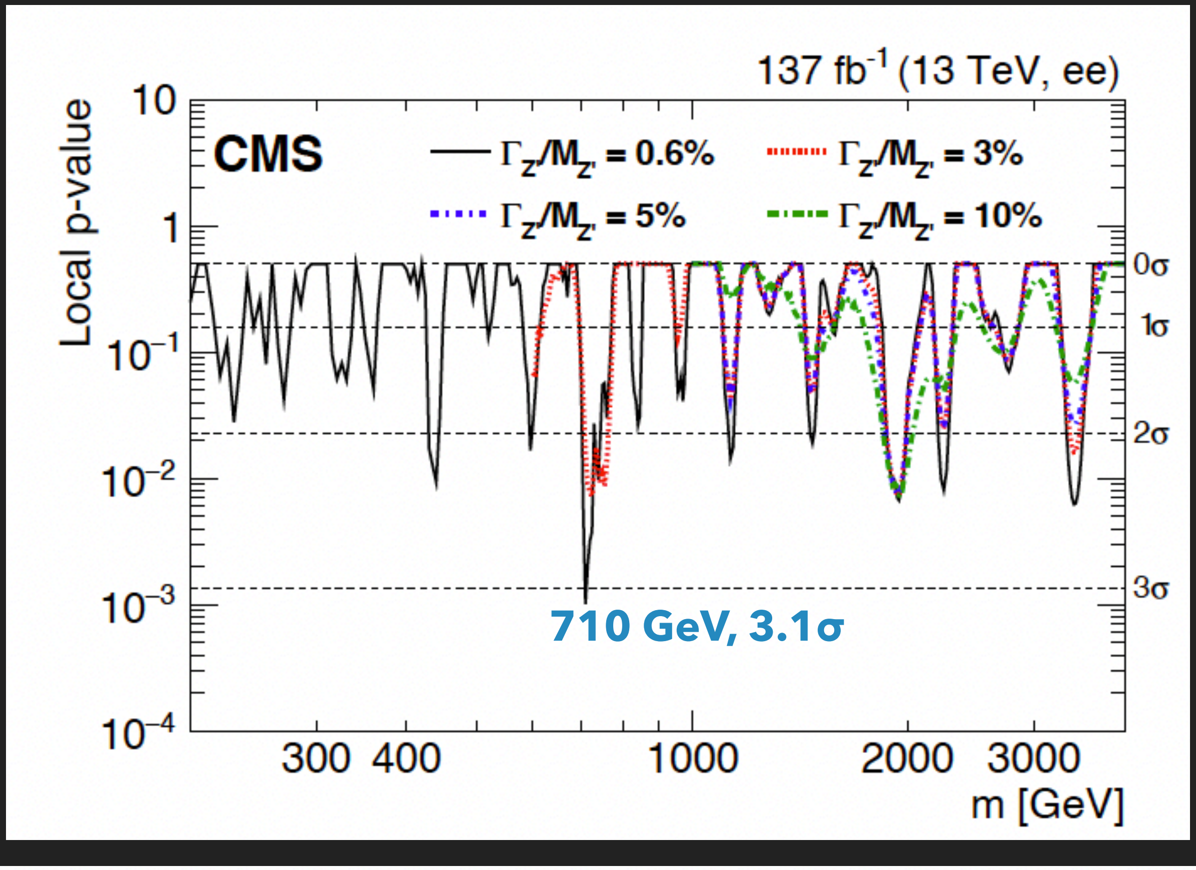
More on the event count



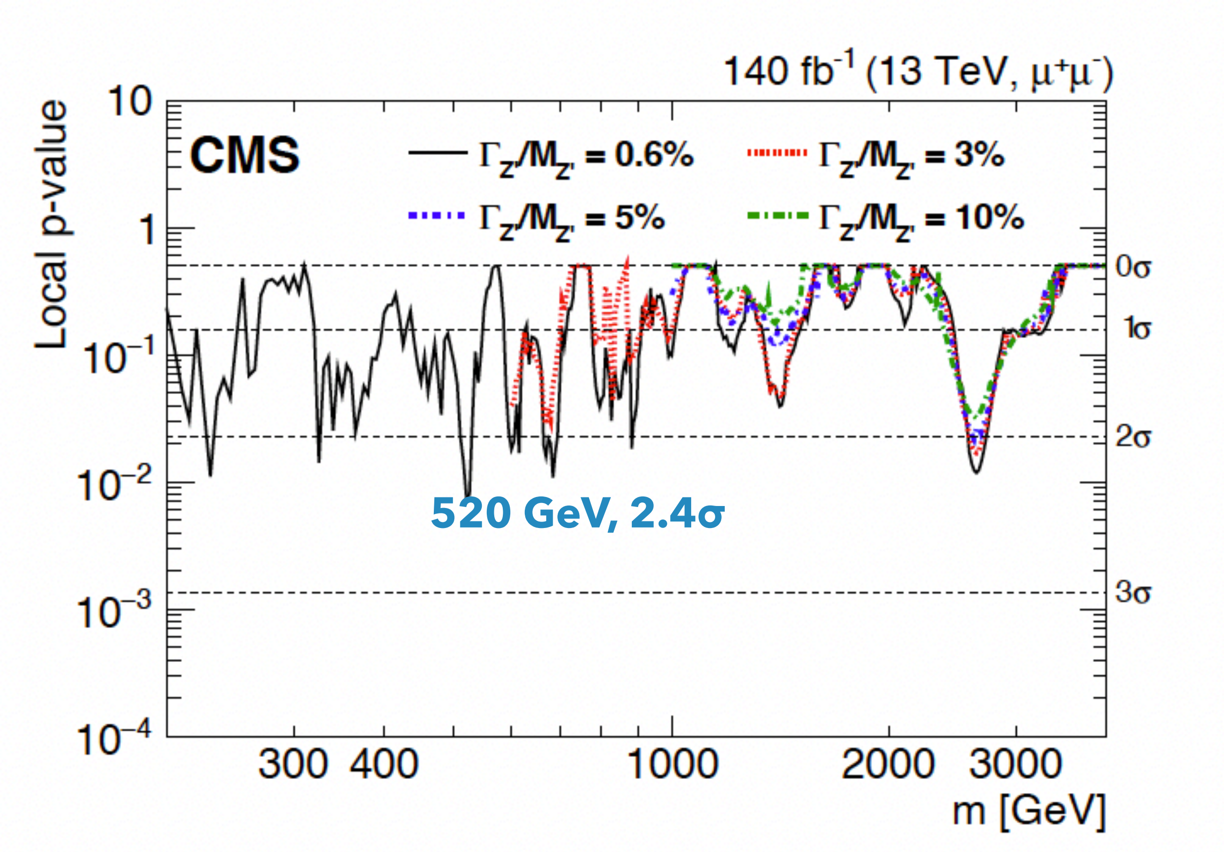
m_{ee} range [GeV]	Observed yield	Total background	DY	Other prompt lepton backgrounds	Jet mis-identification
60–120	28194452	28200000 ± 710000	28000000 ± 710000	153000 ± 8000	11300 ± 5700
120–400	912504	942000 ± 37000	744000 ± 31000	179000 ± 11000	18900 ± 9500
400–600	16192	16400 ± 770	10900 ± 477	4910 ± 340	534 ± 267
600–900	3756	3660 ± 190	2800 ± 150	757 ± 52	103 ± 51.4
900–1300	704	696 ± 47	590 ± 42	89.8 ± 6.8	16.0 ± 8.0
1300–1800	135	131 ± 12	118 ± 11	11.0 ± 1.0	2.82 ± 1.41
>1800	44	29.2 ± 3.6	26.8 ± 3.5	1.60 ± 0.22	0.82 ± 0.41

$m_{\mu\mu}$ range [GeV]	Observed yield	Total background	DY	Other prompt lepton backgrounds	Jet mis-identification
60–120	164075	166000 ± 9360	165000 ± 9300	994 ± 89	—
120–400	977714	1050000 ± 60400	836000 ± 47000	210000 ± 19000	3070 ± 1540
400–600	24041	26100 ± 1580	16700 ± 970	9120 ± 820	212 ± 106
600–900	5501	5610 ± 337	4170 ± 250	1370 ± 120	74.0 ± 37.0
900–1300	996	1050 ± 65	863 ± 52	169 ± 15	19.9 ± 10.0
1300–1800	183	195 ± 13	169 ± 10	19.9 ± 1.8	6.7 ± 3.4
>1800	42	44.3 ± 3.4	38.7 ± 2.5	3.3 ± 0.3	2.2 ± 1.1

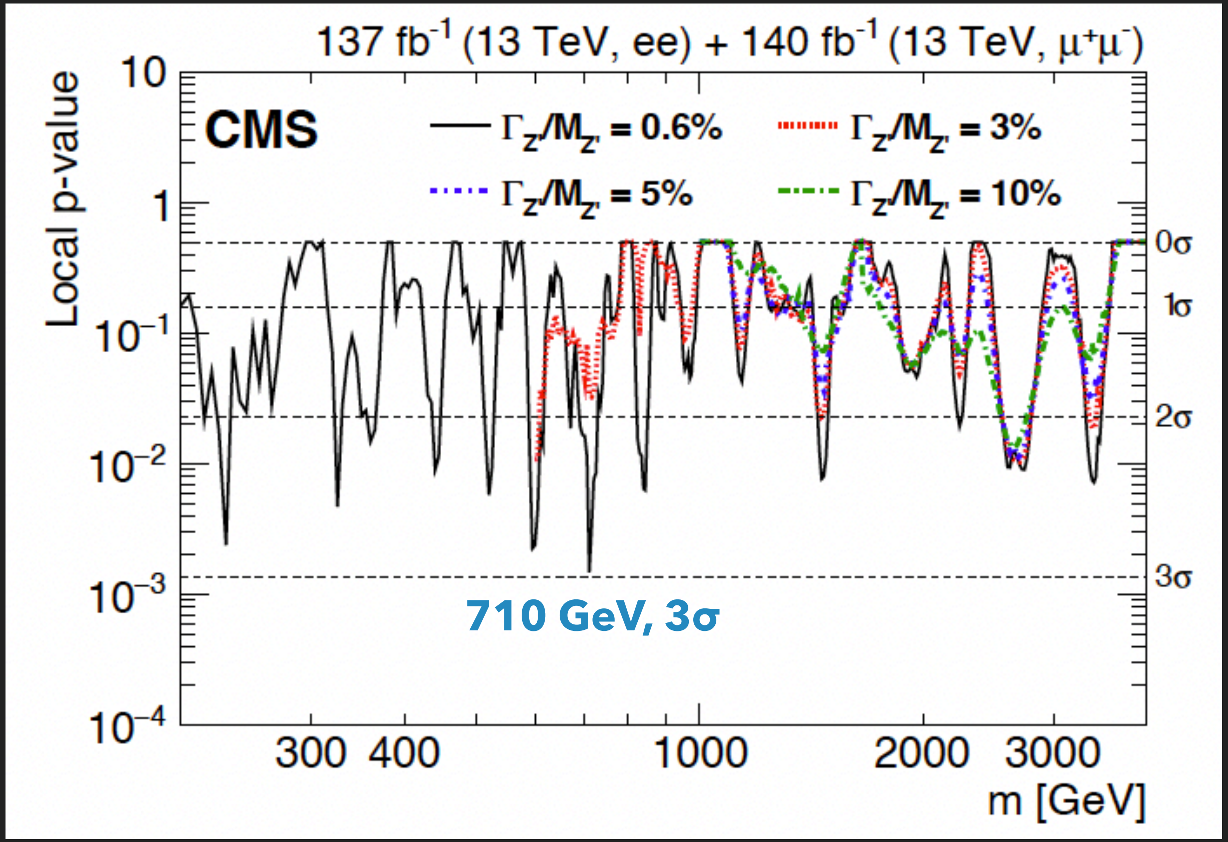
Quantifying differences between data and simulation



710 GeV, 3.1σ



520 GeV, 2.4σ

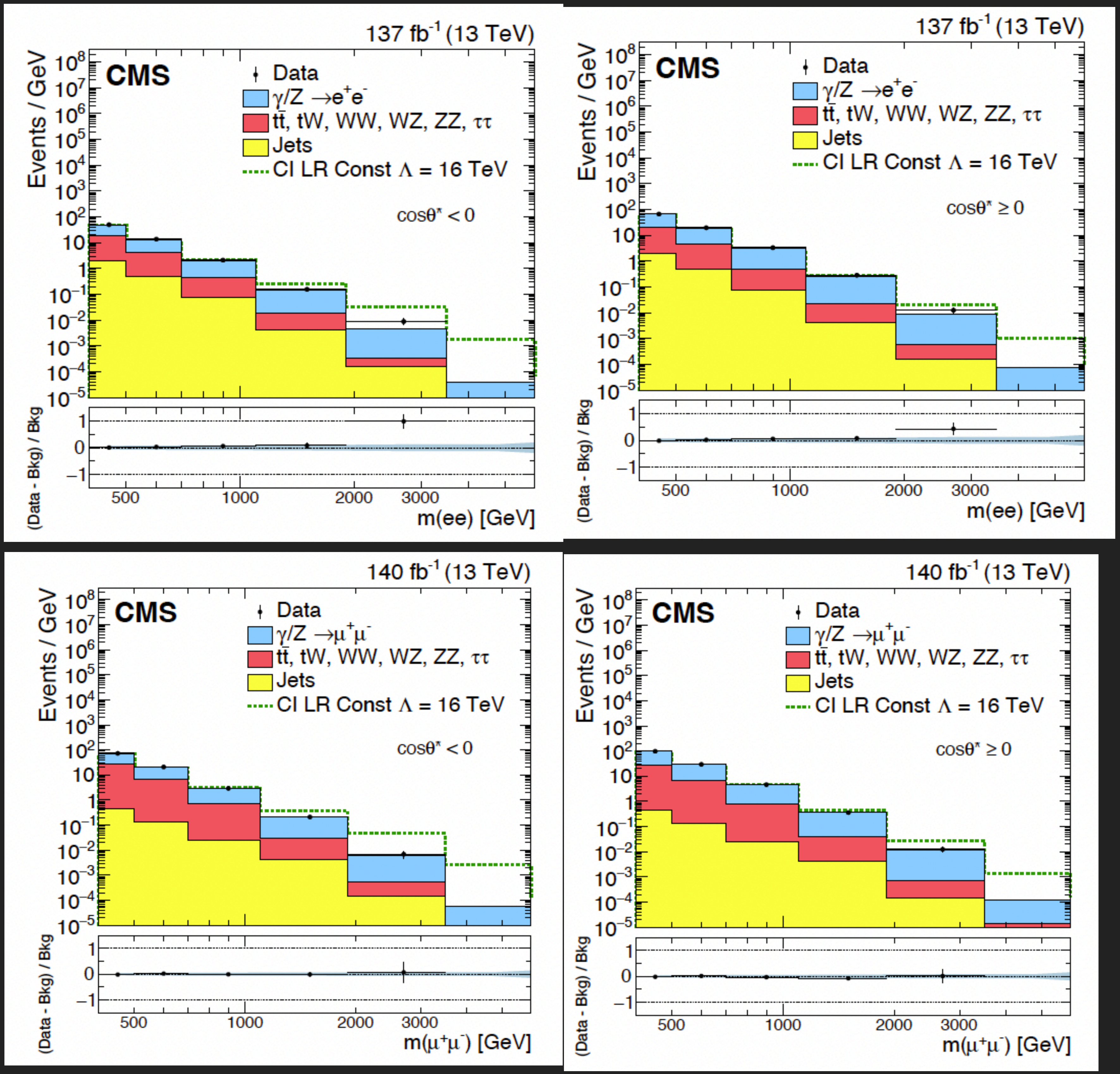


710 GeV, 3σ

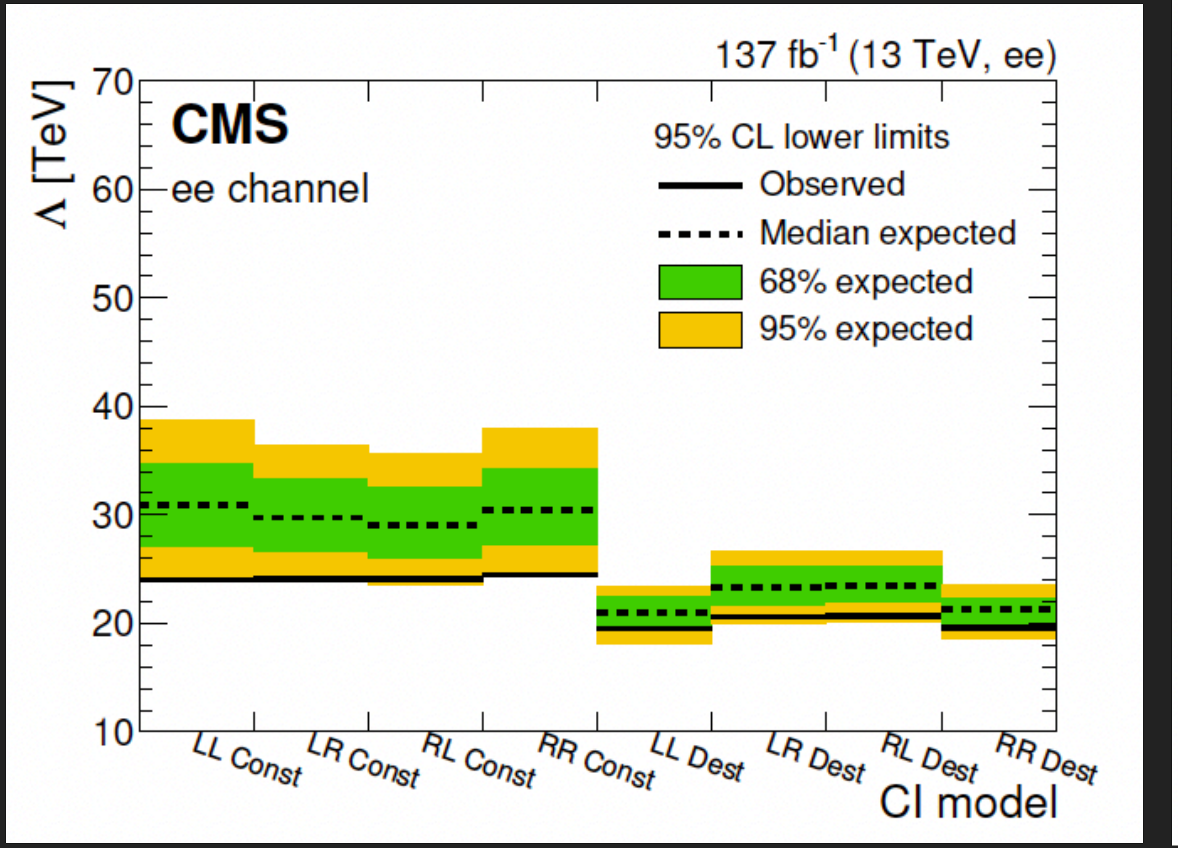
- Unbinned maximum likelihood fit to perform the statistic alanalysis (simultaneously for the electron and muon channel)
- Signal shape: Convolution of Breit-Wigner function and double-sided crystal ball
- Background model: Functions fitted to the background estimates to determine the initial fit parameters
- Background only local p-values are shown
- Global ~ 0.9σ between 700 and 800 GeV

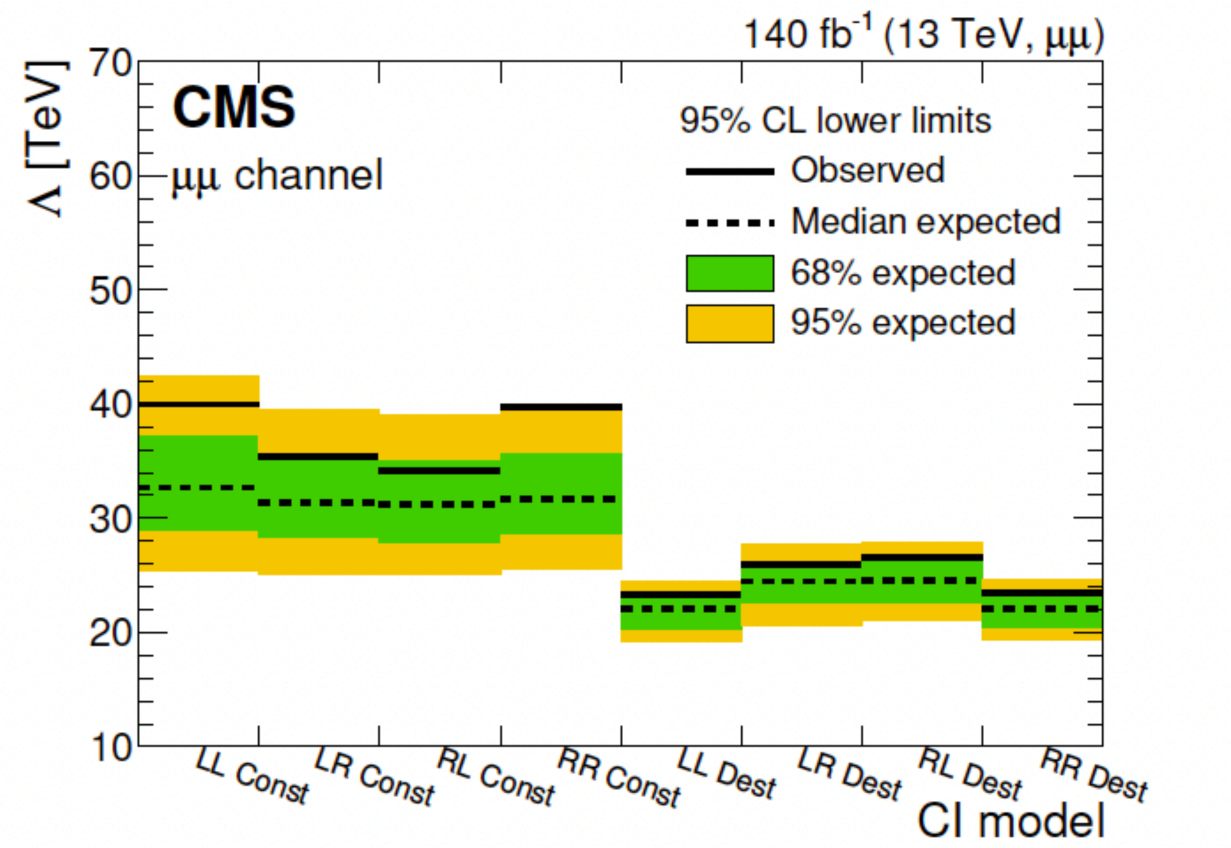
Non-resonant searches in high mass tails

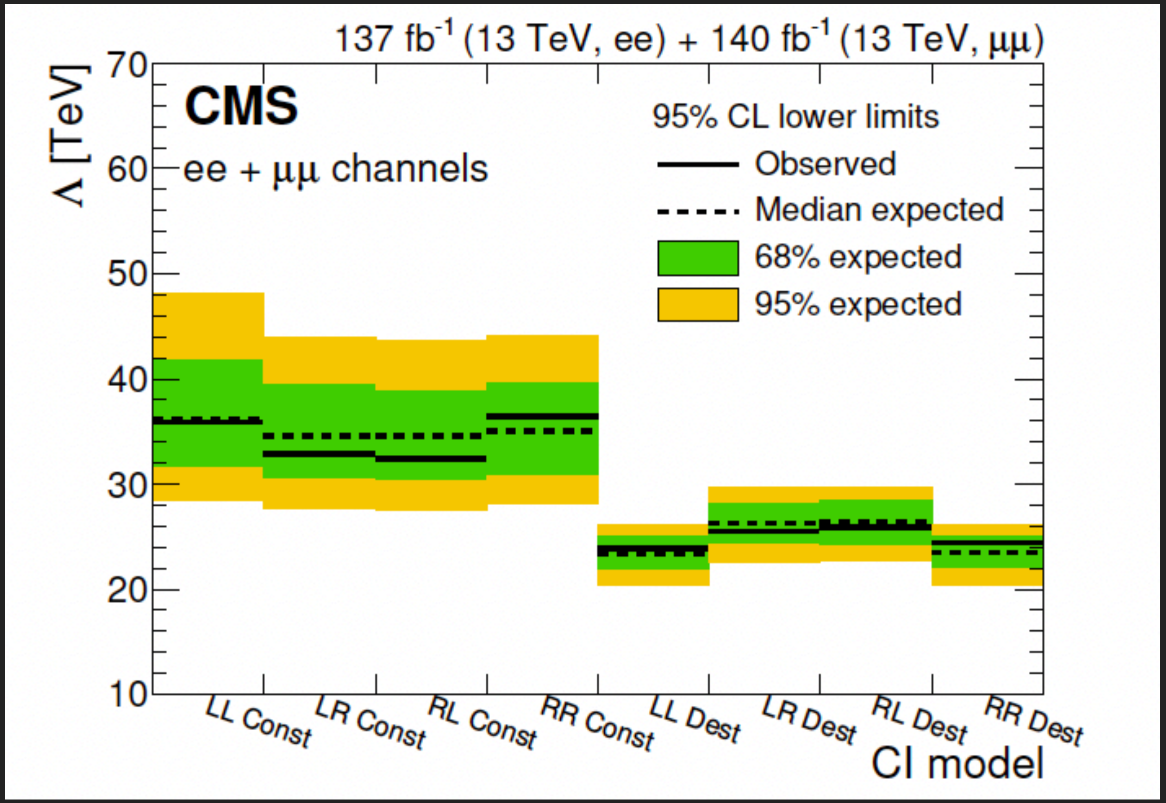
- Signal model: Four-fermion contact interaction, and spin-2 graviton in ADD model
- Separate m_{ll} into bins of $\cos\theta^* < 0$ and $\cos\theta^* > 0$ (Colin-Soper frame)
    - Angle between negatively charged lepton and the z axis
- Highest sensitivity from high mass bins.
- LR with $\cos(\theta^*) < 0$ has better S/B ratio
- Fit $\cos(\theta^*) < 0$ and $\cos(\theta^*) > 0$ simultaneously



Non-resonant searches in high pT tails

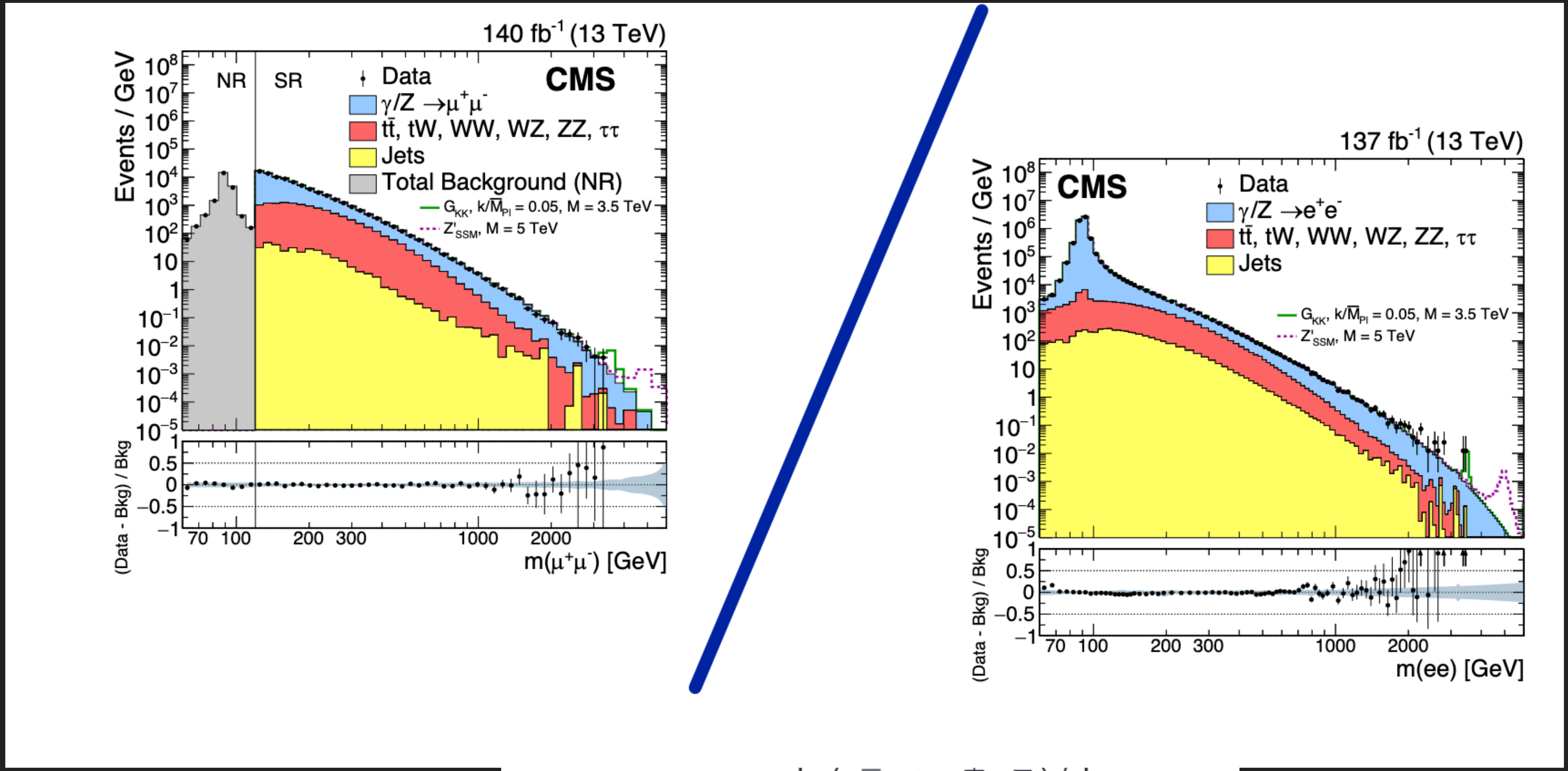






- Set limit on CI energy scale λ
- Due to binning in cosθ* (and better S/B in cosθ* < 0), weakness in limits in LR/RL (constructive) due to reduced signal compared to LL/RR is recovered
- Limits in electron channel are weaker than those in the muon channel
  - Excess of events seen

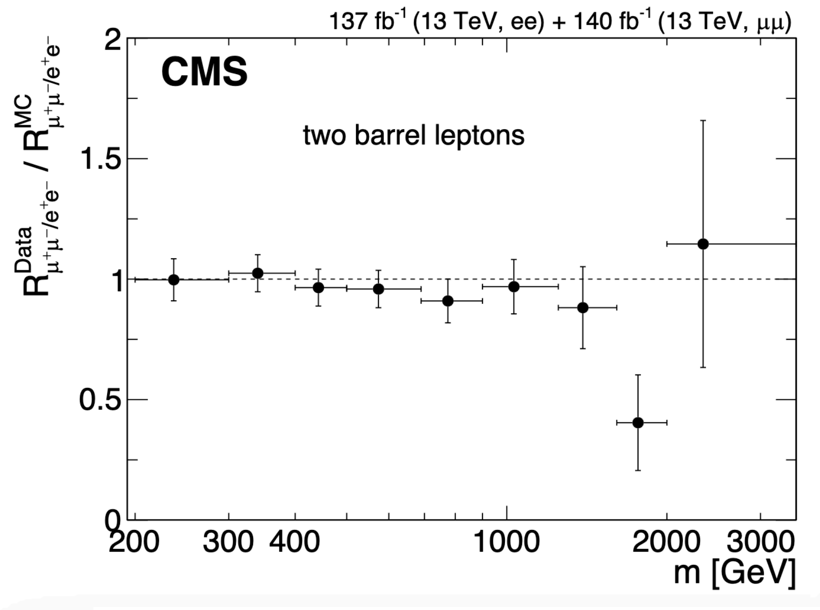
Ratio μμ/ee - Lepton Flavour Violation

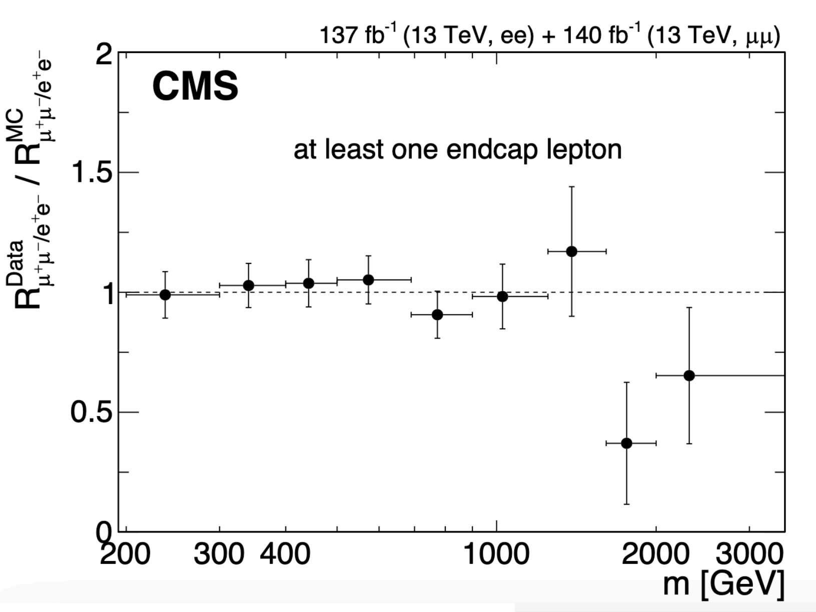


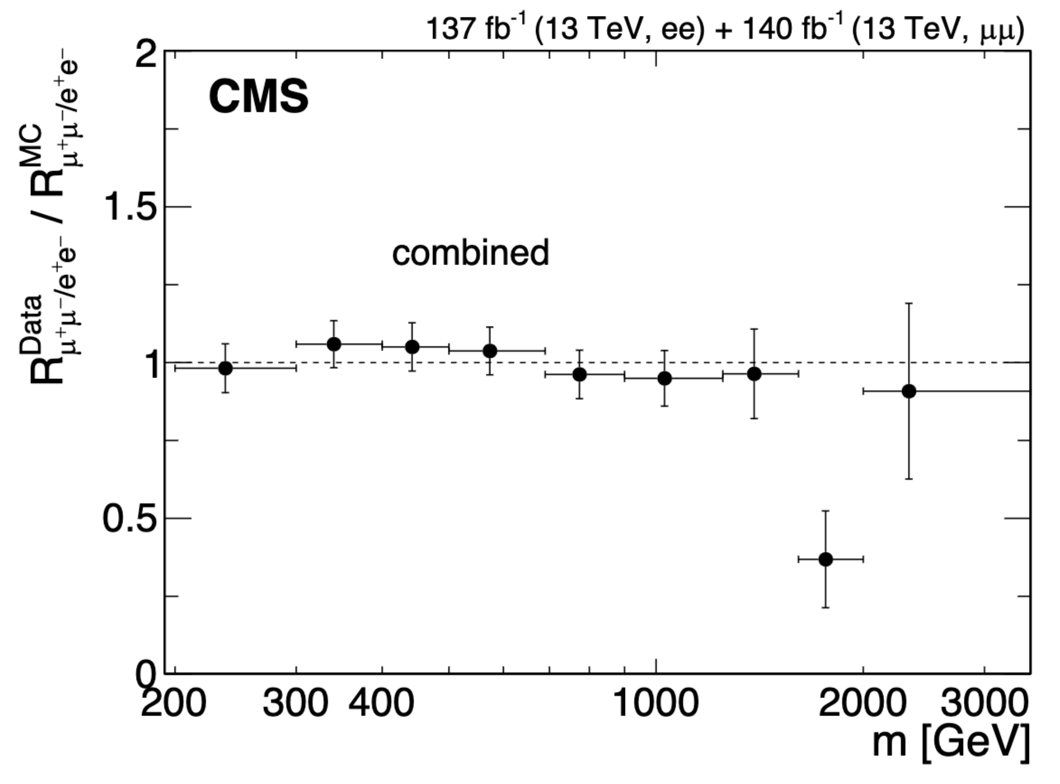
$$R_{\mu^+\mu^-/\mathrm{e^+e^-}} = \frac{\mathrm{d}\sigma(q\bar{q} \to \mu^+\mu^-)/\mathrm{d}m_{\mu^+\mu^-}}{\mathrm{d}\sigma(q\bar{q} \to \mathrm{e^+e^-})/\mathrm{d}m_{\mathrm{e^+e^-}}}$$

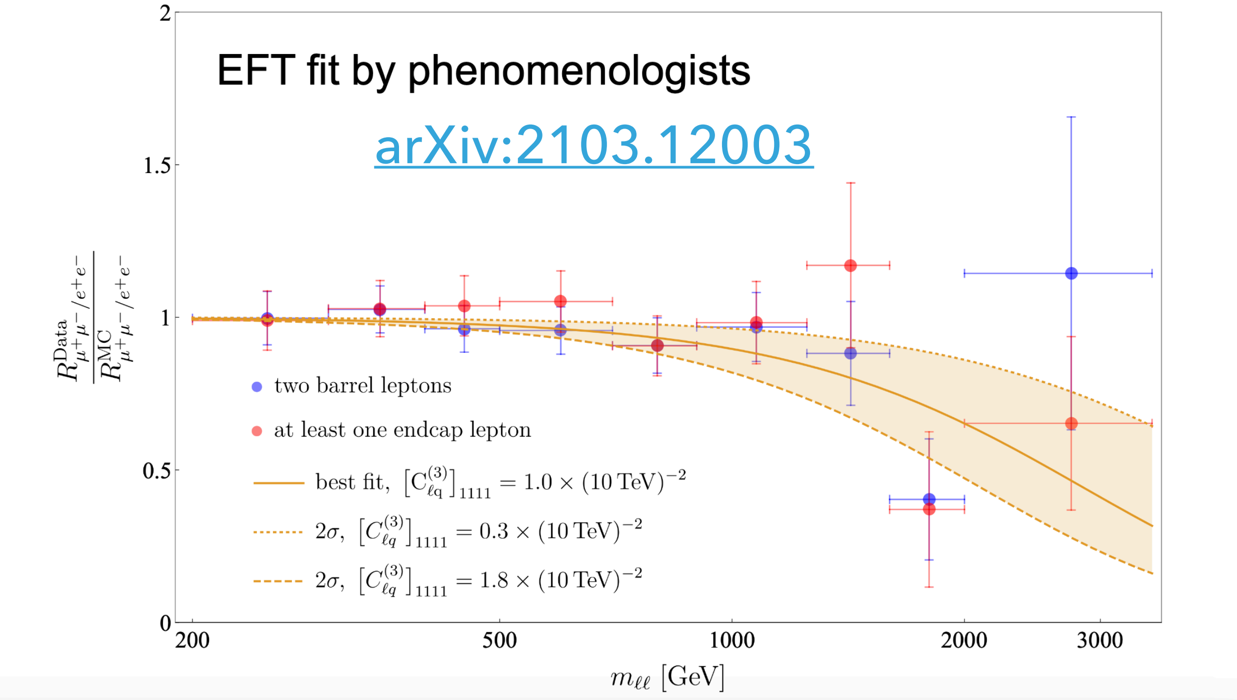
- First-time test of LFV at TeV scale
- Differential ratio in two bins of η. Data is unfolded
- Departures due to new physics between 200-400 GeV negligible (Greljo and Marzocca)
- To correct for any differences in efficiencies between the two, normalize the above variable in this region to 1

Ratio μμ/ee - Lepton Flavour Violation








EFT fit by phenomenologists

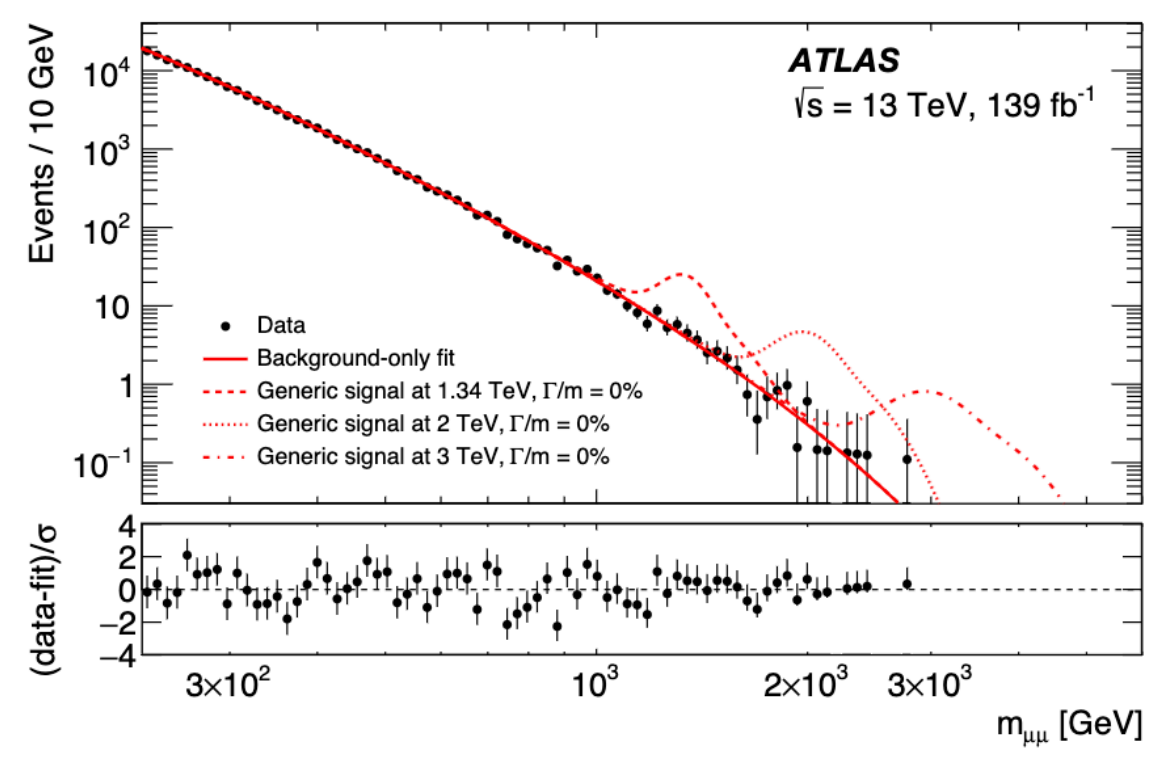
arXiv:2103.12003

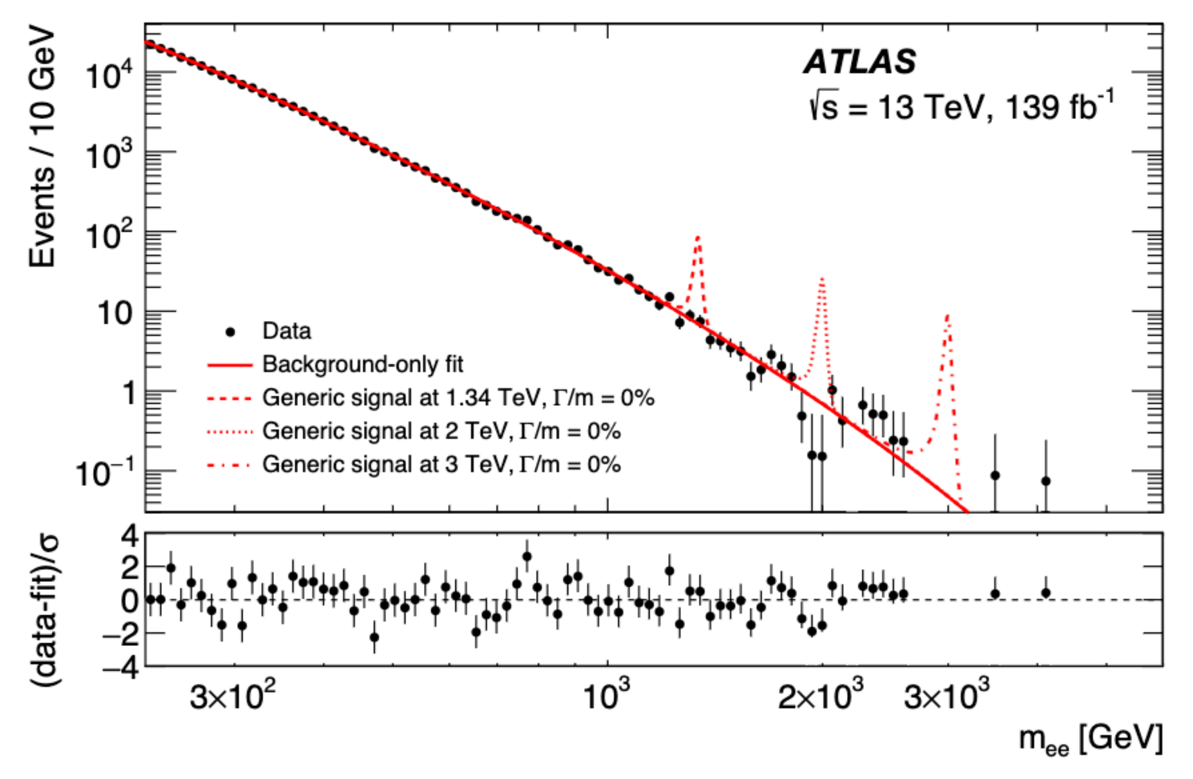
- Good agreement up to 1.5 TeV
- Slight deviation in the electron channel caused by slight excess in the dielectron channel

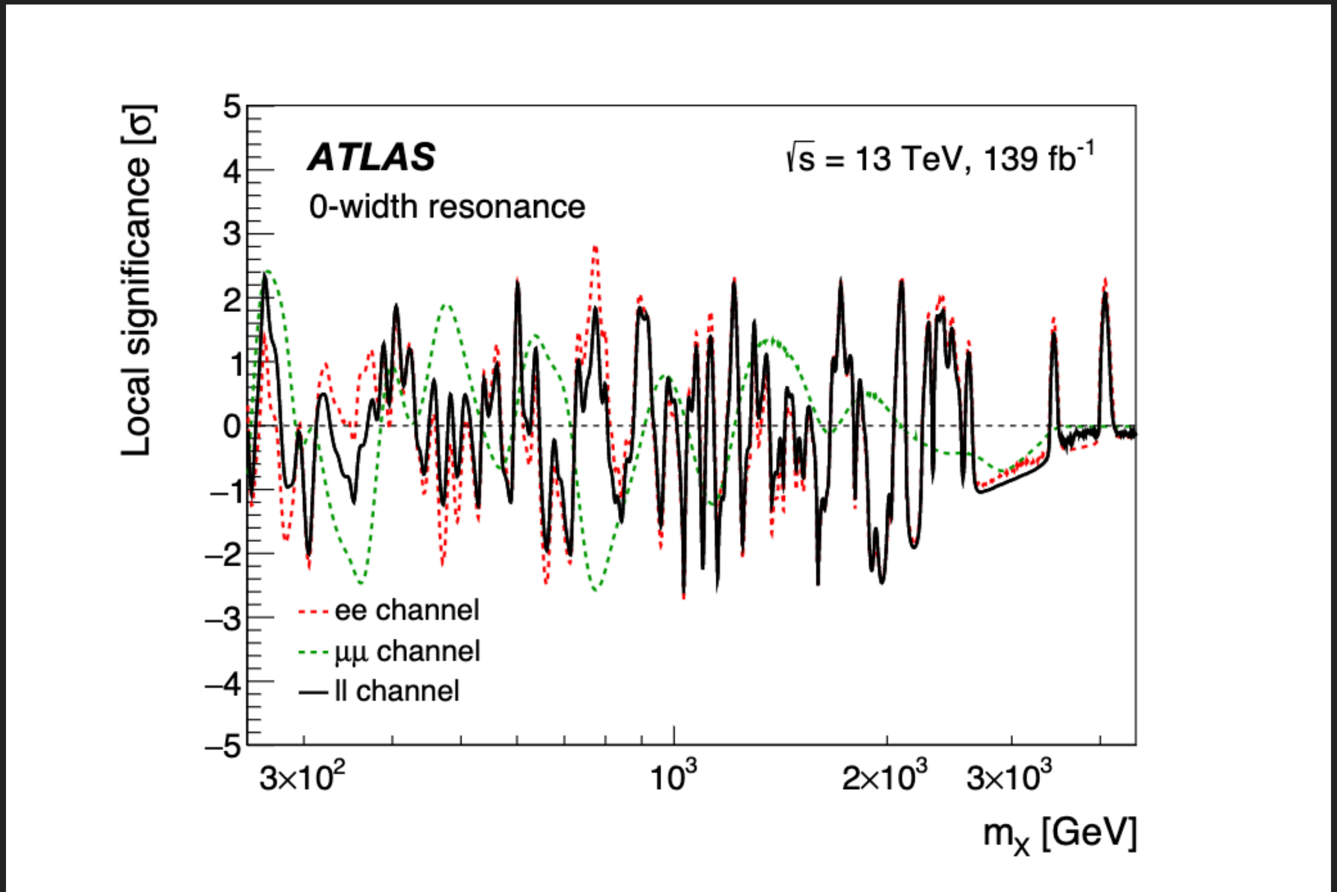
- Fitted with four fermion contact interaction (that explains Cabibo Angle Anomaly) that generates effects in the neutral and charged current process using

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\text{SM}} + [C^{(3)}_{\ell q}]_{1111}\Big[&(\bar{d}\gamma^\mu P_L d - \bar{u}\gamma^\mu P_L u)\bar{e}\gamma_\mu P_L e \\ &+ (\bar{u}\gamma^\mu P_L u - \bar{d}\gamma^\mu P_L d)\bar{\nu}\gamma_\mu P_L \nu \qquad (4)\\ &+ 2\left(\bar{d}\gamma^\mu P_L u \bar{\nu}\gamma_\mu P_L e + \bar{u}\gamma^\mu P_L d \bar{e}\gamma_\mu P_L \nu\right)\Big],\end{aligned}$$

What about ATLAS?: resonant



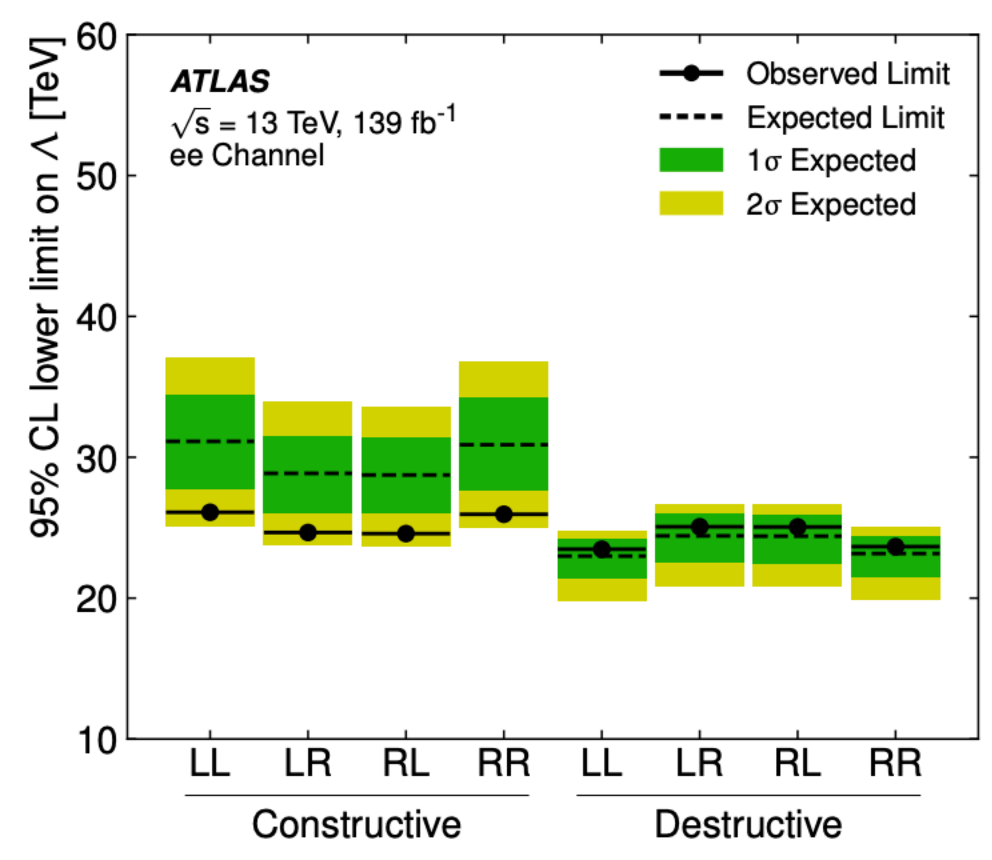


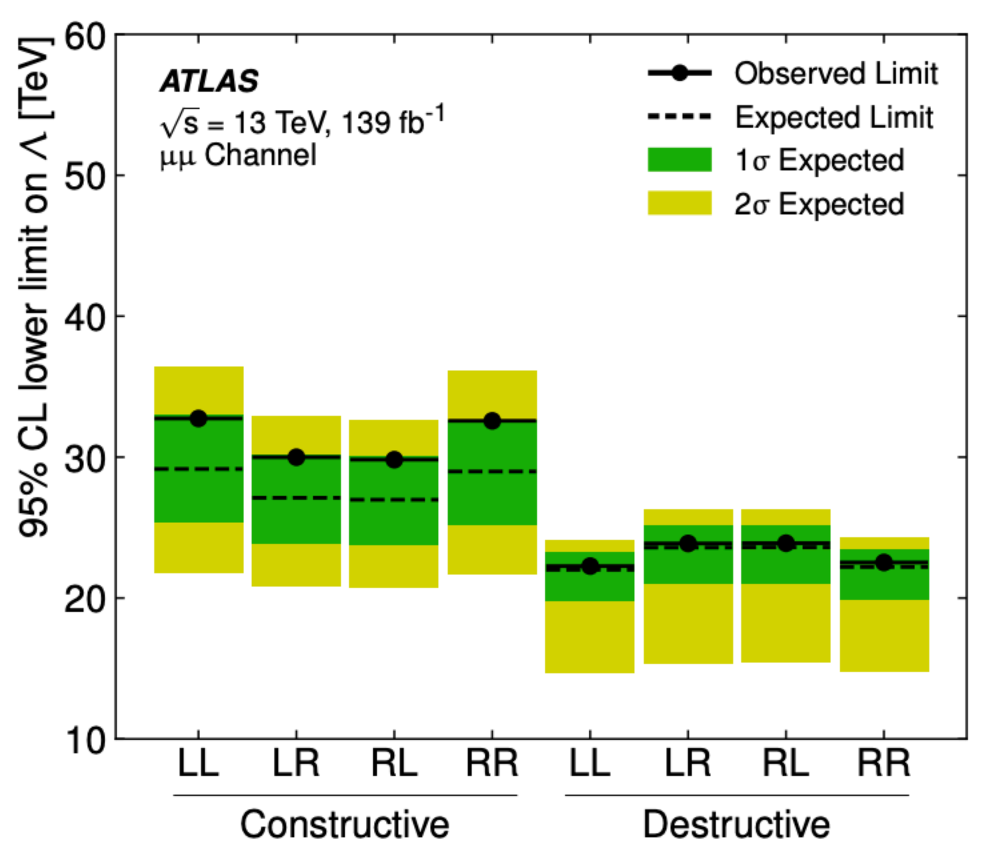


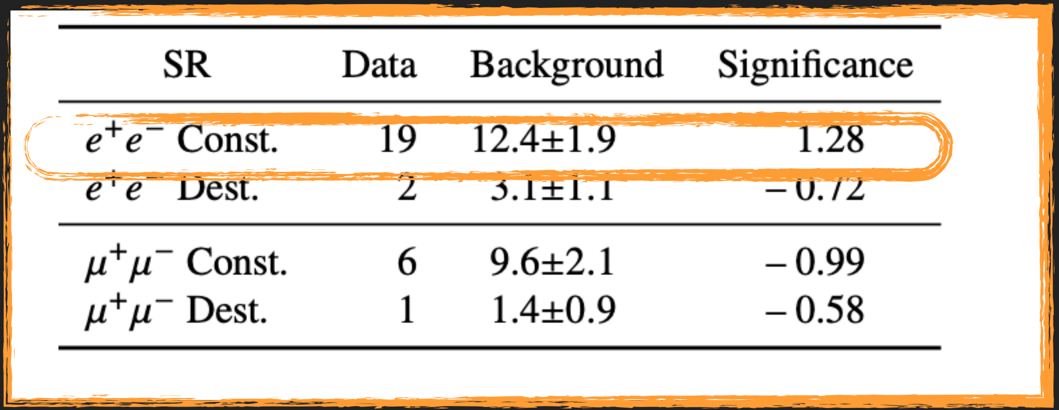
- Highest observed mass in
  - mee = 4.06 TeV
  - mμμ = 2.75 GeV
- Largest deviation in the
  - ee channel: 774 GeV, local p-value = 2.9σ
  - μμ channel: 267 GeV, local p-value = 2.4σ
  - ee+ μμ channel: 264 GeV, local p-value = 2.3σ

What about ATLAS?: non-resonant

arXiv:2006.12946







SR	Data	Background	Significance
e^+e^- Const.	19	12.4±1.9	1.28
e^+e^- Dest.	2	3.1±1.1	−0.72
$\mu^+\mu^-$ Const.	6	9.6±2.1	−0.99
$\mu^+\mu^-$ Dest.	1	1.4±0.9	−0.58

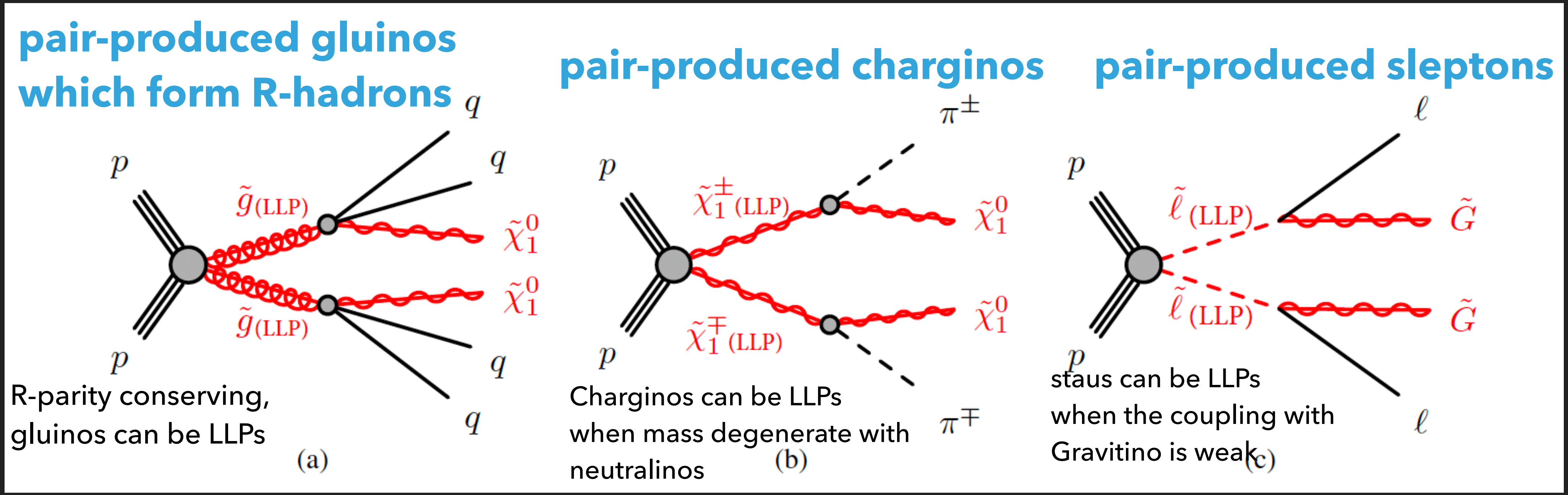
- Observed bounds in the electron channel slightly weaker than that in the muon channel (as in CMS) due to slight excess of events in the electron channel

- Results recasted to bounds on the [C_{lq}]1111 operator (arXiv:2103.12003)
  - In case of CMS, the authors provided the best fit value of ~1 /(10 TeV)^2

$$[C^{(3)}_{\ell q}]_{1111} \lesssim 1.4/(10\,\mathrm{TeV})^2\,,$$

Heavy Long-Lived Charged Particles in ATLAS

JHEP06(2023)158



pair-produced gluinos which form R-hadrons

pair-produced charginos

pair-produced sleptons

R-parity conserving, gluinos can be LLPs

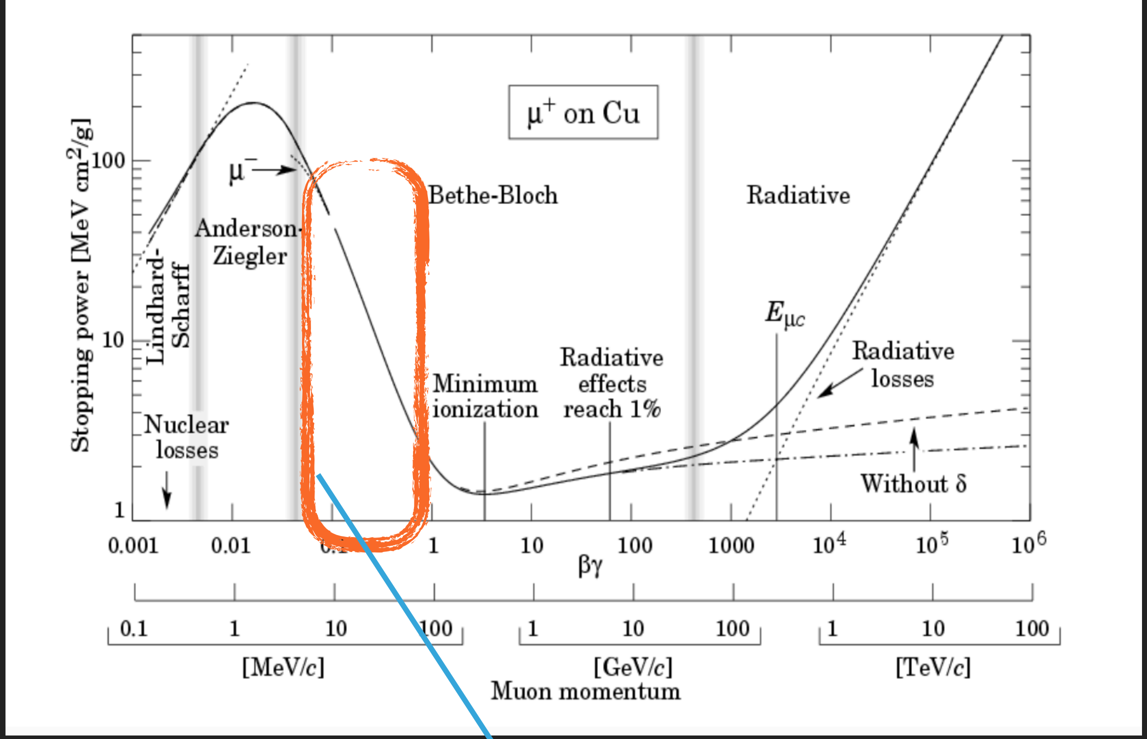
Charginos can be LLPs when mass degenerate with neutralinos

staus can be LLPs when the coupling with Gravitino is weak

Supplementary

- Massive, long-lived charged particles. These move slower than the speed of light
  - Loose energy in the tracker via ionization loss and hence high dE/dx following Bethe Bloch relation
- Trajectories are solely reconstructed by inner tracking system
- dE/dX measurement provided by pixel detector layers and hence agnostic to the decay activity
  - Sensitivity to lifetimes O(1ns) (since pixel is upto 13cm) and mass range from 100 GeV to 3 TeV
- This identification method does not depend on the way LLP interacts in the ATLAS calorimeters
  - results valid for any other LLP model
- Interpretation for pair-production of R-hadrons, charginos and staus

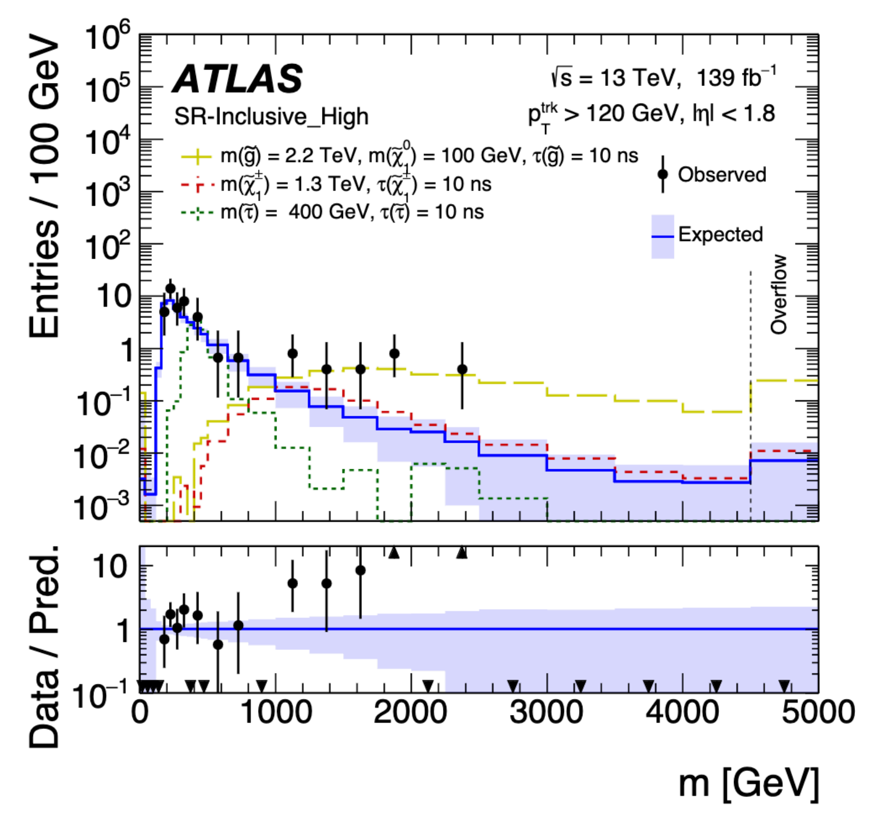
Bethe Bloch curve

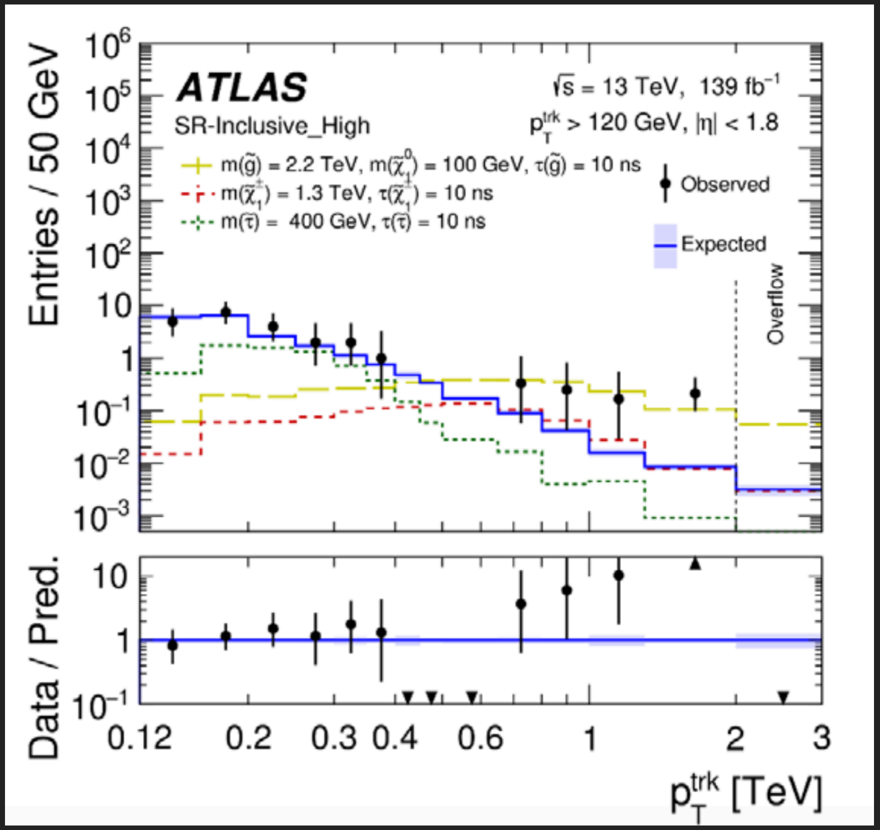


Energy deposited by LLPs

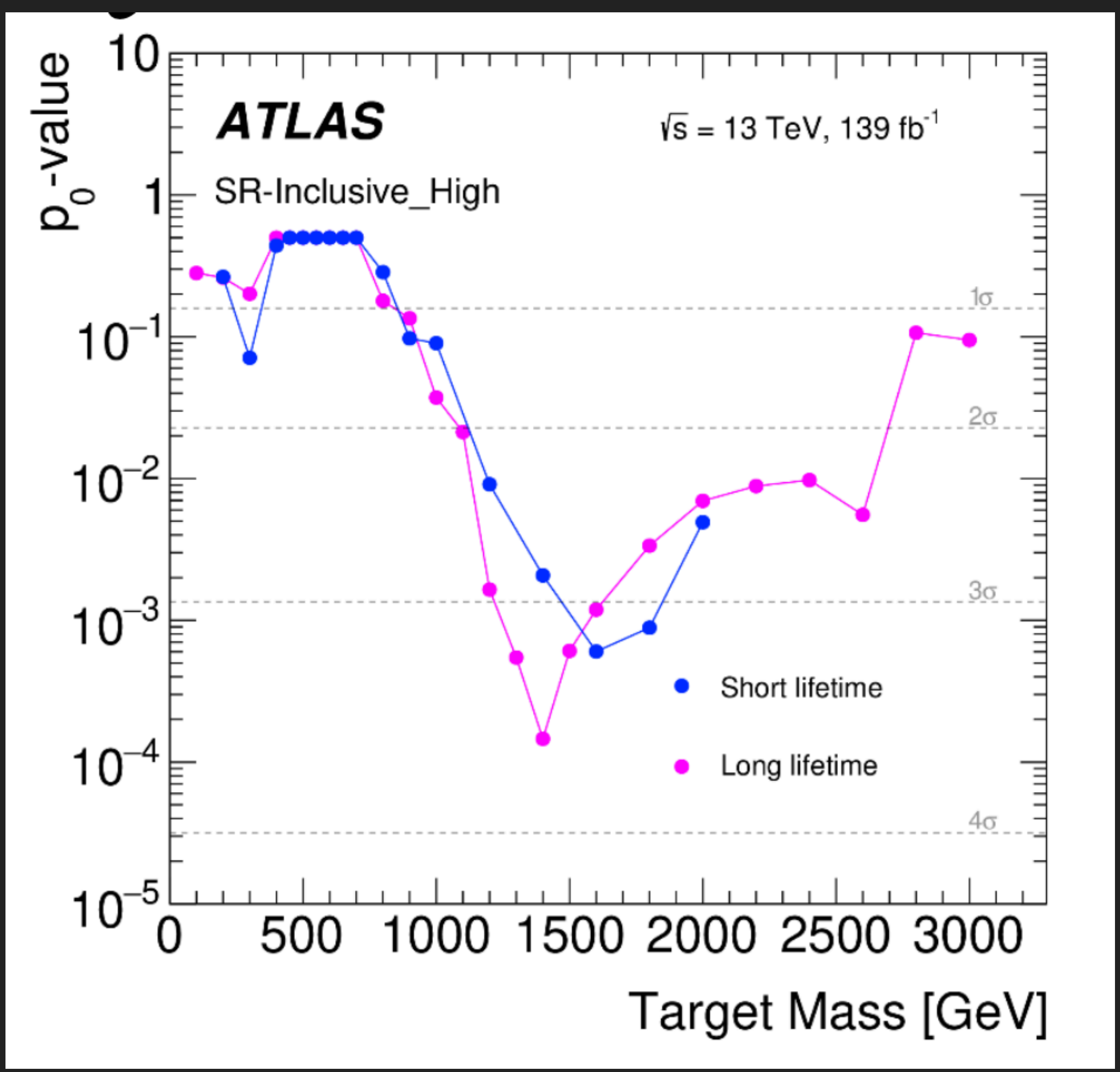
Heavy Long-Lived Charged Particles

- Trigger on p_T^{miss} (from neutralinos or gravitinos)
- Require at least on high-p_T track with various quality and background rejection requirements
- Measure dE/dx (in MeV g^{-1} cm^2) using inner detector:
    - Reconstruct track mass: $m_{dE/dx} = p_{reco}/\beta\gamma$ (<dE/dx>corr)
    - Signal regions: low (1.8 <= dE/dx <=2.4), high (dE/dx > 2.4)
    - Done for particles with 0.3 <= βγ <= 0.9;
        - Low threshold is the noise threshold that is used in the tracker reconstruction for readout (355 eh pairs)
        - Higher threshold is just below the regime of MIP (where dE/dX becomes quasi independent of βγ)





Statistical Analysis



CMS analysis in progress

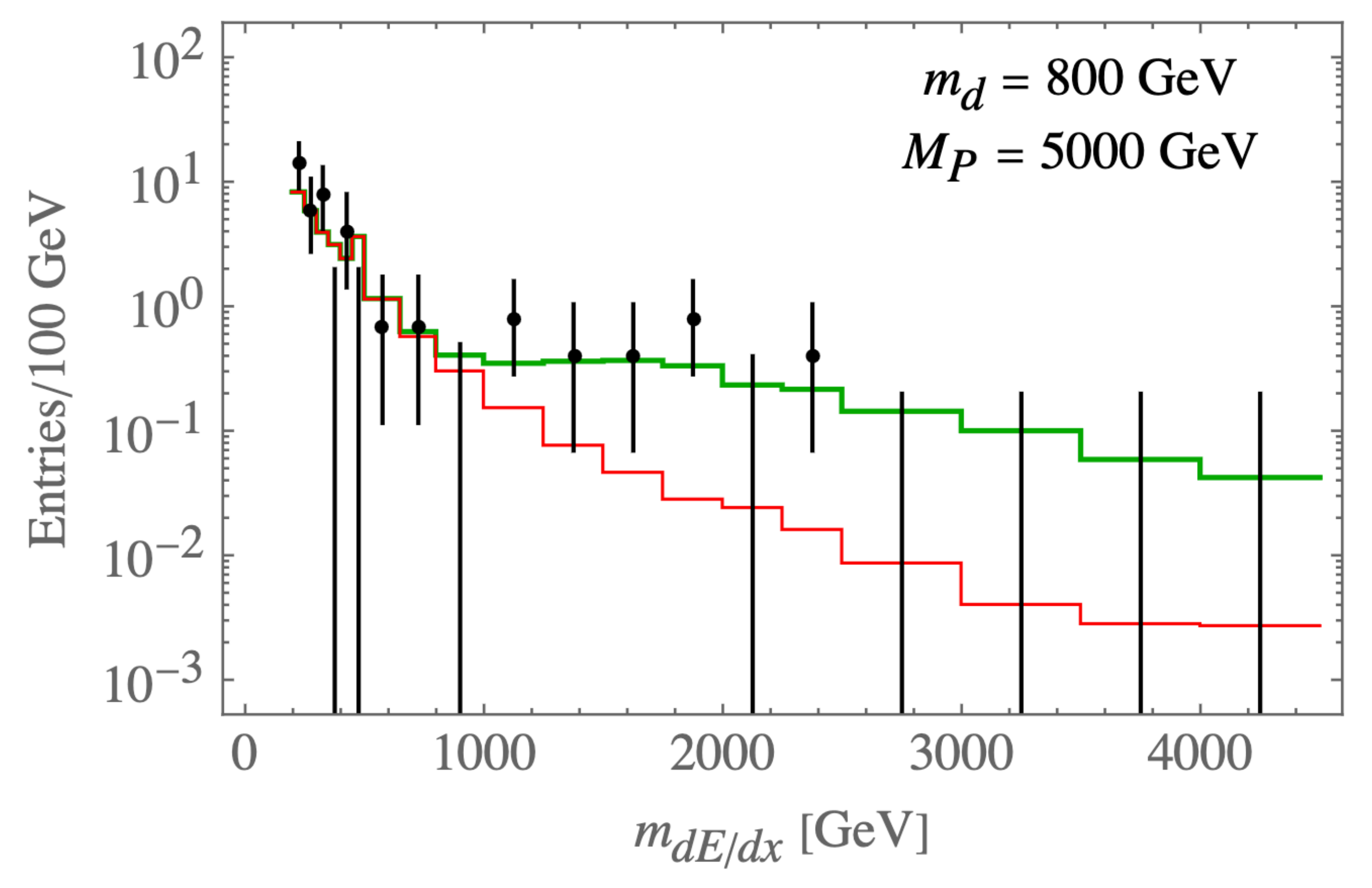
supplementary

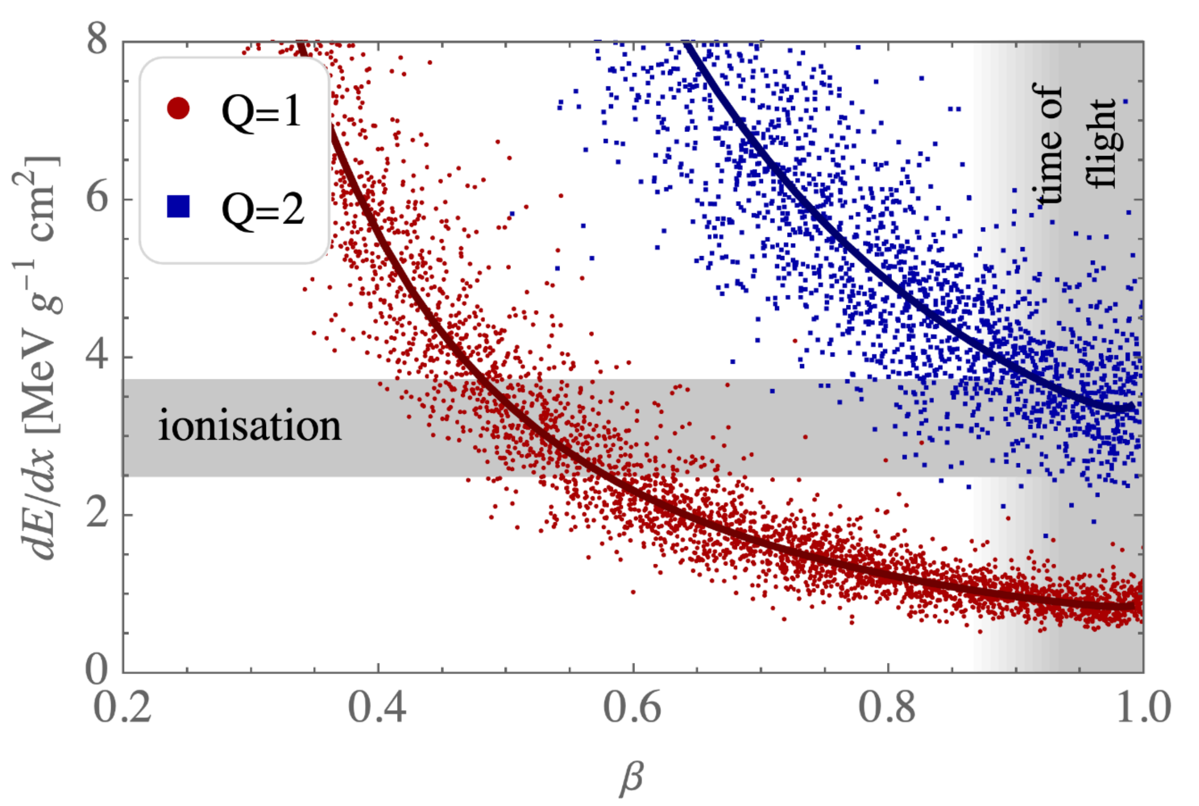
- 7 excess events with 1100 < m < 2800 GeV (expected 0.7 +/- 0.4). p-value ~3.6σ for signal mass = 1.4 TeV(global is ~3.3σ)
  - 2.4 <= dE/dx <= 3.7 MeV $g^{-1}cm^{2}$
    - Predicted β = 0.5–0.6, but measured β ~ 1 (from ToF, MS, Calo)
  - Not consistent with the heavy (and hence slow) LLP hypothesis

Another Interpretation

- Doubly-charged LLPs have β values compatible with measured dE/dx!
- Resonant production of relatively light daughter particles d from massive particle P –> boosted
- Good match for kinematic properties of excess events

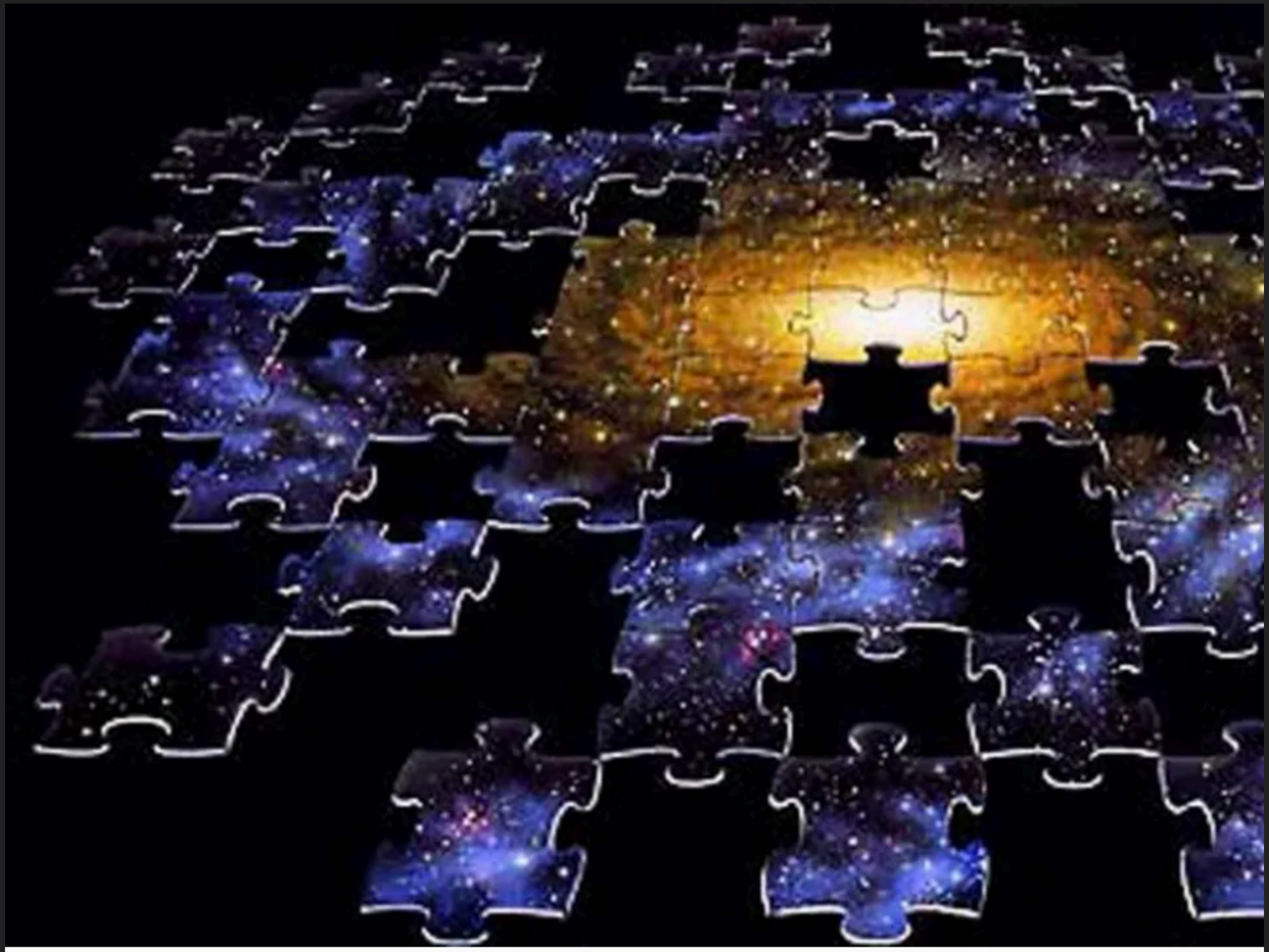
arXiv: 2205.04473





Outlook

- Many intriguing anomalies have been seen in the last few years with local p-value >~ 3σ
  - Although history is full of examples where 'bumps' came and went away.
  - In this case, we see a few correlated excesses
- Do all these excesses or anomalies point to the same solution or multiple solutions
  - Assess to which extensions of the SM these anomalies point to
- Important to keep an eye on Run 3 data to see how these evolve



We just need to keep fitting pieces of a big puzzle together and light will show up!

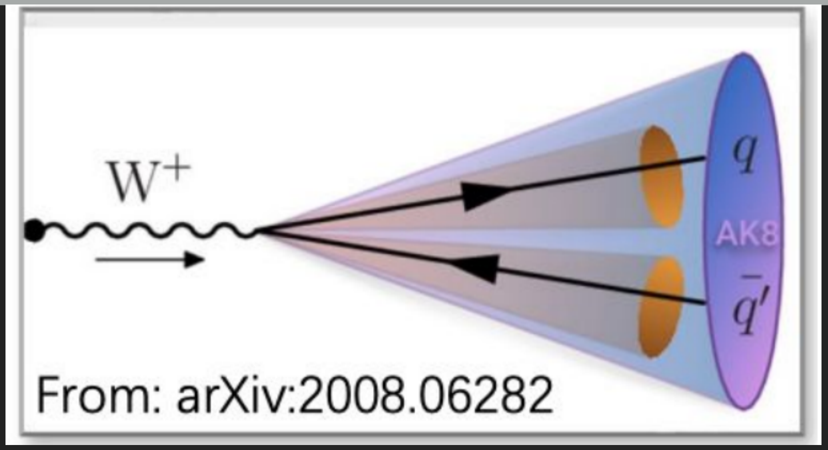
Thank you

Acknowledgement

- Most of the topics covered in this talk are motivated from
    - K.Pedro’s talk in Wine and Cheese seminar
    - G.Landsberg’s talk in DESY Theory Workshop on Higgs, Flavor, and Beyond

Backup

CMS: Search for Wγ resonance using hadronic decays of Lorentz-boosted W bosons



- Interpretation: 2HDM, technicolor,
- It is a bump search for a Wγ resonance over a smooth background
- W boson to its hadronic decays, with the final state products forming a single large-radius jet (high Lorentz boost of W)
- Using jet substructure techniques, background from γ+jet is reduced
- Jet mass and the sub-structure variable (N-subjettiness - tells how likely a wide jet is composed of N jets) reduce the backgrounds from QCD

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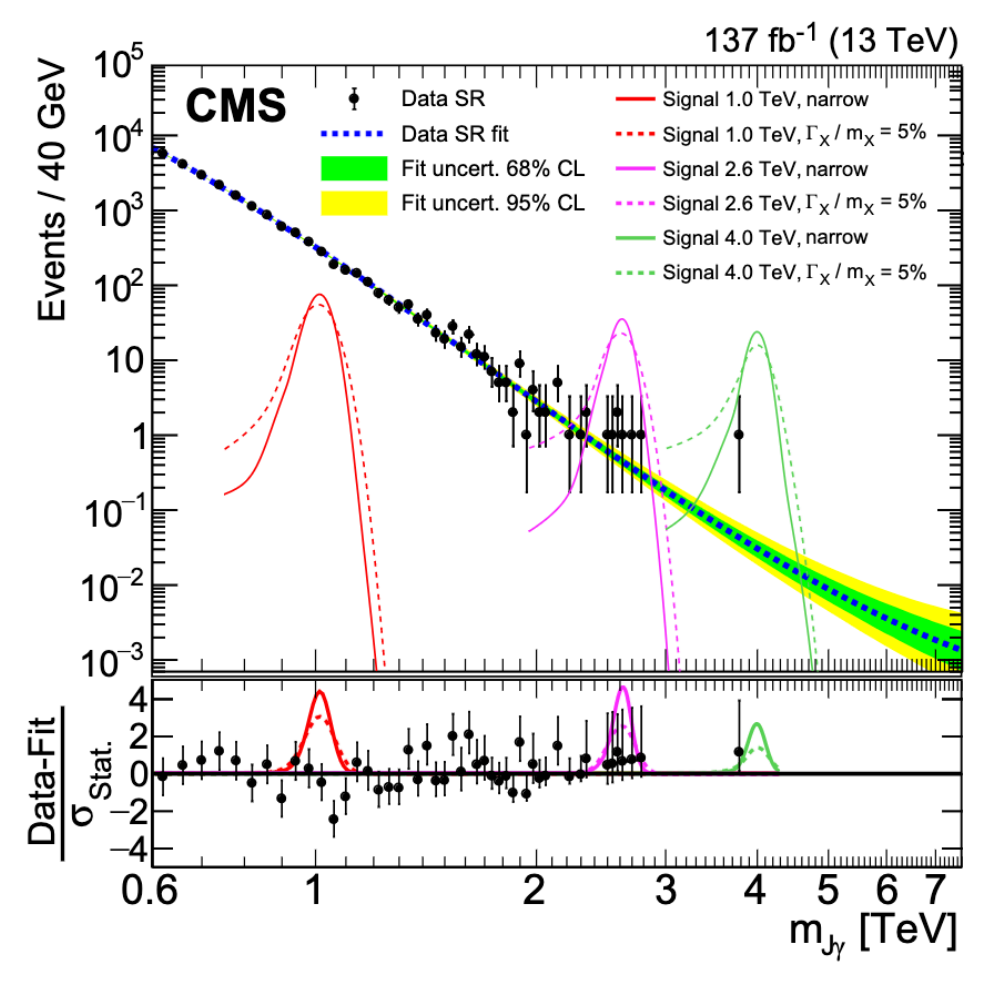
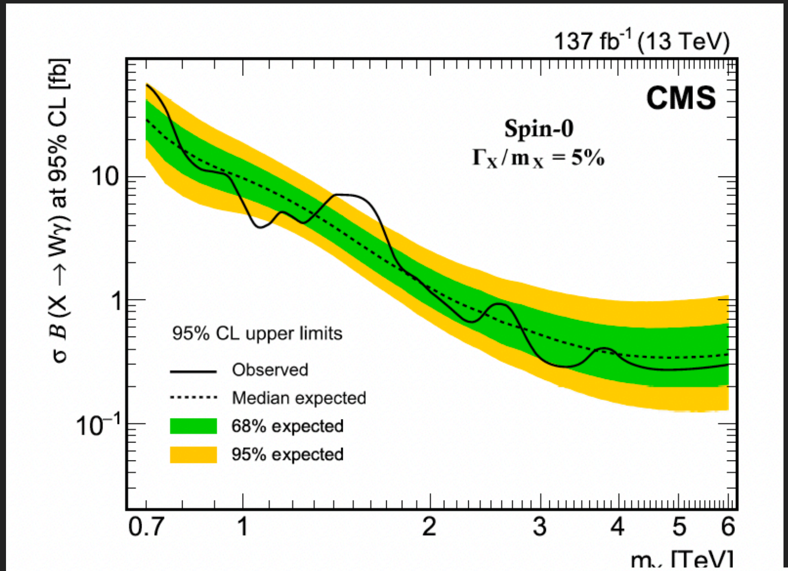
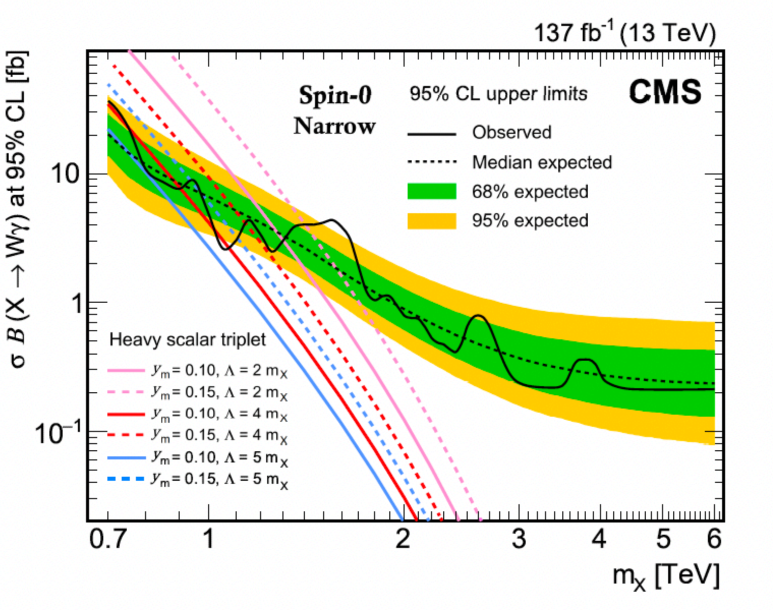


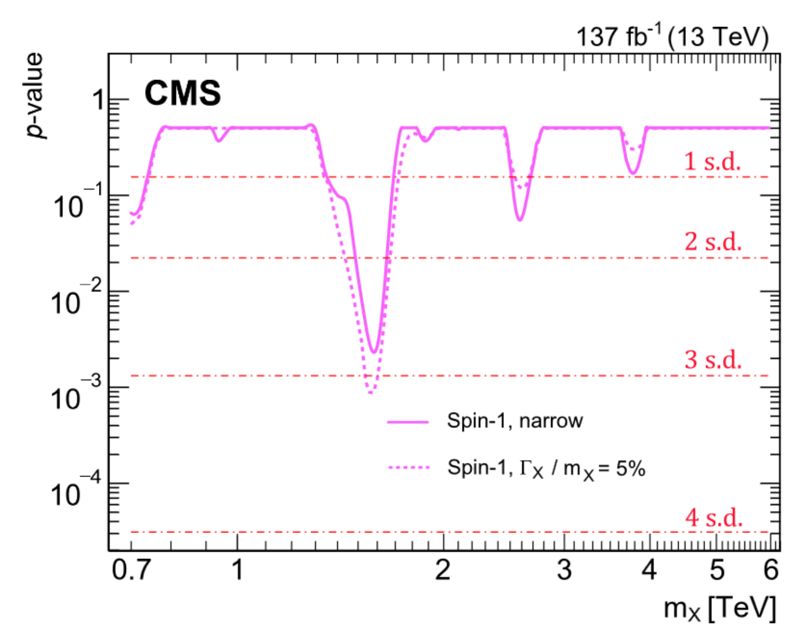
- Narrow resonance signal: CB + gaussian
- Broad resonance signal: CB + 2 gaussian
- Bias studies performed for the choice of functional form of the background

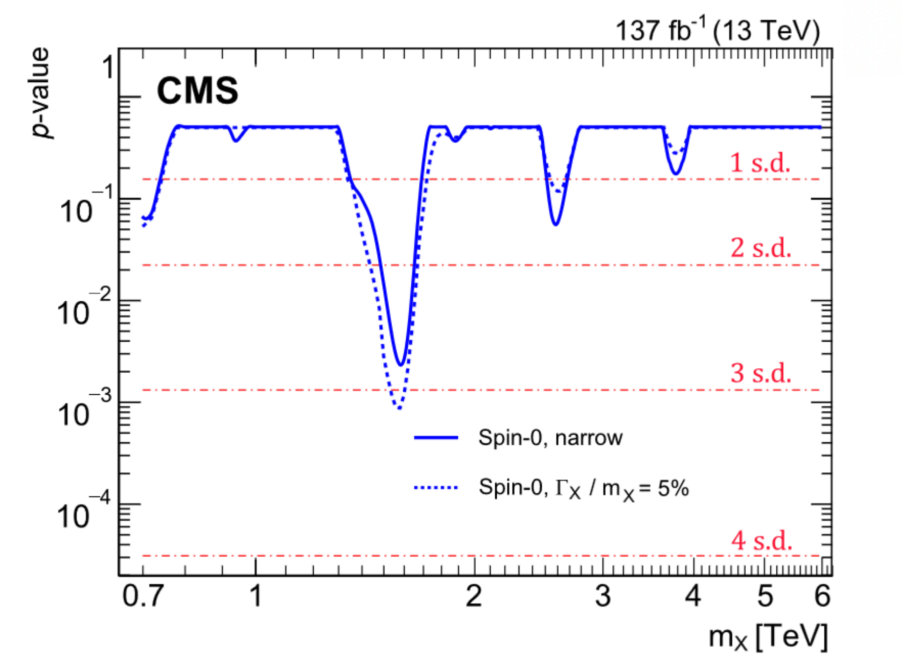
Wγ resonance: Statistical analysis

- Model specific upper limits on the σxBR for both narrow and broad resonance (both spin-0 and spin-1)
  - Model independent limits are also provided
- Largest excess is seen around 1.58 TeV with a local significance of 2.8 (3.1)σ for narrow (broad) signals for both spin hypotheses
- Global significance is 1.1 (1.7)









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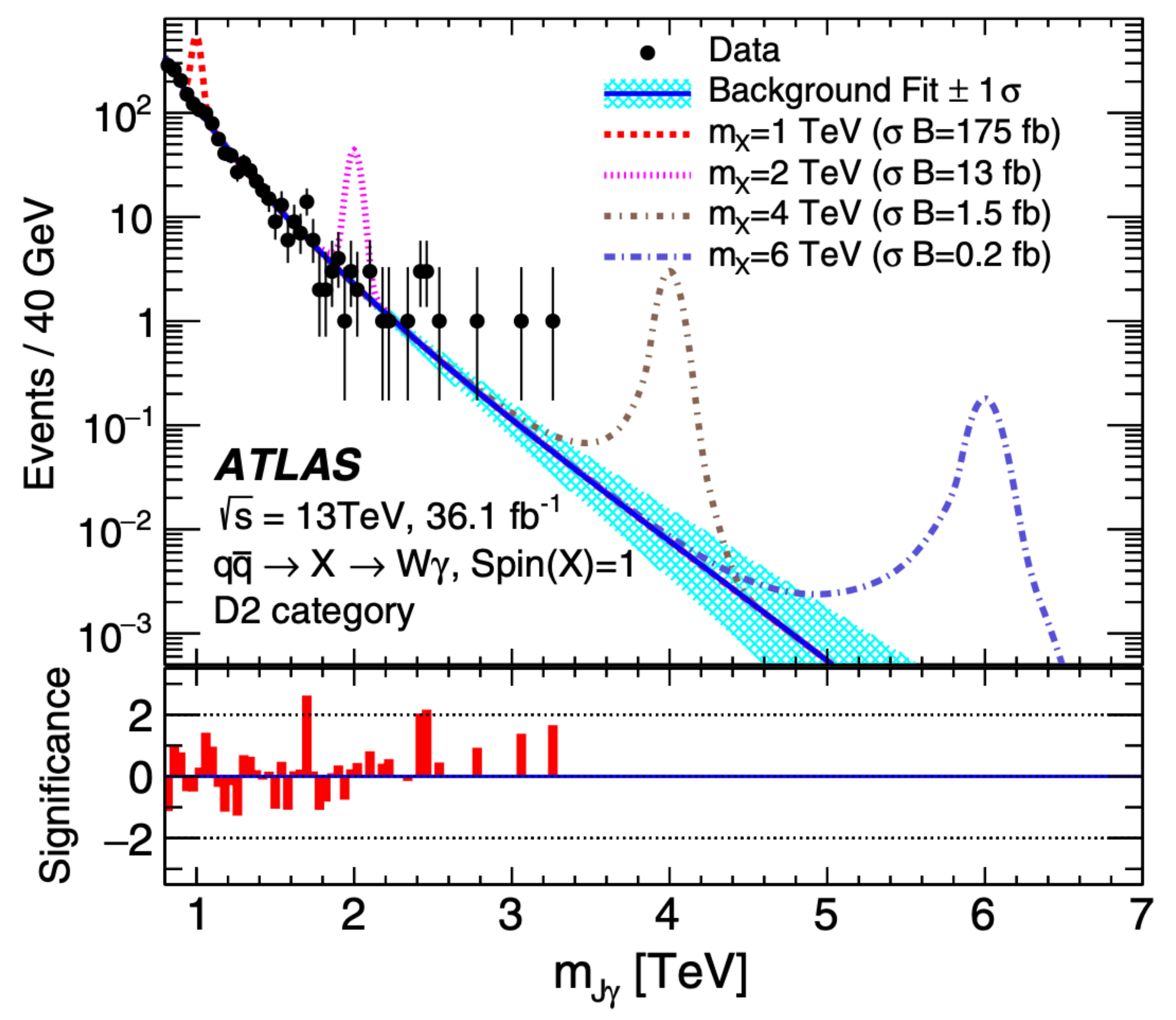
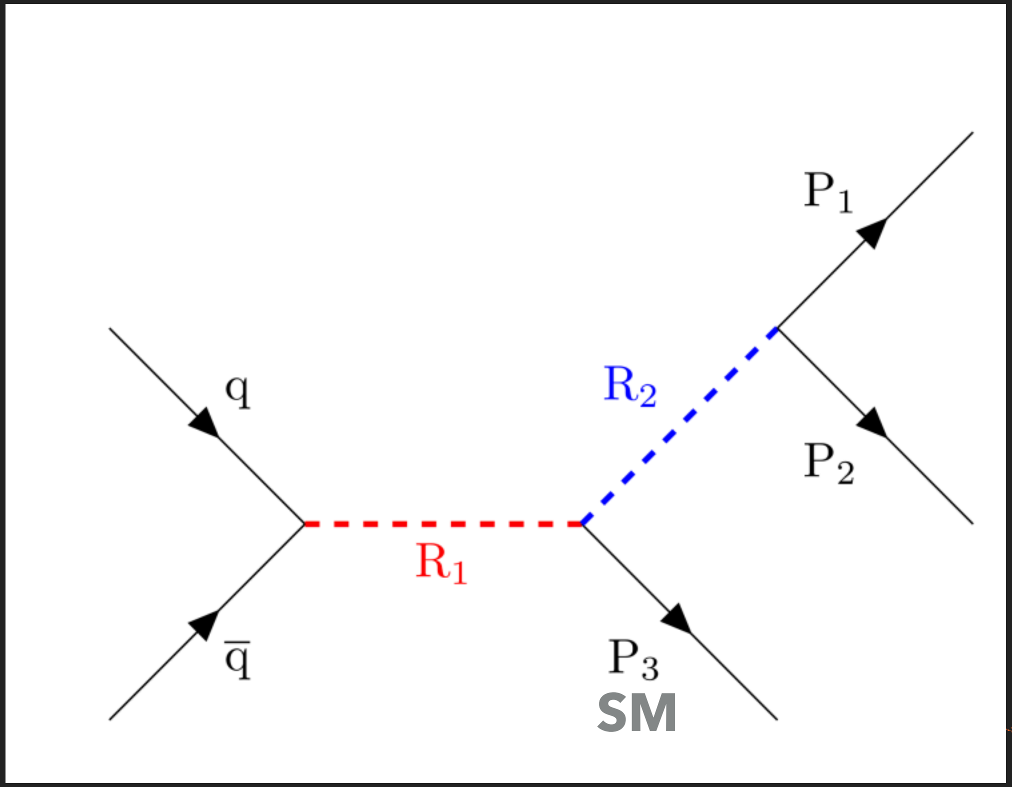
What about ATLAS?



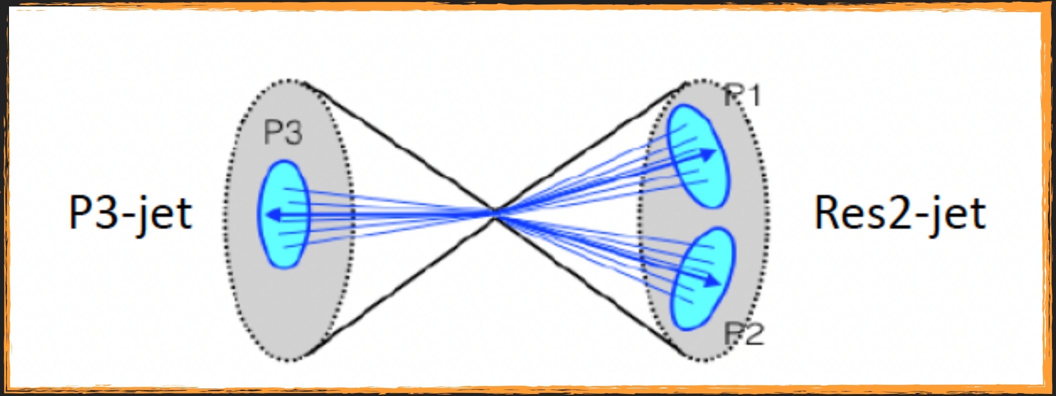
- Similar search in ATLAS.
- Results available with 2015+2016 data
- Smallest local p-value corresponds to a significance of 2.7σ is found ~2.5 TeV. This has a global significance of < 1σ

PhysRevD.98.032015

High mass resonance decaying to a jet and Lorentz boosted resonance



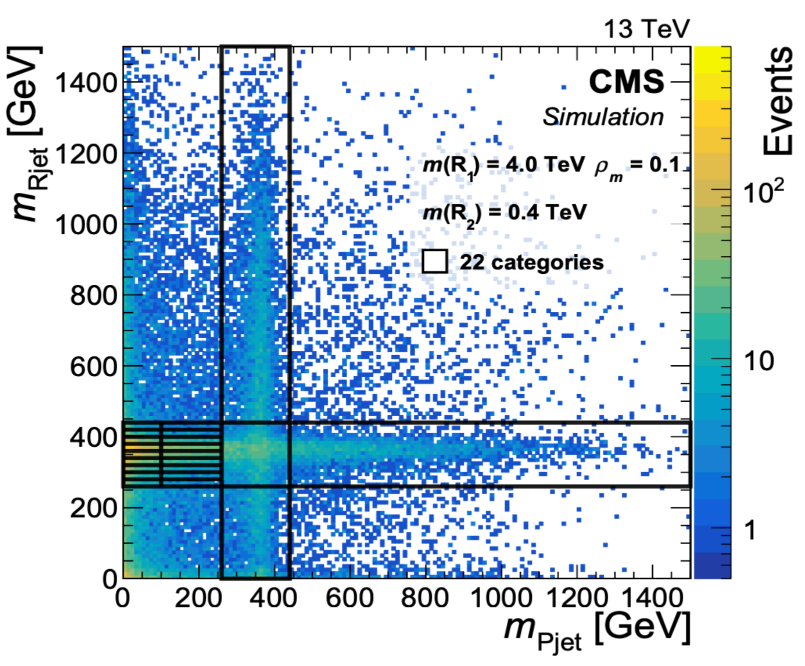
- Search for a high mas hadronic resonance –> parton and Lorentz-boosted resonance (decays to a pair of partons)
- Interpretation: Warper extra dimensions model.
  - High mass resonance is a Kaluza-Klien gluon (decays to radion and gluon) and boosted resonance is radion (further decays to two gluons)
- Done for the first time in the final state of two jets. Previous searches considered tagged with additional jet, photon, or a lepton

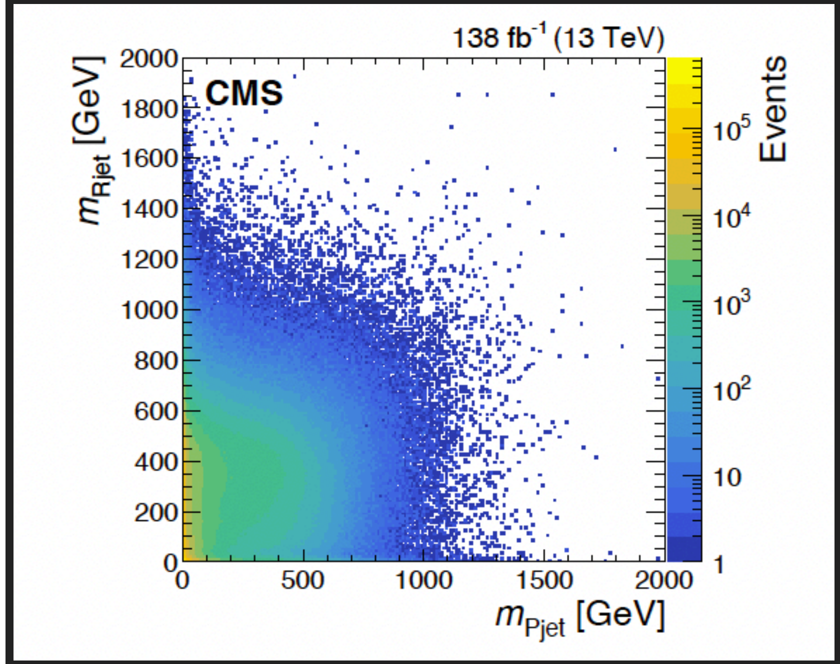


PhysLetB.2022.137263

- Experimental signature: 2 jets
  - Two large-radius (wide) resolved jets, one coming from R2 (R2-jet) and one coming the third parton (P3-jet) with P1, P2 and P3 as gluons
- Focus on ρ_m = M(R2)/M(R1) < ~ 0.2
  - P1, P2 boosted and hence reconstructed as one wide jet
  - Sensitive to M(R1) > 2 TeV
- Jets reconstructed with ΔR = 1.5 using soft drop technique (pT > 100 GeV)
- Main backgrounds: Multijet QCD production estimated from data driven methods, several parameteric functional forms.

High mass resonance decaying to a jet and Lorentz boosted resonance





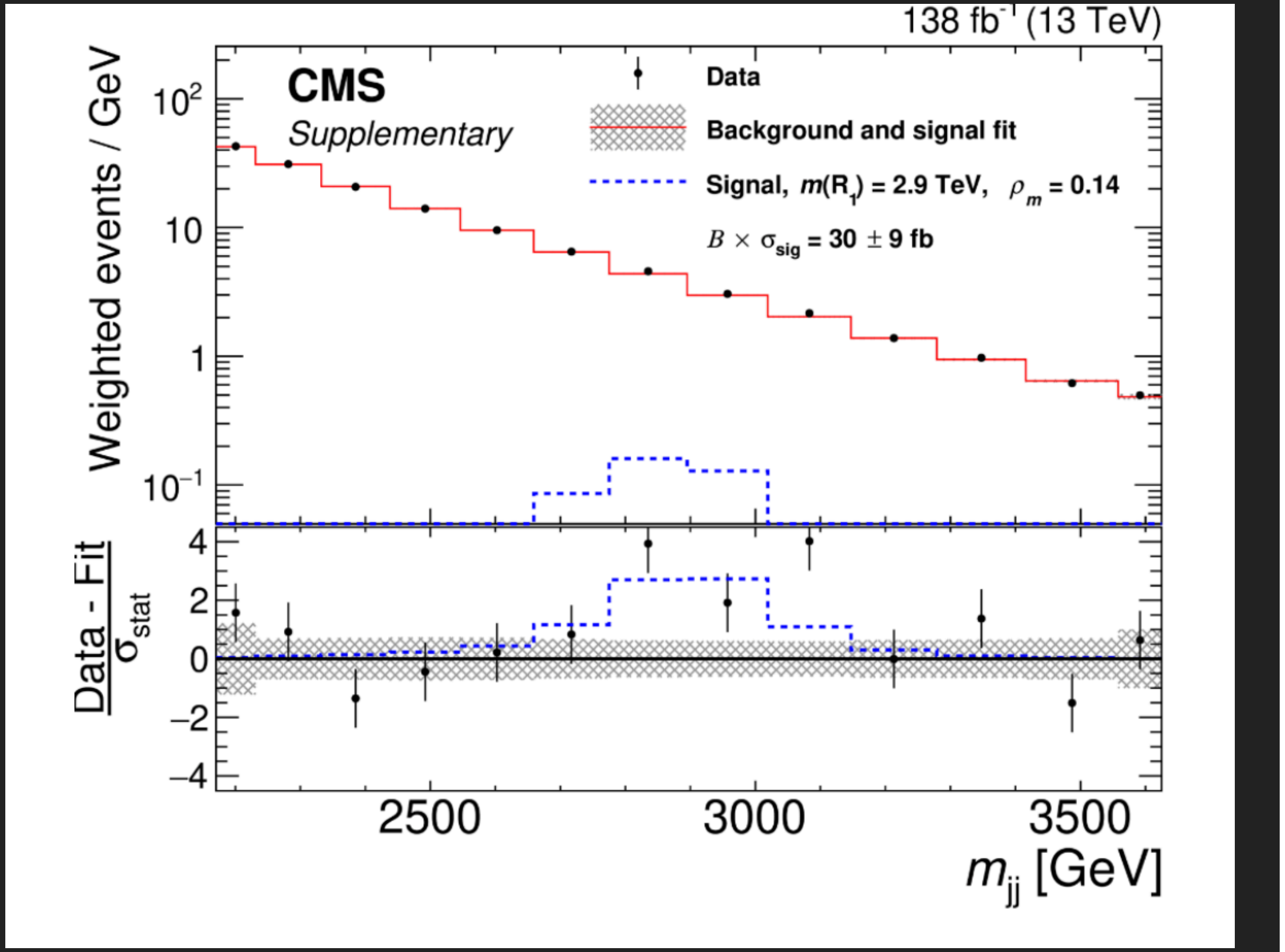
- Events within this cross are used
- Several categories defined in each m(R2)/m(P3) plane for each m(R2)
- Signal modeling: double sided crystal ball
- Parametric function for background:

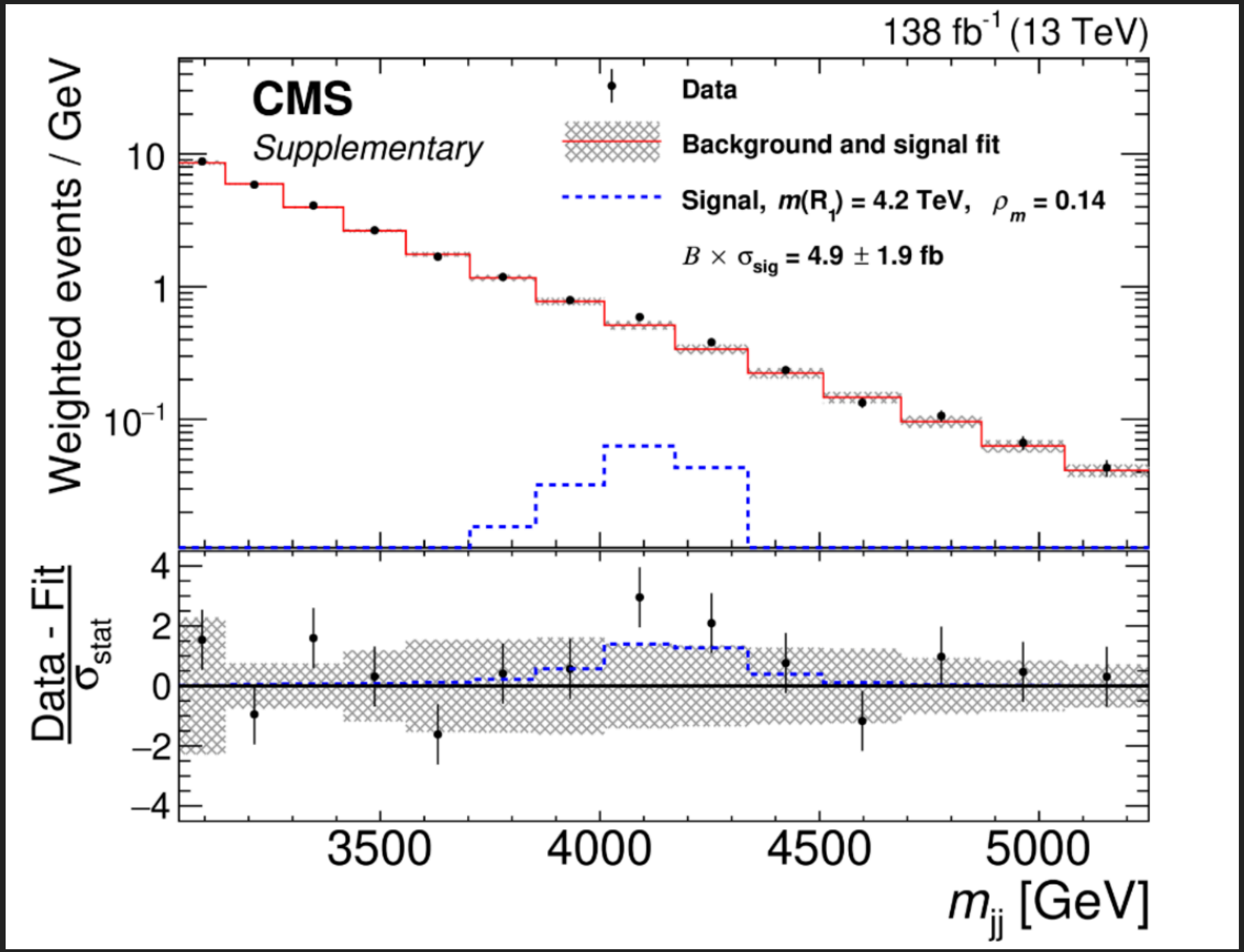
$$f(x) = p_0\,(1-x)^{p_1}\,/\,x^{p_2}$$

- Selection:
  - $|\Delta\eta| < 1.3$ to reject QCD background (t-channel)
  - $m_{jj} > 1.6$ TeV
- Strategy: Discrimination between signal and QCD background by exploiting jet substructure information and kinematics of the decay
- Utilize the 2D plan of m_{Rjet} VS m_{Pjet}
  - Vertical axis of the cross represents wrong tagging of P3 as R2

S+B fit : Largest deviations

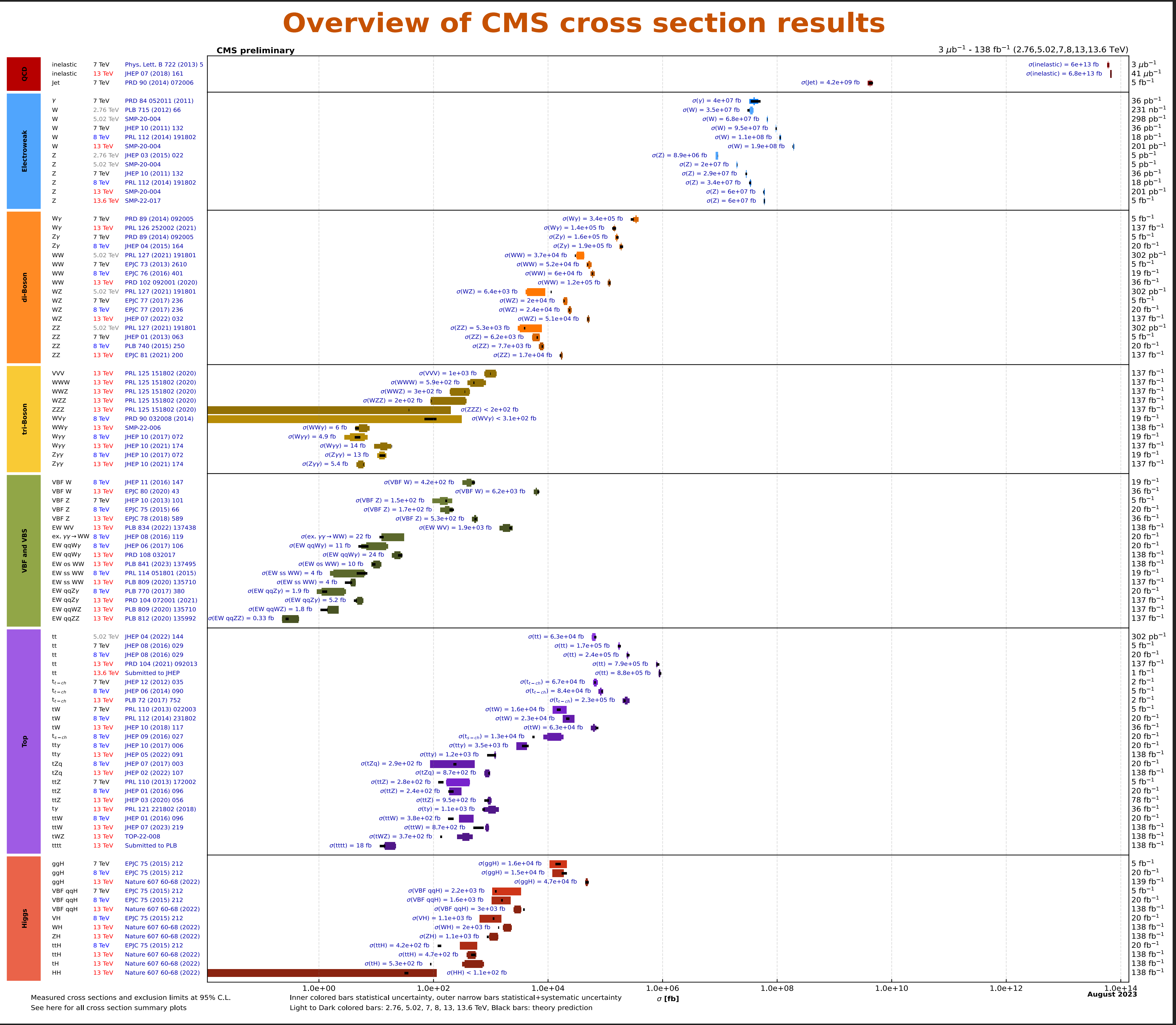
supplementary material





- Maximum likelihood fit in the dijet mass performed in the SRs
- Simultaneous fit to m_{jj} spectrum in all the categories
- Largest excess: 1.8σ global (3.2σ local) for m(R1) = 2.9 TeV and ρ_m = 0.14

The Standard Model till now

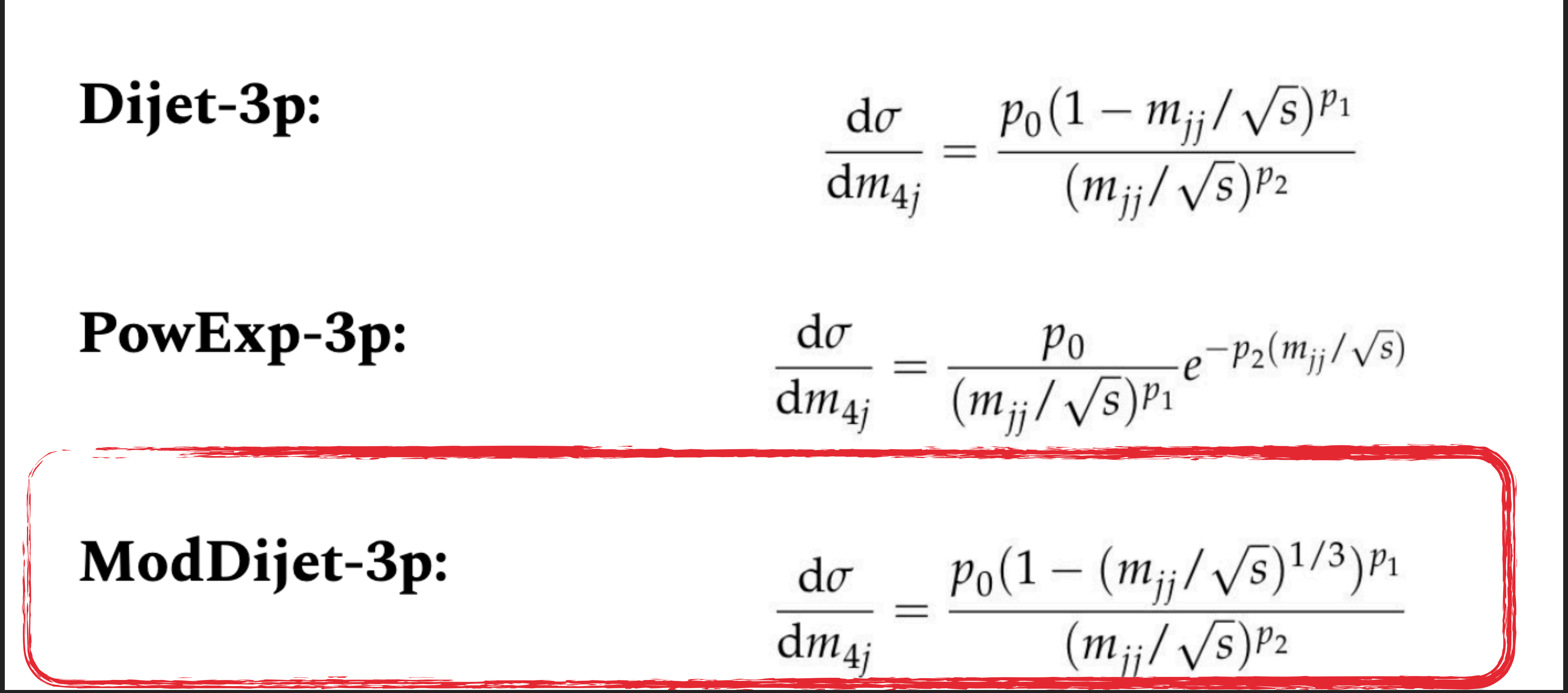


- Similar plot exists for ATLAS as well
- Excellent agreement with the SM across various energies
- However, SM is not the complete model because …

High mass di-jet resonance

- Why scalar diquark: Large cross-section due to high probability of finding up quark at high fractional momentum within the proton
- New background estimate: From a control region where the $|\Delta\eta_{jj}|$ is large
- Yields smaller systematic uncertainties when performed in the same dijet mass range as the "fit method".
- Improves the sensitivity for broad resonance by a factor of two depending on resonance mass and width
- HLT with pT jet > 550 GeV with dR > 0.8 || H_T > 1050 GeV
- Wide jet algorithm: Two leading jets are used seeds and other jets as the 'can be clustered jets'. If dR < 1.1 between leading jet and the nearby jet, then they are added to the nearest leading jet to obtain two wide jets
  - Reduces the sensitivity of the analysis to gluon radiation
- Background from t-channel dijet (dominant mode) events has the same angular distribution as Rutherford scattering (proportional to $1/[1-\tanh(|\Delta\eta|/2)]^2$ –> peaks at large value of $|\Delta\eta|$ (distance in η between the two jets)
  - Signal region is $|\Delta\eta| < 1.1$
- s-channel: decreases with increasing $|\Delta\eta|$

Background estimate in Di-jet for |Δη| < 1.1



Dijet-3p:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{4j}} = \frac{p_0(1 - m_{jj}/\sqrt{s})^{p_1}}{(m_{jj}/\sqrt{s})^{p_2}}$$

PowExp-3p:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{4j}} = \frac{p_0}{(m_{jj}/\sqrt{s})^{p_1}} e^{-p_2(m_{jj}/\sqrt{s})}$$

ModDijet-3p:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{4j}} = \frac{p_0(1 - (m_{jj}/\sqrt{s})^{1/3})^{p_1}}{(m_{jj}/\sqrt{s})^{p_2}}$$

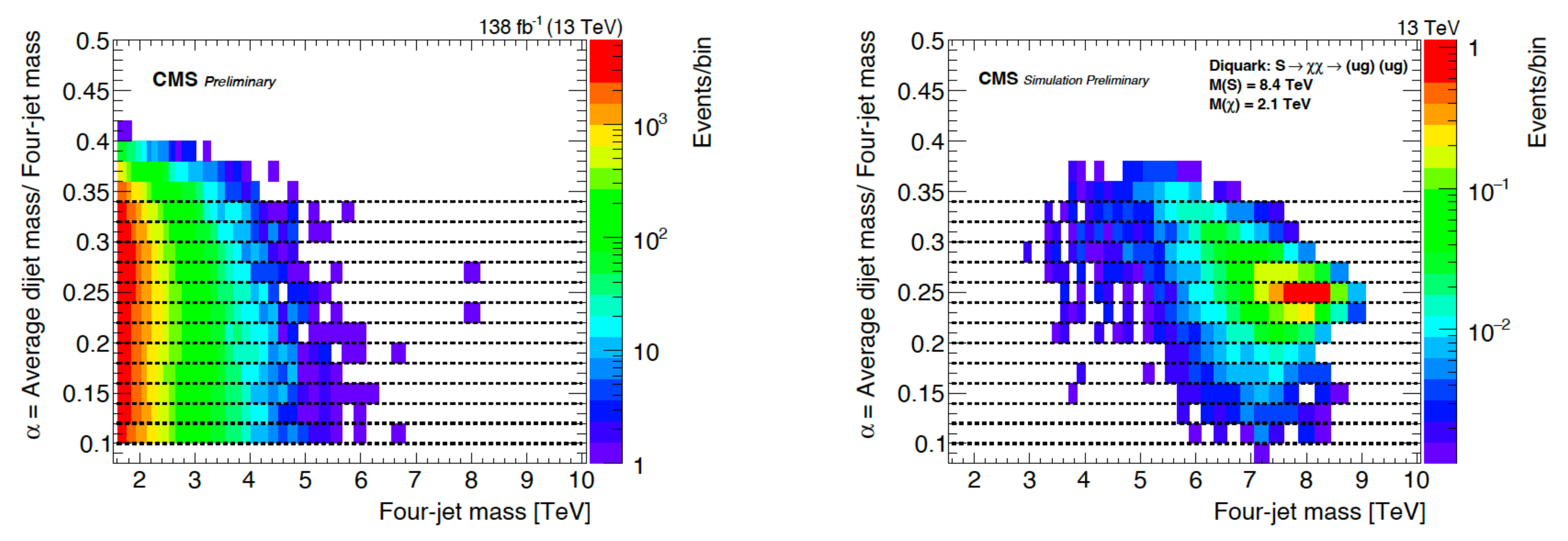
Main function

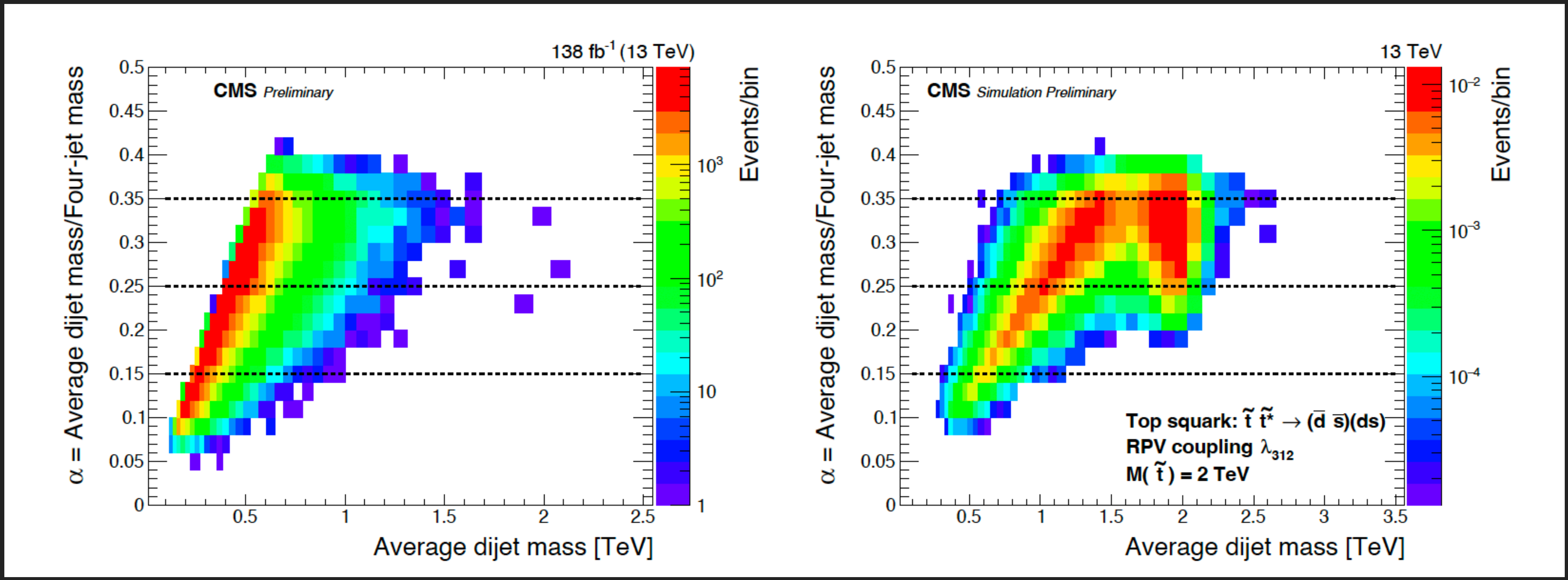
- Signal from simulation and background parameterized as shown above.
- Parameters are left floating in the likelihood fit
- Acceptance x efficiency is ~ 10-15%

Dijet – ratio method to estimate the background

- Two control regions are defined in the region 1.1 < |Δη| < 2.6
    - 1.5 < |Δη| < 2.6 : to predict the main QCD background in the SR
    - 1.1 < |Δη| < 1.5 : constrain theoretical and experimental systematic uncertainties
- Why new method or ratio method for mjj > 2.4 TeV
    - mjj ~ 2pT cosh(|Δη|/2). So lower |Δη| means low mjj for low pT. Trigger is thus efficient for mjj lower dijet mass than in CRs which has higher |Δη| that corresponds to roughly around 2.4 TeV of mjj
    - Hence fit method for mjj < 2.4 TeV and afterwards CRs when trigger makes them more efficient

Binning in a - CMS paired dijet

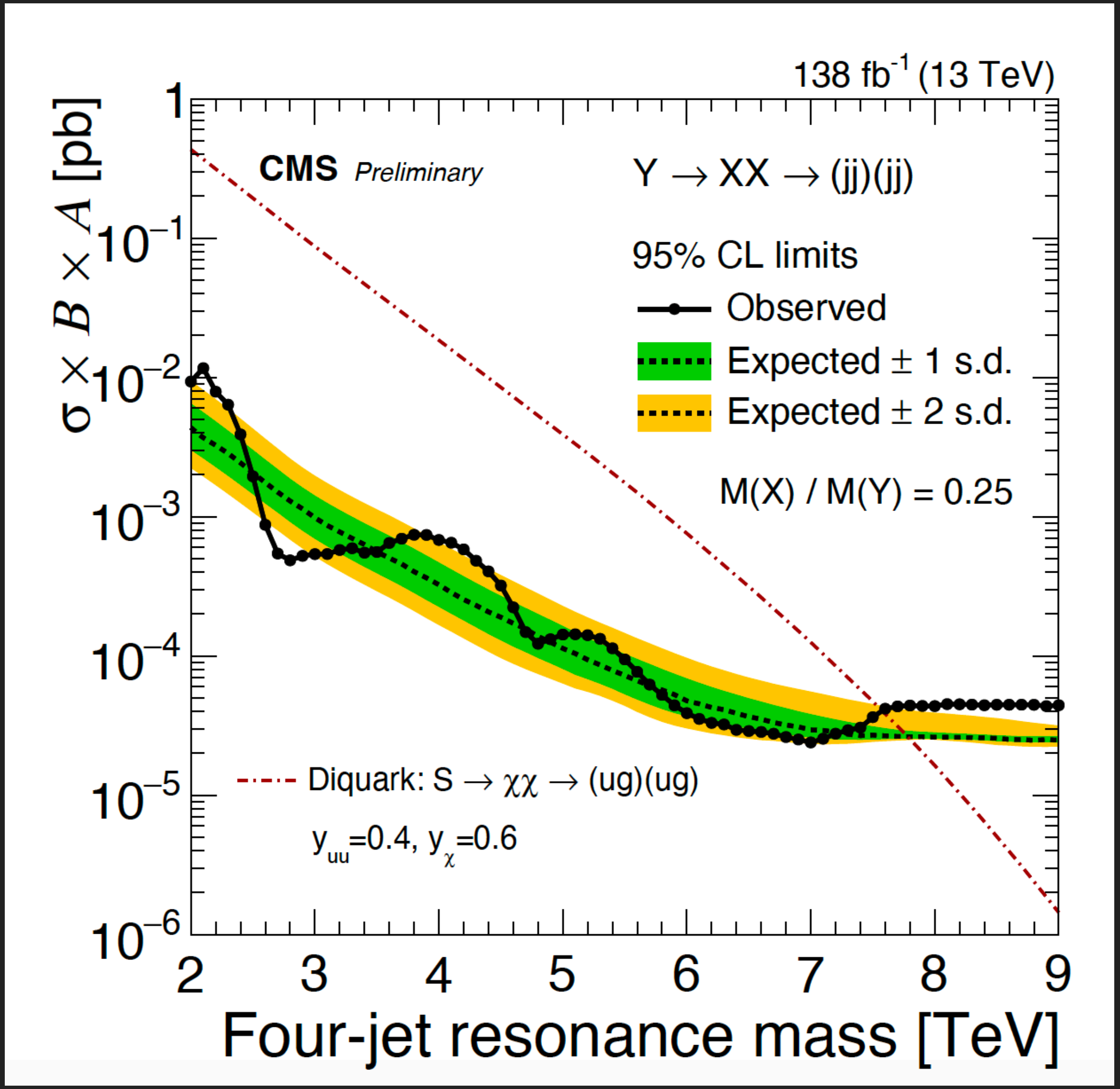




- Top for resonant analysis and bottom for non-resonant
- 13 (3) bins in a for resonant (non-resonant)
- In resonant, a is an unbiased variable to bin in m4j.
- In non-resonant, a utilizes the signal shape

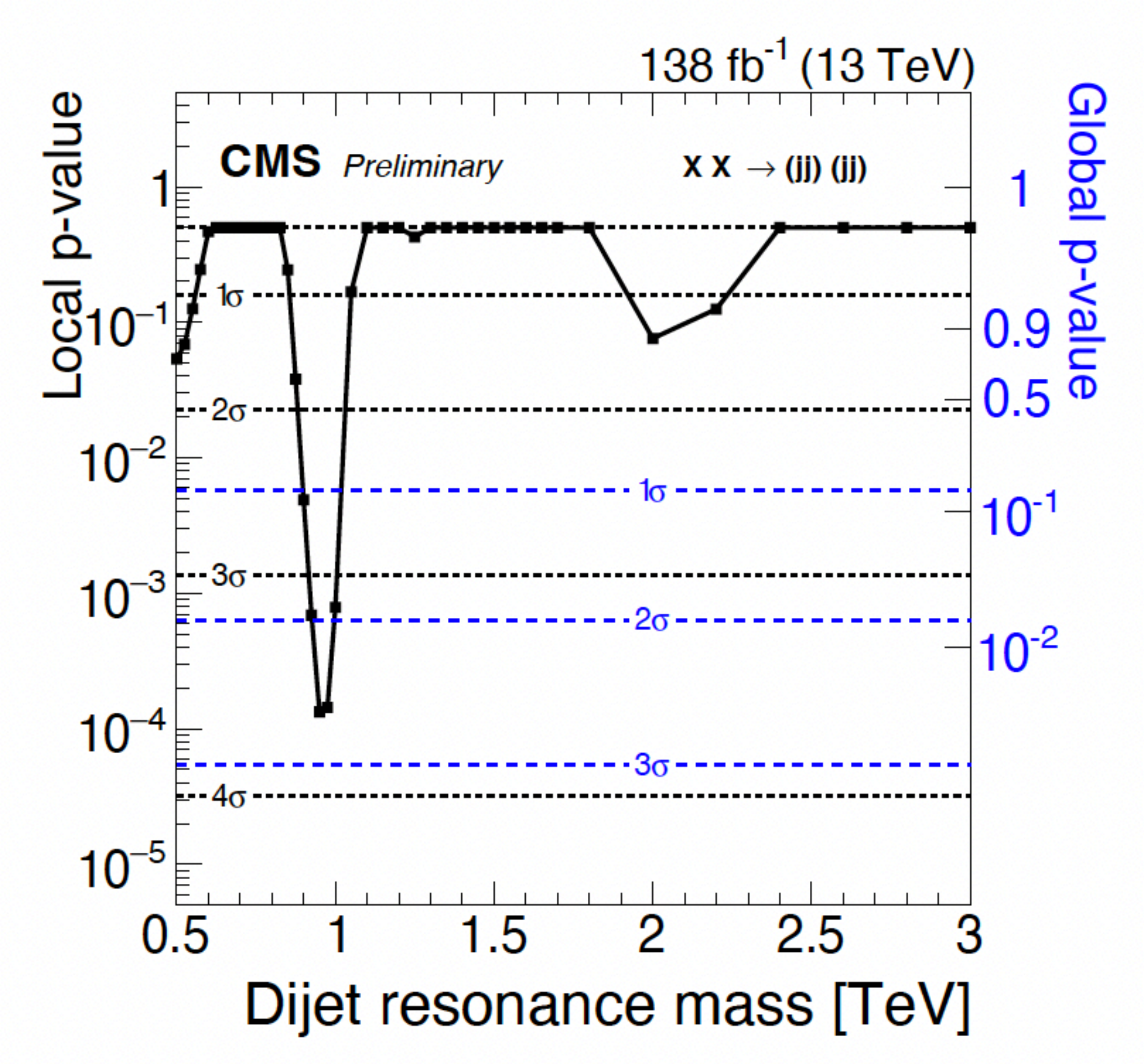
Statistical checks performed in paired dijet - CMS

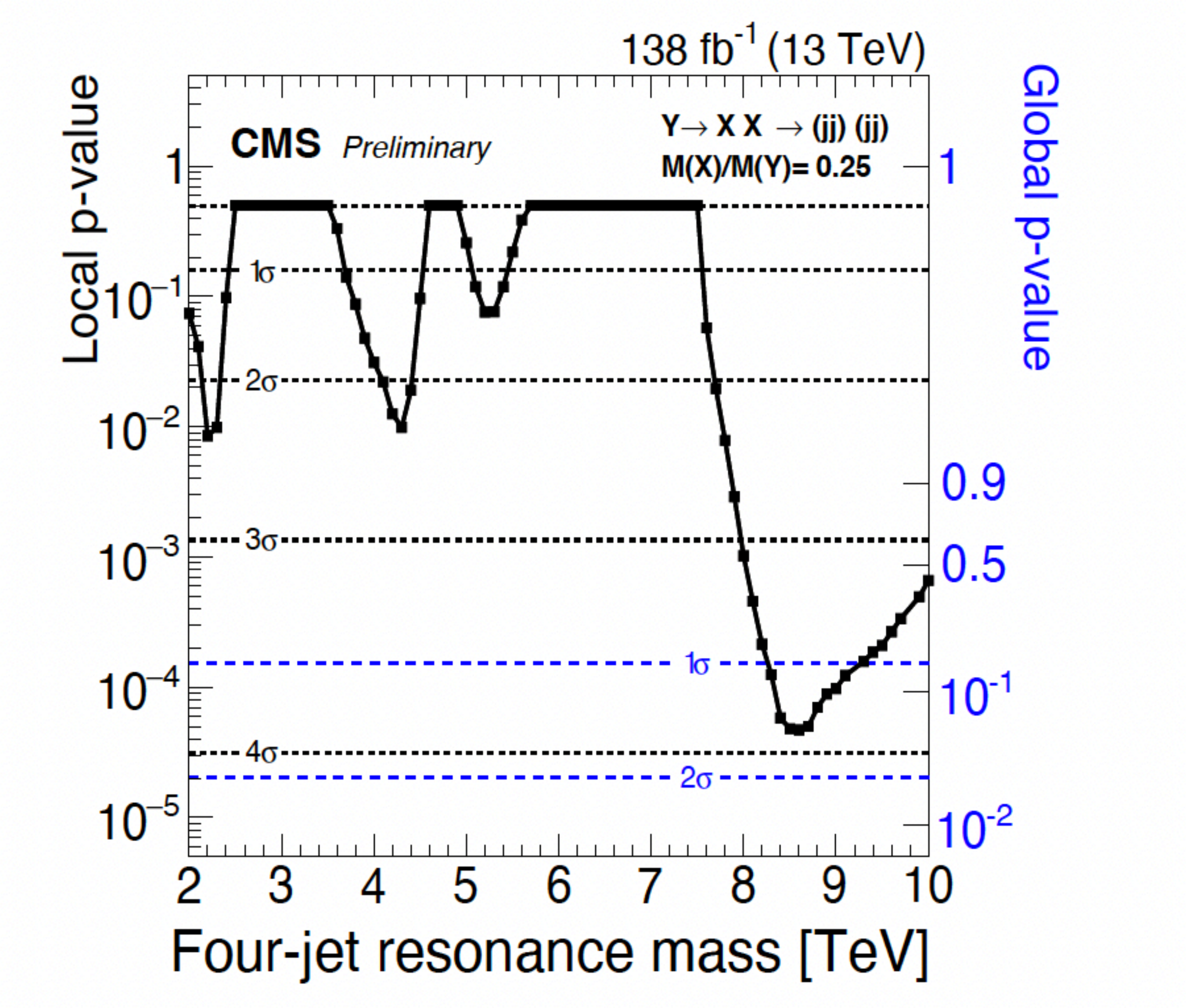
- Extensive bias and signal injection tests: no significant bias found for any signal mass hypothesis
- Tests were performed by generating toys from each background function, with or without signal injected, and measuring the signal strength returned by the full (envelope) fitting procedure
- Systematic uncertainty:
  - Signal: JER (~10% on the final four-jet and dijet resolution - gaussian) and JES (~2%), luminosity (~1.6% - lognormal)
  - Background: Uncertainty from the fit
  - All other sources (e.g. PDFs) are negligible
- Test statistic: Likelihood ratio (CLs method)



Limits for the special case where α=1/4 - corresponding to the two high mass events and the highest observed significance

Correlation in observation between resonant and non-resonant search - merged dijet CMS





- Most significant signal hypothesis in non-resonant search: Dijet resonance mass of 0.95 TeV, 3.6σ deviation
- Second highest in resonant is ~ 3 TeV in m4j (in alpha = 0.17)

More on the excess of events in dijet search

$$\mathrm{d}\sigma/\mathrm{d}m = p_0(1-x^{1/3})^{p_1}/(x^{p_2+p_3\log x+p_4\log^2 x})$$

ModDijet-5p

$$\mathrm{d}\sigma/\mathrm{d}m = p_0(1-x)^{p_1}/(x^{p_2+p_3\log x+p_4\log^2 x})$$

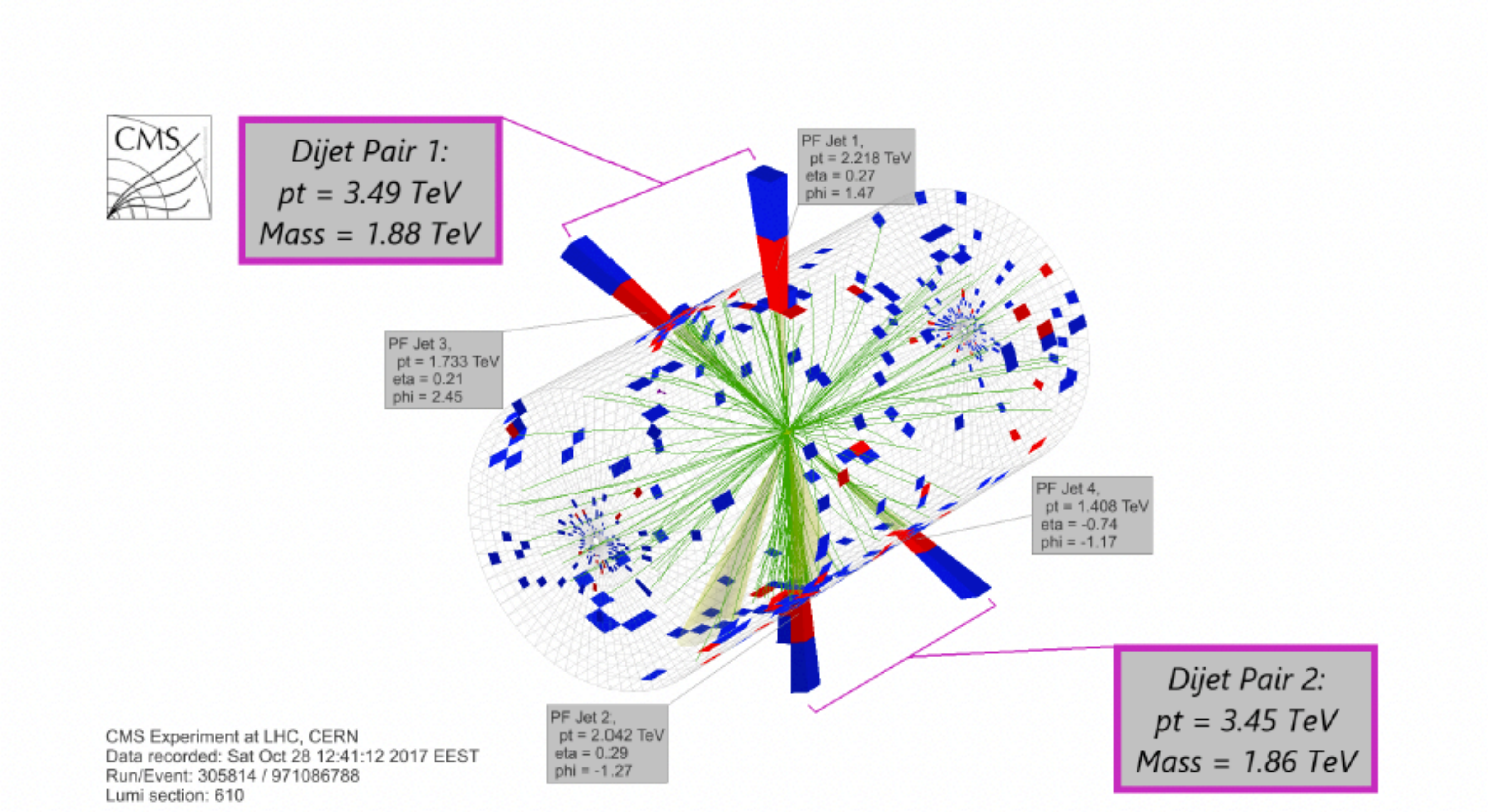
Dijet-5p

$$\mathrm{d}\sigma/\mathrm{d}m = p_0 e^{-p_1 x - p_2 x^2 - p_3 x^3}/x^{p_4}$$

PowExp-5p

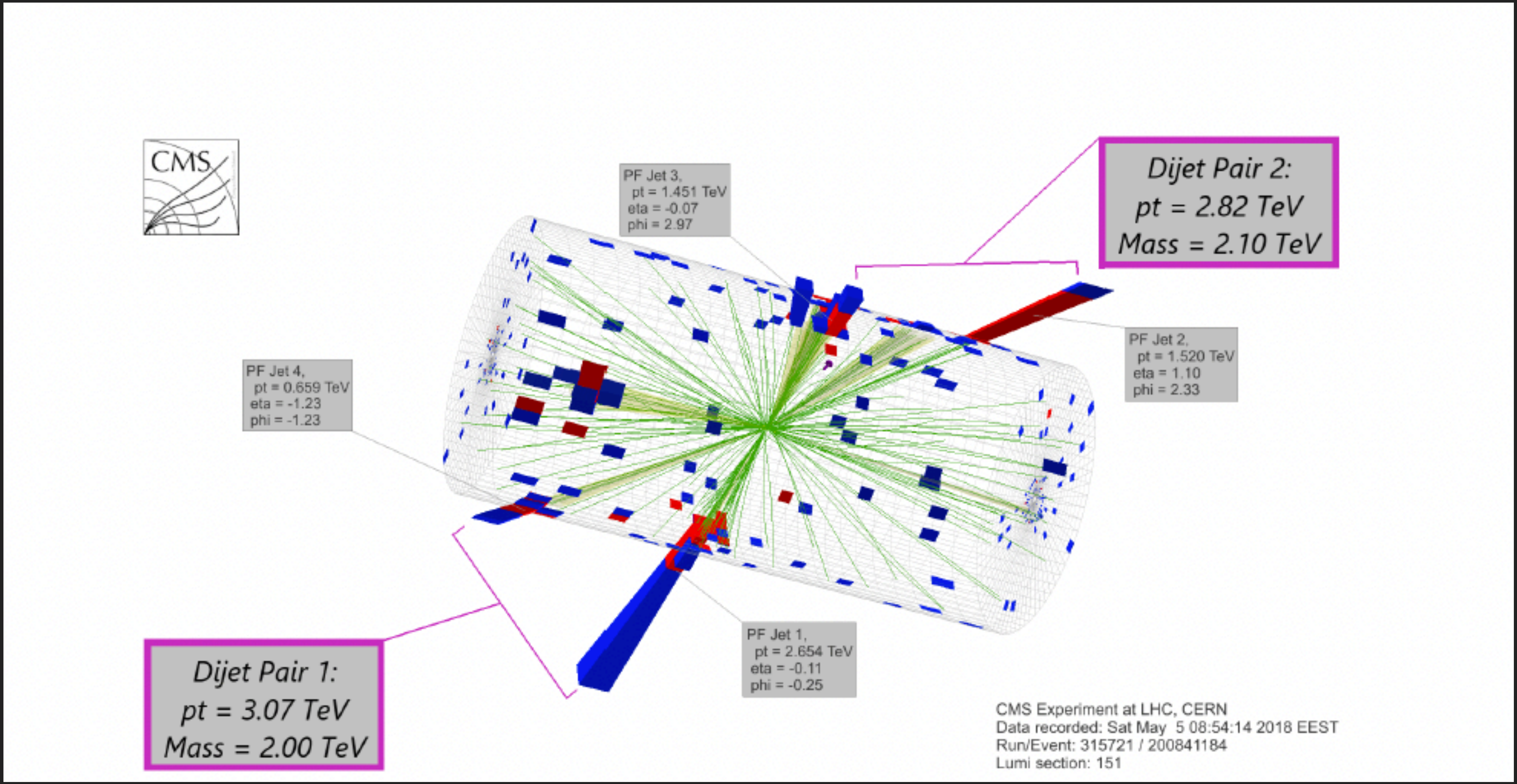
- These appear in the bin of $0.22 < \alpha < 0.24$ and $0.26 < \alpha < 0.28$
- Background only fits are performed using the same function forms but with 5 parameters

First event seen in 2018



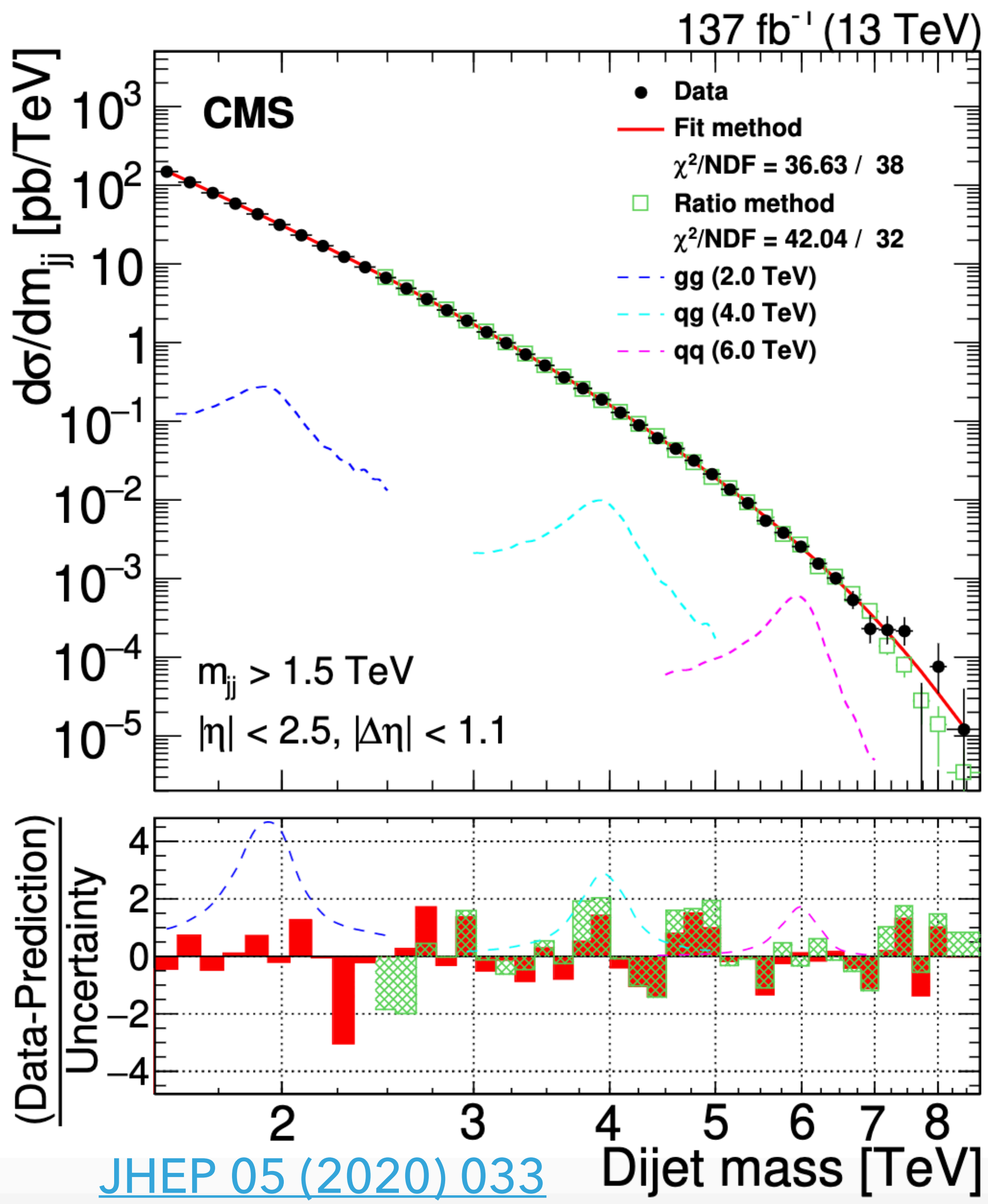
- $|\Delta\varphi| = 3.1$ and $|\Delta\eta| = 0.4$
- Small mass asymmetry = 0.005

Second event seen in 2018

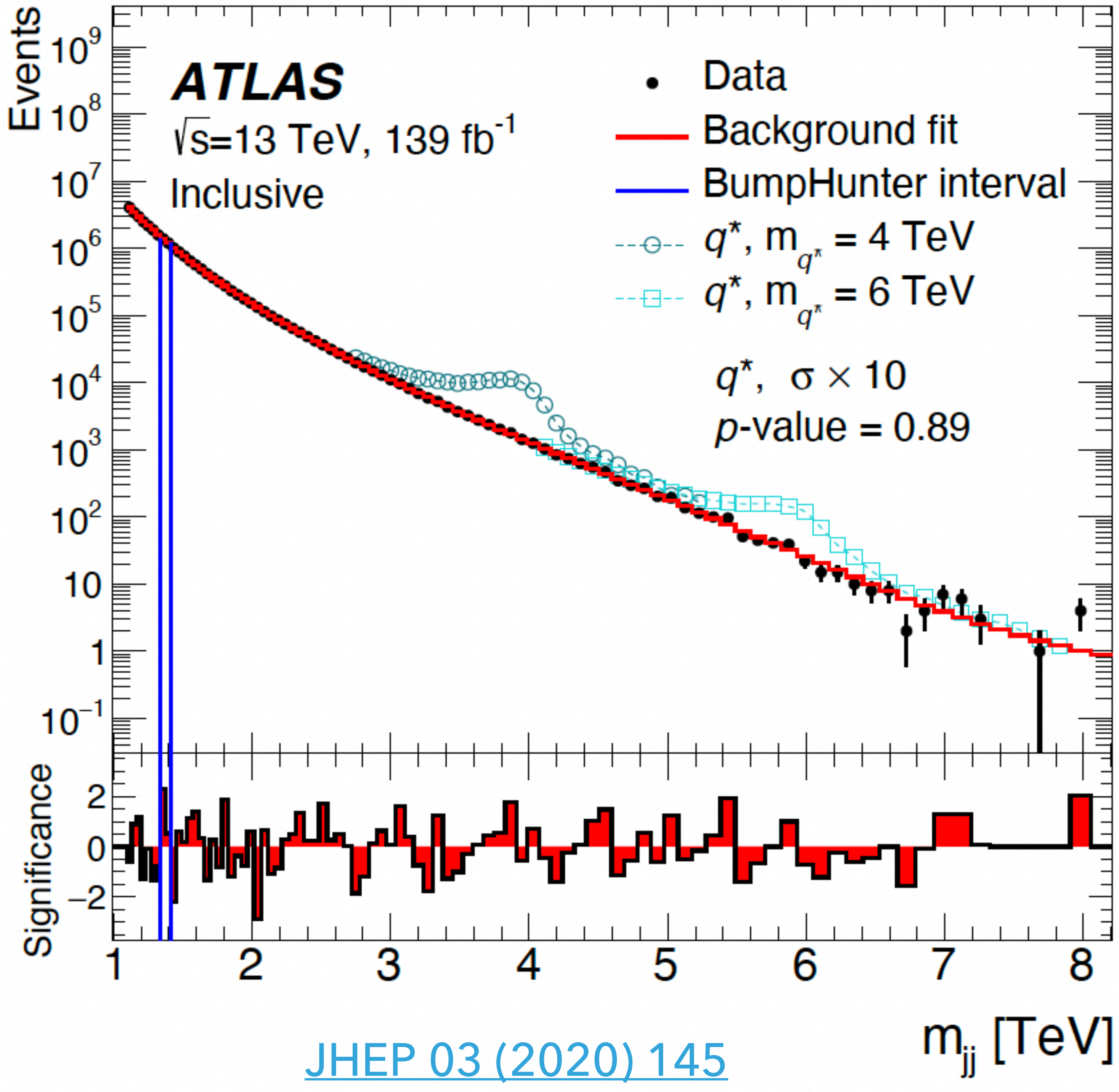


- |Δφ| = 3.1 and |Δη| = 1.06
- Small mass asymmetry = 0.02

Inclusive dijet search in CMS and ATLAS



[JHEP 05 (2020) 033]

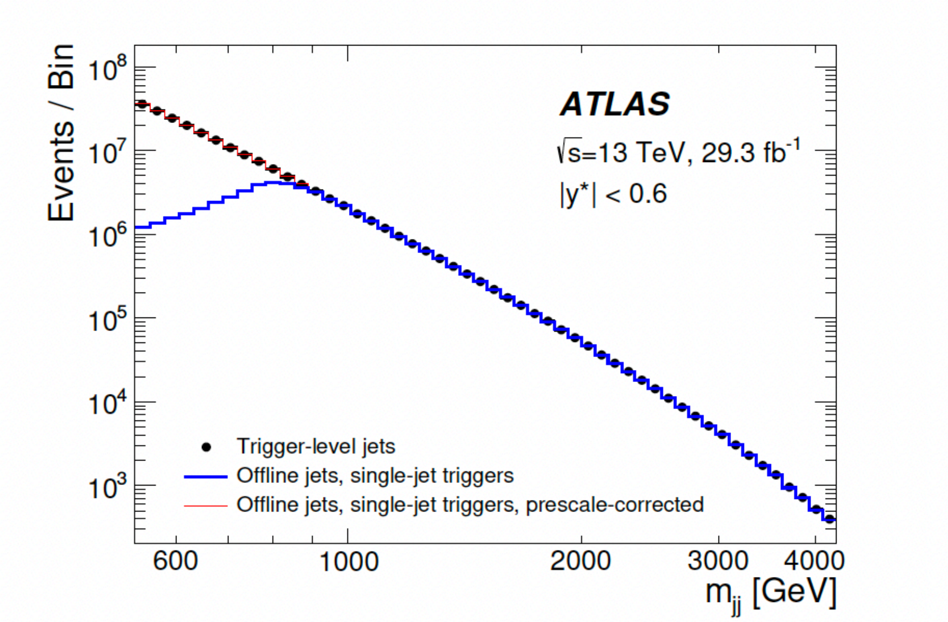


[JHEP 03 (2020) 145]

- Both CMS and ATLAS see some events near or above 8 TeV – something to keep an eye on in Run 3!

ATLAS low mass dijet search

- HLT: jet with pT > 85 GeV and |η| < 2.8
- For 700 GeV < m_{jj} < 1800 GeV, events are required to have y* = (y1-y2)/2 < 0.6
- For m_{jj} > 450 GeV, events are required to have y* = (y1-y2)/2 < 0.3 and E_T > 75 GeV
  - Selects higher-pT jets at a given mjj and thus provides a mass distribution that is unbiased by the leading jet selection from m_{jj} = 450 GeV



What about dijet search in ATLAS?

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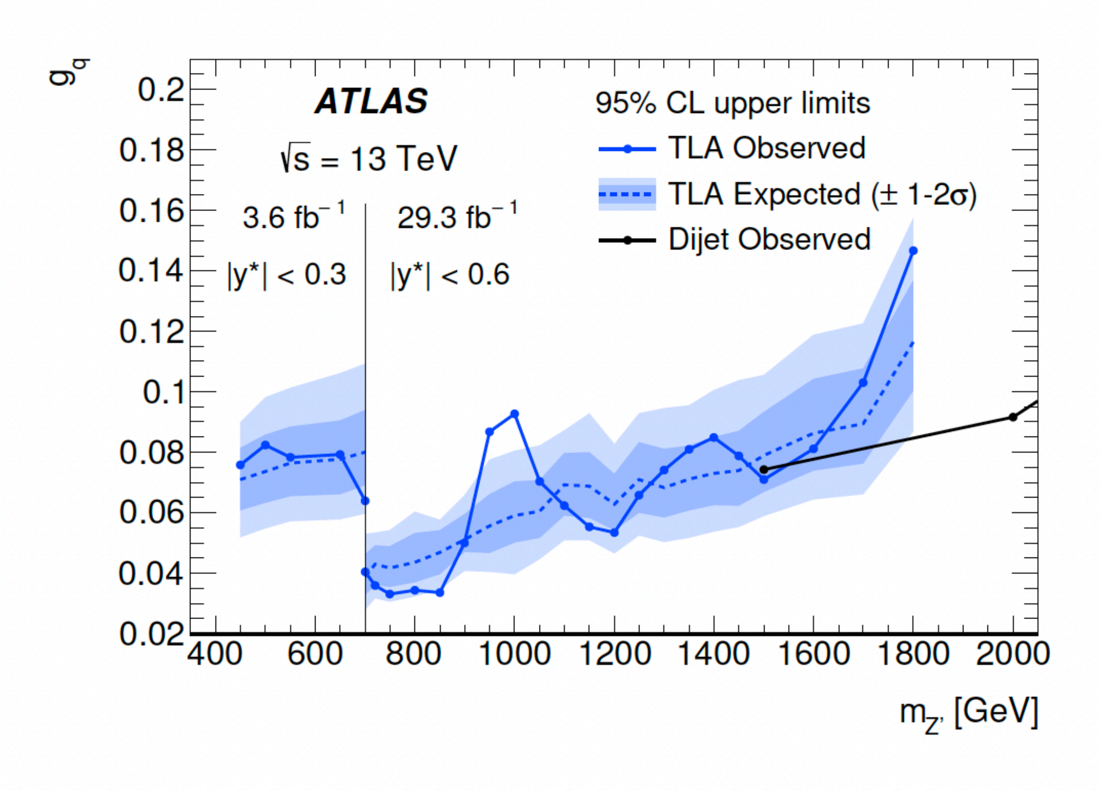


g_q = coupling to the quarks in Z′ model

- Most discrepant interval is 889–1007 GeV
- Corresponds to a global significance of 0.16σ however

- No similar paired dijet analysis in ATLAS for resonant search.
- However there is similar for non-resonant search using scouting data (2016)
  - 450 GeV < m_{jj} < 1800 GeV
- Parametric form to fit the falling background
-

Leptoquarks - CMS

- Model used to generate LQ:
  - $\widetilde{R_2}$ model for scalar LQs
  - U1 model for vector LQs in which LQs couple only to the left-handed fermions of the third generation
  - These can also couple to q-ν in addition to q-l
  - All signal samples generated with β=1, i.e. all decays to q-l
- Kinematic properties independent of λ for λ<1.5, samples with λ=1 are generated. For values higher than that, dedicated production
- κ=1 (Yang-Mills) and 0 (minimal coupling) are considered
- In case of non-resonant production via t-channel, no interference with SM DY process
  - Reduction in the signal yield < 5% for λ>1 and hence negligible
- τh > 50 GeB selected in the analysis

Event selection of leptoquarks

- Resonant:
    - 0b jet and 1 bjet
    - Requirement on $m_{vis} > 100$ GeV to remove DY events
- Non-resonant:
    - $|\eta_1+\eta_2|/2 < 1.1$, $|\Delta\eta| < 3$ between two τ decay candidates
    - Orthogonal to the resonant category by requiring no jets with pT > 50 GeV and hence is called 0jet category
    - Binned in m_{vis} since signal purity increases with m_{vis}
    - $\chi = \exp(\,|\eta(\tau_1) - \eta(\tau_2)|\,)$ as the sensitive variable and measured from $1 < \chi < 30$ implying a maximum value of $|\Delta\eta| = 3.4$

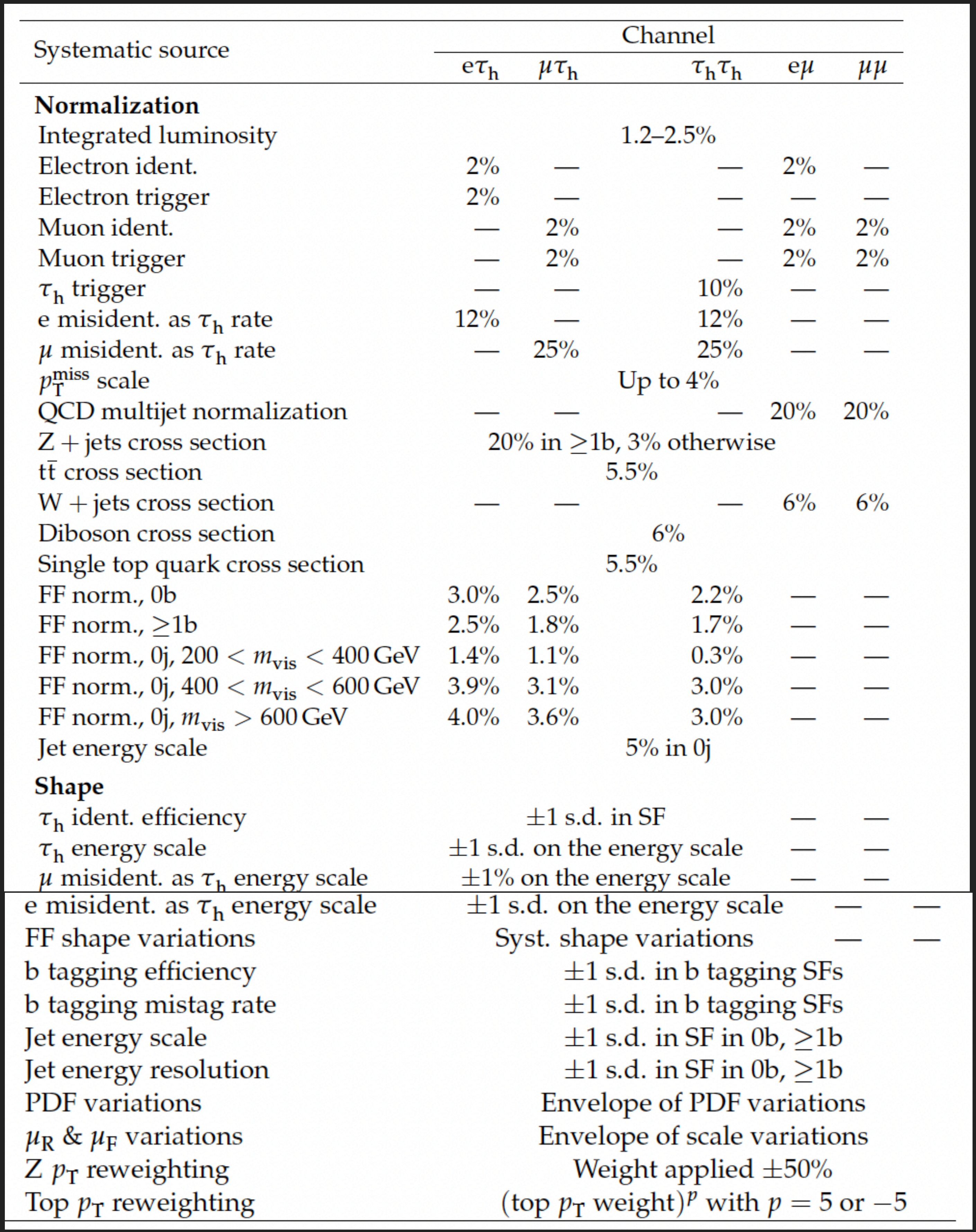
Background estimation in LQs CMS

- $l\tau_h$ and $\tau_h\tau_h$: $j \rightarrow \tau_h$ from data-driven - others from simulation
  - This method is validated in two validation regions: By inverting the leading jet pT requirement, i.e., pT < 50 GeV and other by using those in which τ_h does not pass the tau ID criteria –> good Data MC agreement
- eμ and μμ: Similar approach

LQ - More understanding about the excess

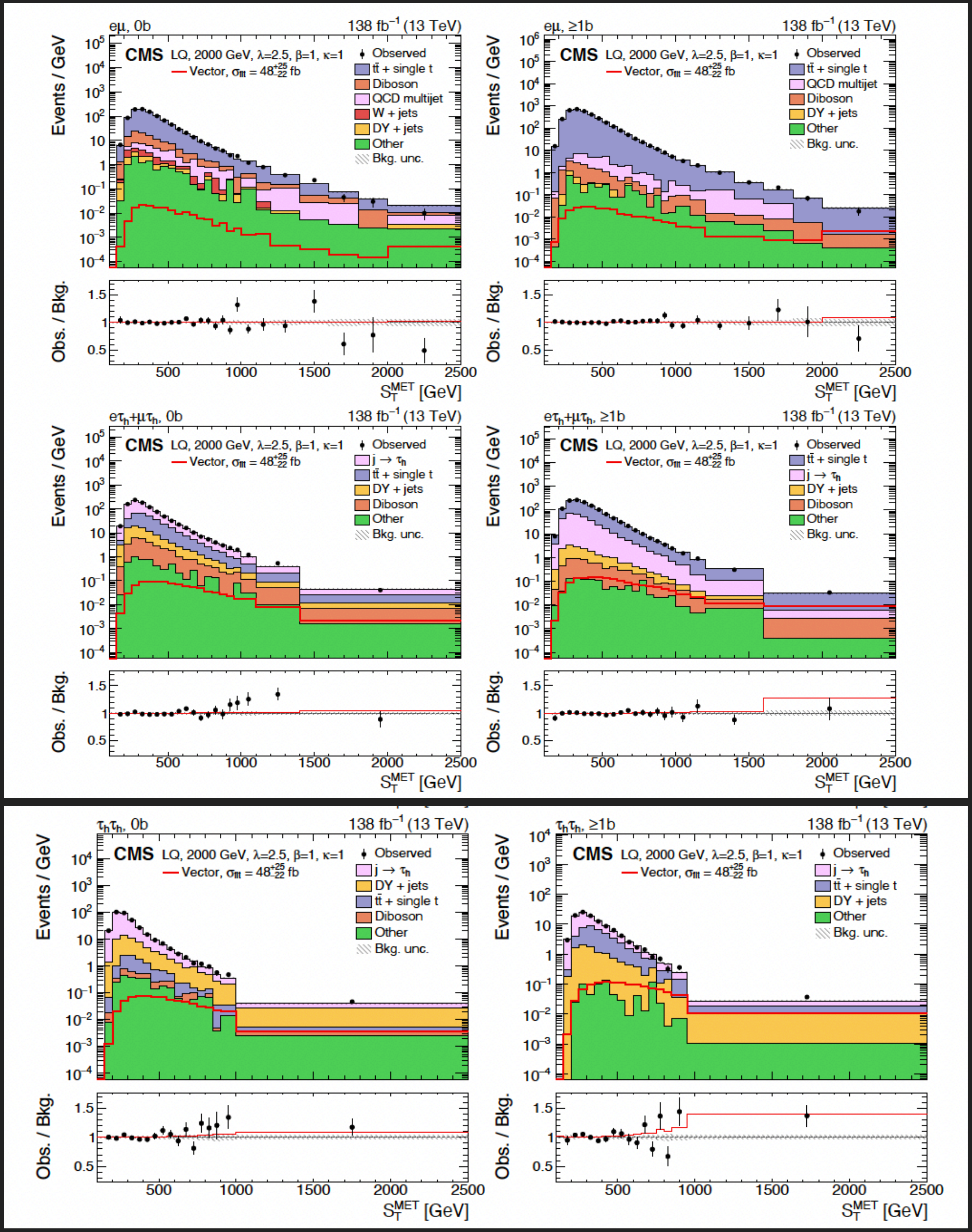
- The fit of the total LQ signal is performed again, bit with one independent signal normalization parameter in each of the three jet categories (0, 0b, >=1b) while keeping common nuisance parameters.
- For each fitted cross-section, a significance is computed while leaving the other two signal normalization parameters freely floating. For the mLQ = 2000 GeV, λ=2.5, the local significances are 0j and >=1b categories ranging from 2.5 to 3.2 and 1.8 to 2.0 σ. However, for the 0b category, a local significance between 3.4 and 3.7 σ is found for the scalar and vector LQ models.

Systematic uncertainties in LQs



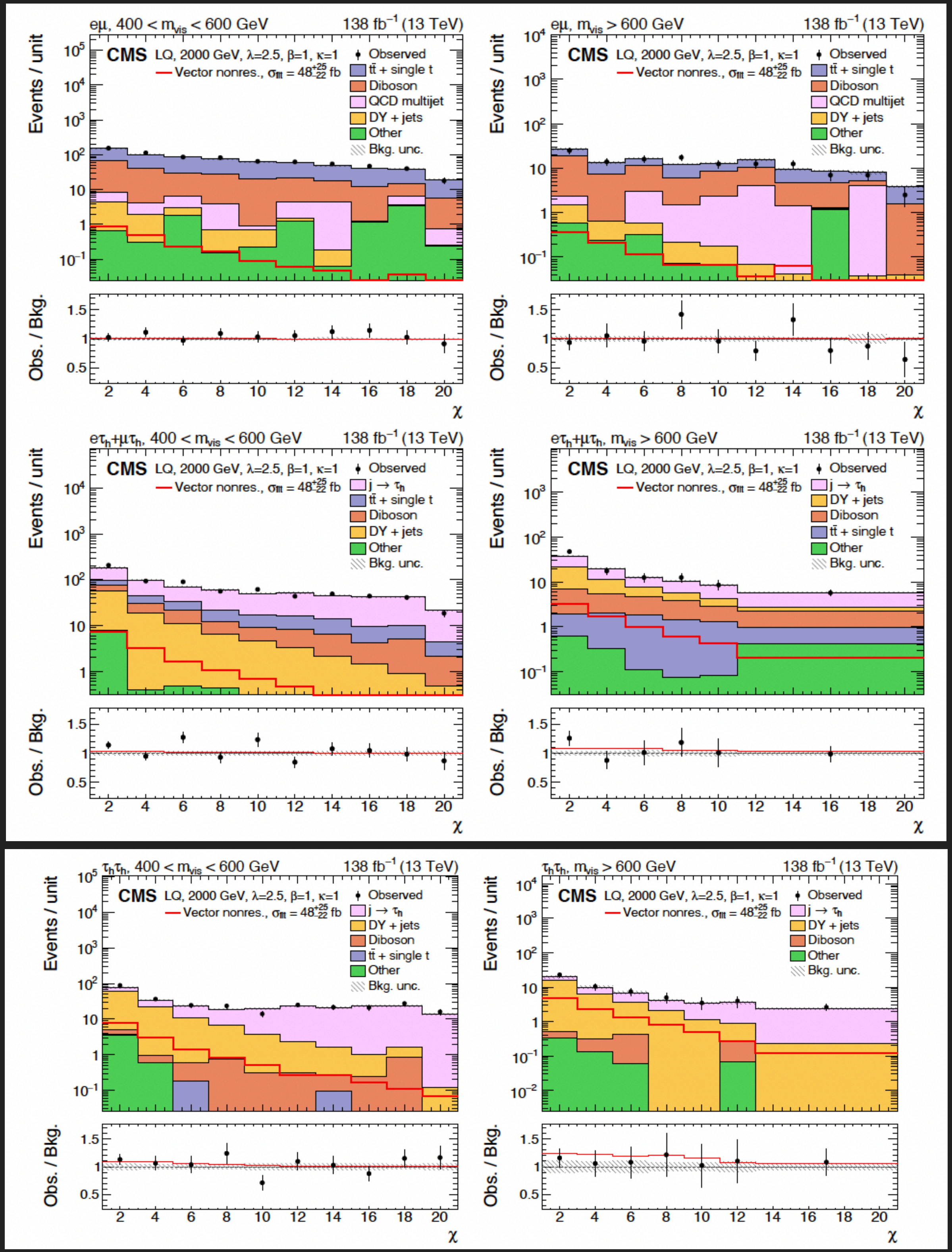
Systematic source	Channel				
	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	$e\mu$	$\mu\mu$
Normalization					
Integrated luminosity	1.2–2.5%				
Electron ident.	2%	—	—	2%	—
Electron trigger	2%	—	—	—	—
Muon ident.	—	2%	—	2%	2%
Muon trigger	—	2%	—	2%	2%
τ_h trigger	—	—	10%	—	—
e misident. as τ_h rate	12%	—	12%	—	—
μ misident. as τ_h rate	—	25%	25%	—	—
p_T^{miss} scale	Up to 4%				
QCD multijet normalization	—	—	—	20%	20%
Z + jets cross section	20% in $\geq$1b, 3% otherwise				
$t\bar{t}$ cross section	5.5%				
W + jets cross section	—	—	—	6%	6%
Diboson cross section	6%				
Single top quark cross section	5.5%				
FF norm., 0b	3.0%	2.5%	2.2%	—	—
FF norm., $\geq$1b	2.5%	1.8%	1.7%	—	—
FF norm., 0j, $200 < m_{vis} < 400$ GeV	1.4%	1.1%	0.3%	—	—
FF norm., 0j, $400 < m_{vis} < 600$ GeV	3.9%	3.1%	3.0%	—	—
FF norm., 0j, $m_{vis} > 600$ GeV	4.0%	3.6%	3.0%	—	—
Jet energy scale	5% in 0j				
Shape					
τ_h ident. efficiency	±1 s.d. in SF			—	—
τ_h energy scale	±1 s.d. on the energy scale			—	—
μ misident. as τ_h energy scale	±1% on the energy scale			—	—
e misident. as τ_h energy scale	±1 s.d. on the energy scale			—	—
FF shape variations	Syst. shape variations			—	—
b tagging efficiency	±1 s.d. in b tagging SFs				
b tagging mistag rate	±1 s.d. in b tagging SFs				
Jet energy scale	±1 s.d. in SF in 0b, $\geq$1b				
Jet energy resolution	±1 s.d. in SF in 0b, $\geq$1b				
PDF variations	Envelope of PDF variations				
μ_R & μ_F variations	Envelope of scale variations				
Z p_T reweighting	Weight applied ±50%				
Top p_T reweighting	(top p_T weight)^p with $p = 5$ or -5				

Post fit plots in LQs (resonance)



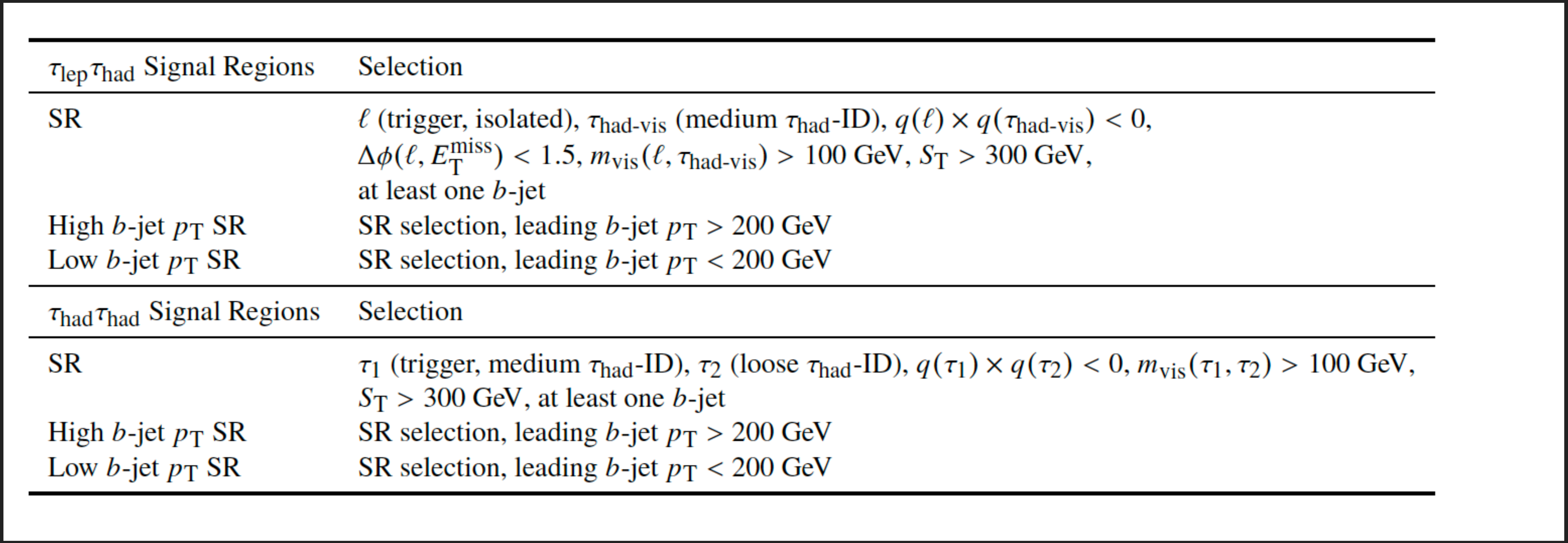
- S_T^{MET} distribution in all the 3 channels for 0b and >=1b jet categories.
- Signal is m_{LQ} = 2000 GeV with λ=2.5 and κ=1 –> normalized to the best-fit xsec
- Binning is such that the total uncertainty in the SM background < 20%

Post fit plots in LQs (non-resonance)



- χ distribution in all the 3 channels for 0 jet category.
- Signal is m_{LQ} = 2000 GeV with λ=2.5 and κ=1 –> normalized to the best-fit xsec
- Binning is such that the total uncertainty in the SM background < 20%

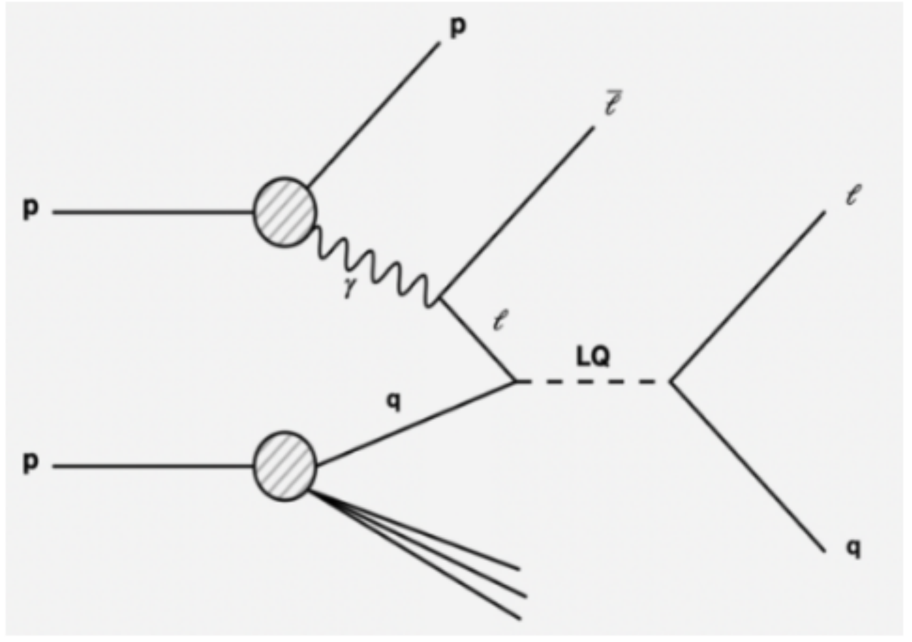
ATLAS LQs selection

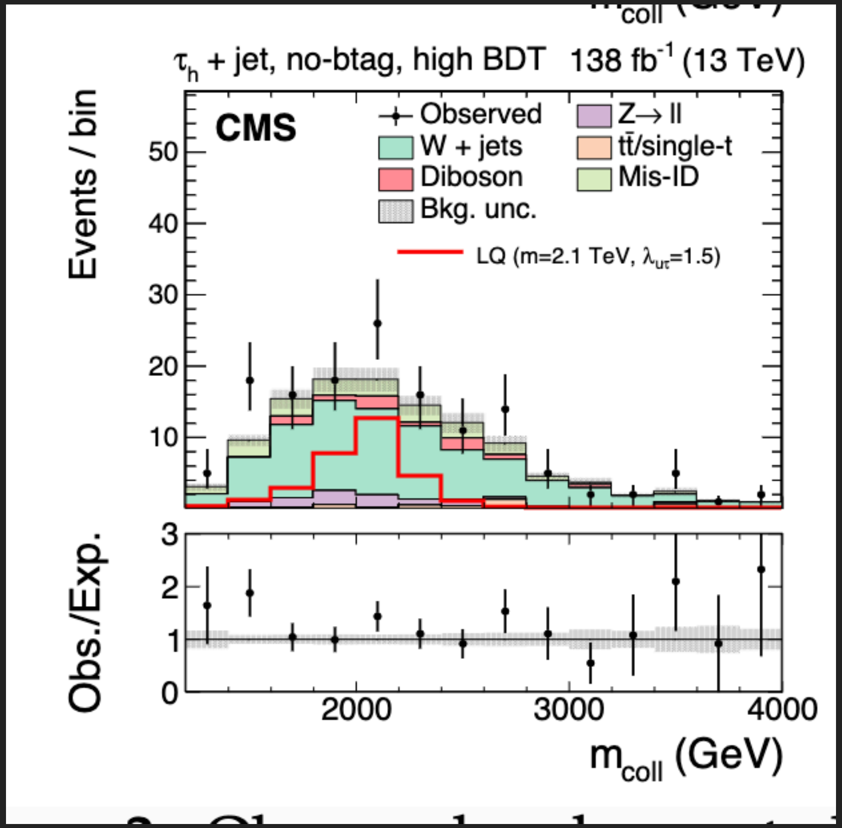


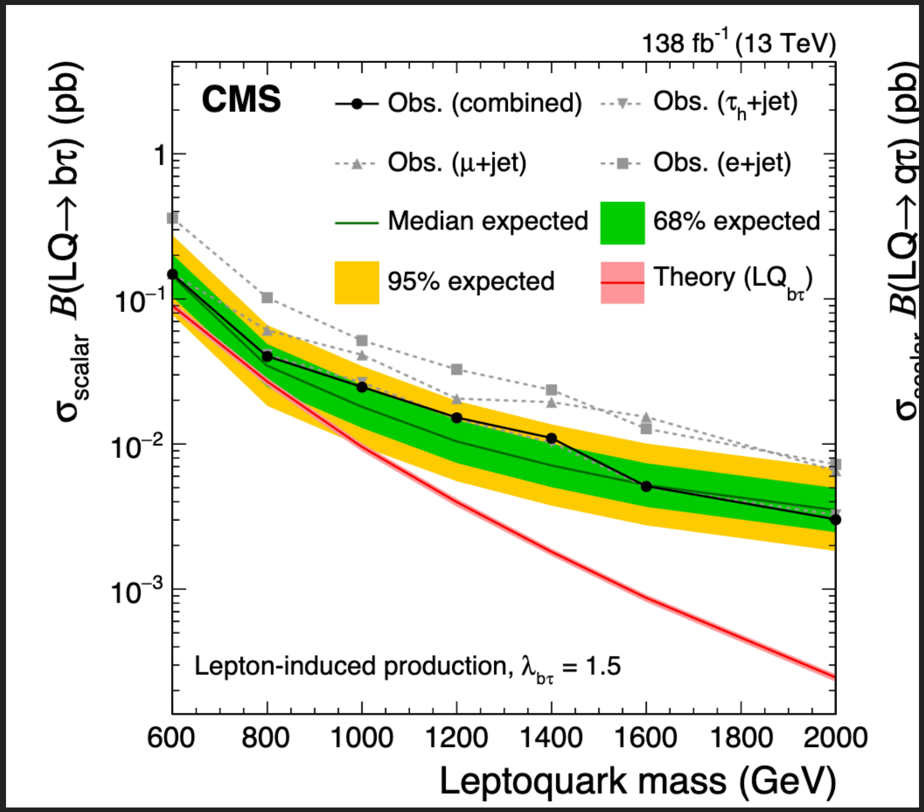
$\tau_{\text{lep}}\tau_{\text{had}}$ Signal Regions	Selection
SR	ℓ (trigger, isolated), $\tau_{\text{had-vis}}$ (medium τ_{had}-ID), $q(\ell) \times q(\tau_{\text{had-vis}}) < 0$, $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}}) < 1.5$, $m_{\text{vis}}(\ell, \tau_{\text{had-vis}}) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet
High b-jet p_{T} SR	SR selection, leading b-jet $p_{\text{T}} > 200$ GeV
Low b-jet p_{T} SR	SR selection, leading b-jet $p_{\text{T}} < 200$ GeV
$\tau_{\text{had}}\tau_{\text{had}}$ Signal Regions	Selection
SR	τ_1 (trigger, medium τ_{had}-ID), τ_2 (loose τ_{had}-ID), $q(\tau_1) \times q(\tau_2) < 0$, $m_{\text{vis}}(\tau_1, \tau_2) > 100$ GeV, $S_{\text{T}} > 300$ GeV, at least one b-jet
High b-jet p_{T} SR	SR selection, leading b-jet $p_{\text{T}} > 200$ GeV
Low b-jet p_{T} SR	SR selection, leading b-jet $p_{\text{T}} < 200$ GeV

arXiv: 2308.06143

LeptoQuarks in Lepton Quark collision







- Recent calculation of lepton PDFs at NLO:
    - Xsec unc < 5% for M < 5 TeV
    - xsec scales with λ^2 –> higher than single LQ gluon initiated process
- Larger sensitivity at high mass and coupling

High mass resonance - CMS

- Common models are Generalized Sequential Model (GSM) containing the sequential SM boson Z'_{SSM}
  - It has SM-like couplings to SM fermions
- LRS extension of the SM based on $SU(2)_L$ X $SU(2)_R$ X $U(1)_{B-L}$ gauge group, B-L refers to the difference the baryon and the lepton numbers
- Narrow width approximation, production cross-section of $Z' = c_u w_u + c_d w_d$, where c's are coupling to the quarks and w's are the pdfs
- With the change of couplings due to mixing of U(1) generators, each class of model has a definite contour in (c_u, c_d) plane
- Also, finite width resonance (12% in width) has similar results as that obtained using narrow width approximation
- DM model: DM interacts with the SM via spin-1 mediator (vector or axial vector)

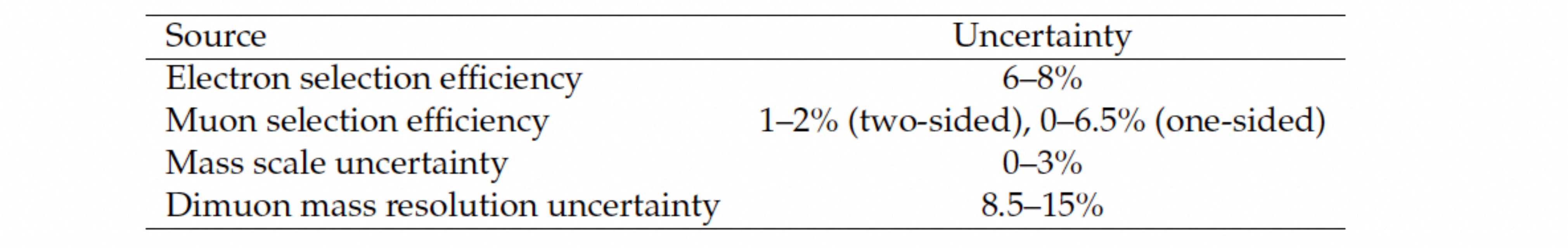
$$\frac{d\sigma_{X\to\ell\ell}}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} + \eta_X \mathcal{I}(m_{\ell\ell}) + \eta_X^2 \mathcal{S}(m_{\ell\ell}),$$

Non-resonant

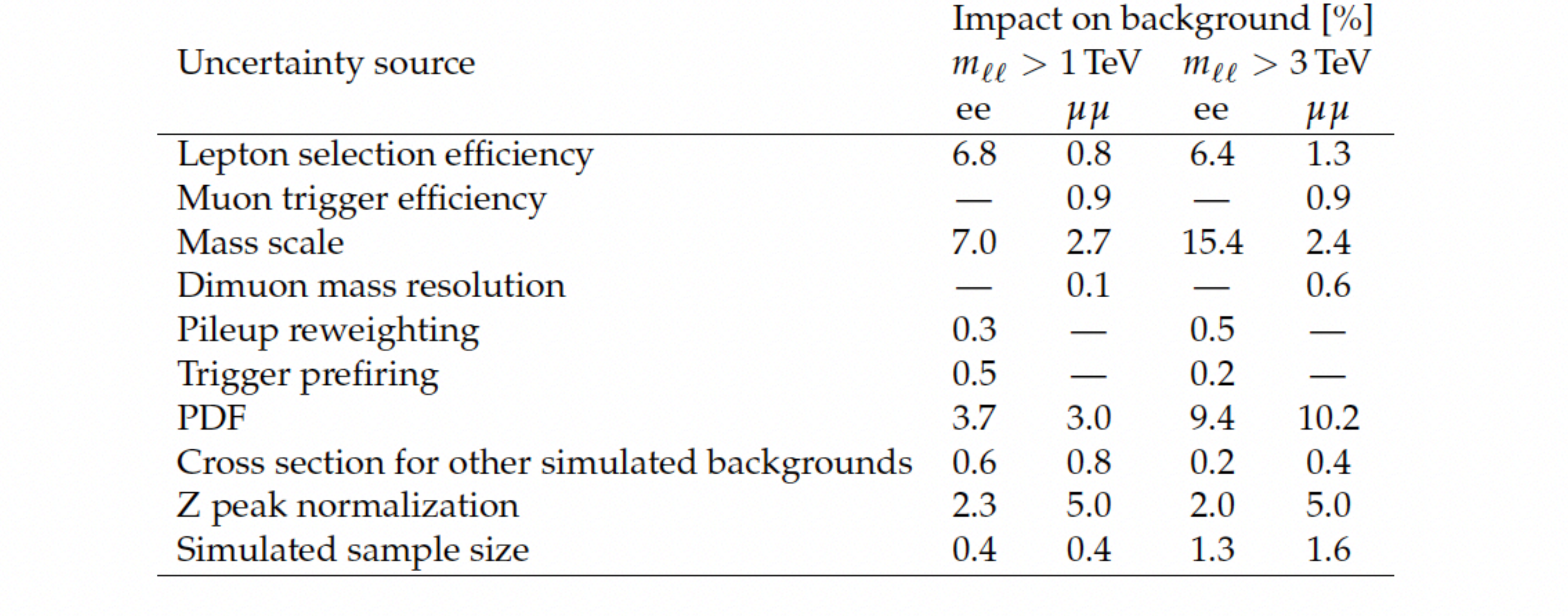
Selection on ee, μμ

- Di-electron channel: No opposite charge requirement since that would result in efficiency loss of 10% for masses of several TeVs
- For muons, it is required since the charge mis-identification probability is low: 10^{-2} for muon momentum of 2 TeV

Sources of systematics in high pT (ee, μμ) search



Source	Uncertainty
Electron selection efficiency	6–8%
Muon selection efficiency	1–2% (two-sided), 0–6.5% (one-sided)
Mass scale uncertainty	0–3%
Dimuon mass resolution uncertainty	8.5–15%



Uncertainty source	Impact on background [%]			
	$m_{\ell\ell} > 1\,\text{TeV}$		$m_{\ell\ell} > 3\,\text{TeV}$	
	ee	$\mu\mu$	ee	$\mu\mu$
Lepton selection efficiency	6.8	0.8	6.4	1.3
Muon trigger efficiency	—	0.9	—	0.9
Mass scale	7.0	2.7	15.4	2.4
Dimuon mass resolution	—	0.1	—	0.6
Pileup reweighting	0.3	—	0.5	—
Trigger prefiring	0.5	—	0.2	—
PDF	3.7	3.0	9.4	10.2
Cross section for other simulated backgrounds	0.6	0.8	0.2	0.4
Z peak normalization	2.3	5.0	2.0	5.0
Simulated sample size	0.4	0.4	1.3	1.6

Background fits in the di-electron and di-muon channels

Electron

$$\begin{cases} m^{\kappa} \exp\left(\sum_{i=0}^{3} \alpha_i m^i\right), & \text{if } m \le m_{\text{threshold}}, \\ m^{\lambda} \exp\left(\sum_{i=0}^{3} \beta_i m^i\right), & \text{if } m > m_{\text{threshold}}, \end{cases}$$

Muon

$$\begin{cases} m^{\mu} \exp\left(\sum_{i=0}^{2} \gamma_i m^i\right), & \text{if } m \le m_{\text{threshold}}, \\ m^{\nu} \exp\left(\sum_{i=0}^{3} \delta_i m^i\right), & \text{if } m > m_{\text{threshold}}. \end{cases}$$

- $m_{\text{threshold}}$ is left floating and ranges from 350 to 750 GeV in the muon channel
- In the electron channel, it is set to 600 GeV
- Limits are calculated in a mass window of +/- 4 times the signal width. This window is symmetrically enlarged until there is a minimum of 100 data events in it (10% stat unc)
    - Dominates at high mass
- Background parameterization uncertainty for high mass resonance is a crucial one. Therefore results only above 700 geV

High pT Di-lepton: LFUV

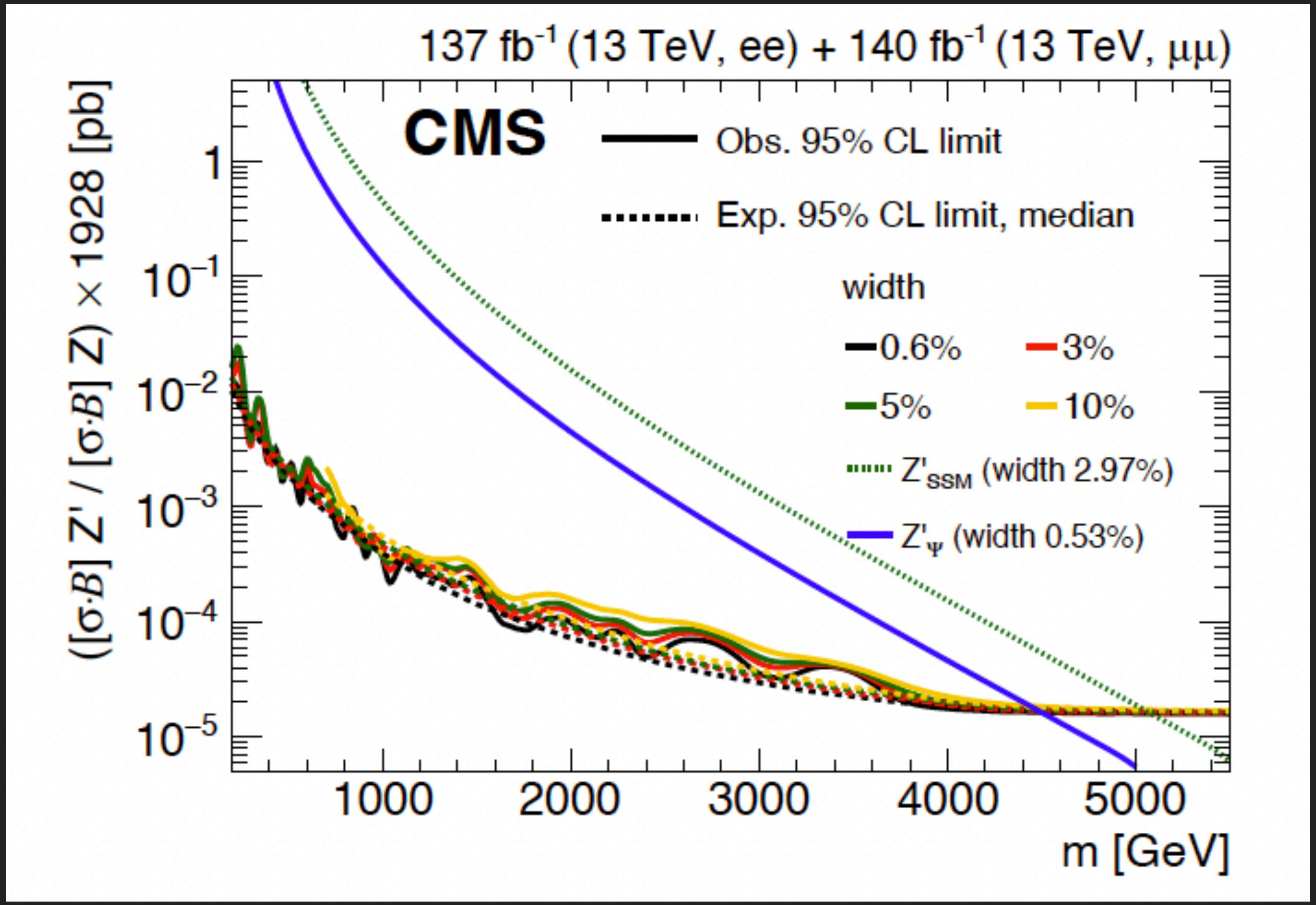
- After normalizing to unity in the region of 200-400 GeV, to account for the remaining mass between the two channels, $R_{\mu^+\mu^-/e^+e^-}$ is measured in the simulation of DY events (following full chain from selection –> unfolding)
  - Inverse of this correction is used to correct the above quantity in data.
    - Size of these corrections: 5% for central leptons and as large as 20% for forward leptons
- Uncertainties like PDF cancel in the flavour ratio

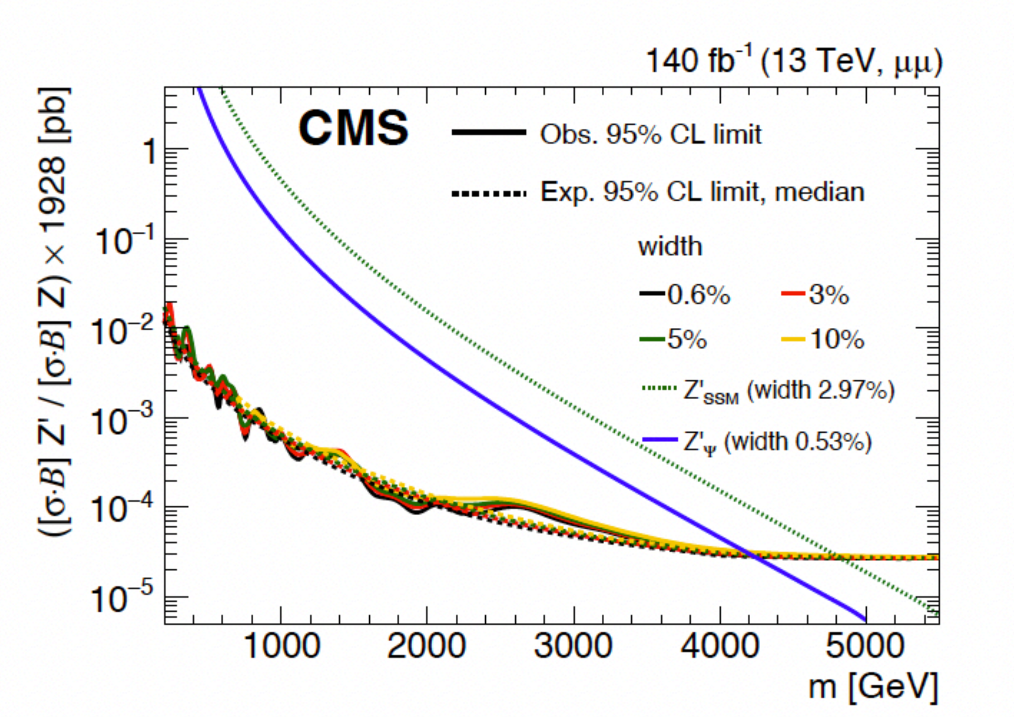
Resonant ee, μμ searches

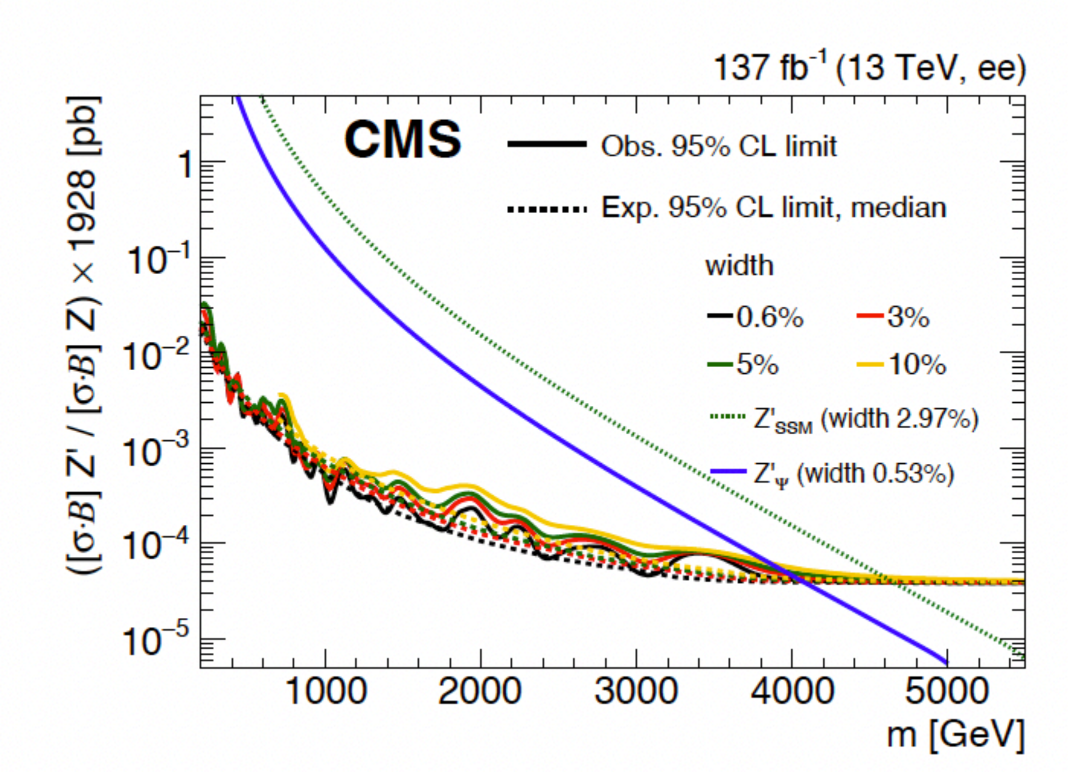
- Quote the upper limit on:

$$R_\sigma = \frac{\sigma(\mathrm{pp} \to \mathrm{Z}' + \mathrm{X} \to \ell\ell + \mathrm{X})}{\sigma(\mathrm{pp} \to \mathrm{Z} + \mathrm{X} \to \ell\ell + \mathrm{X})}.$$

  - This cancels/reduces the common uncertainties
  - Exclude mass below 5.15 TeV for the Z'_{SSM} and 4.56 TeV for Z'_{ψ}
    - Valid for all widths at high mass (negligible background)





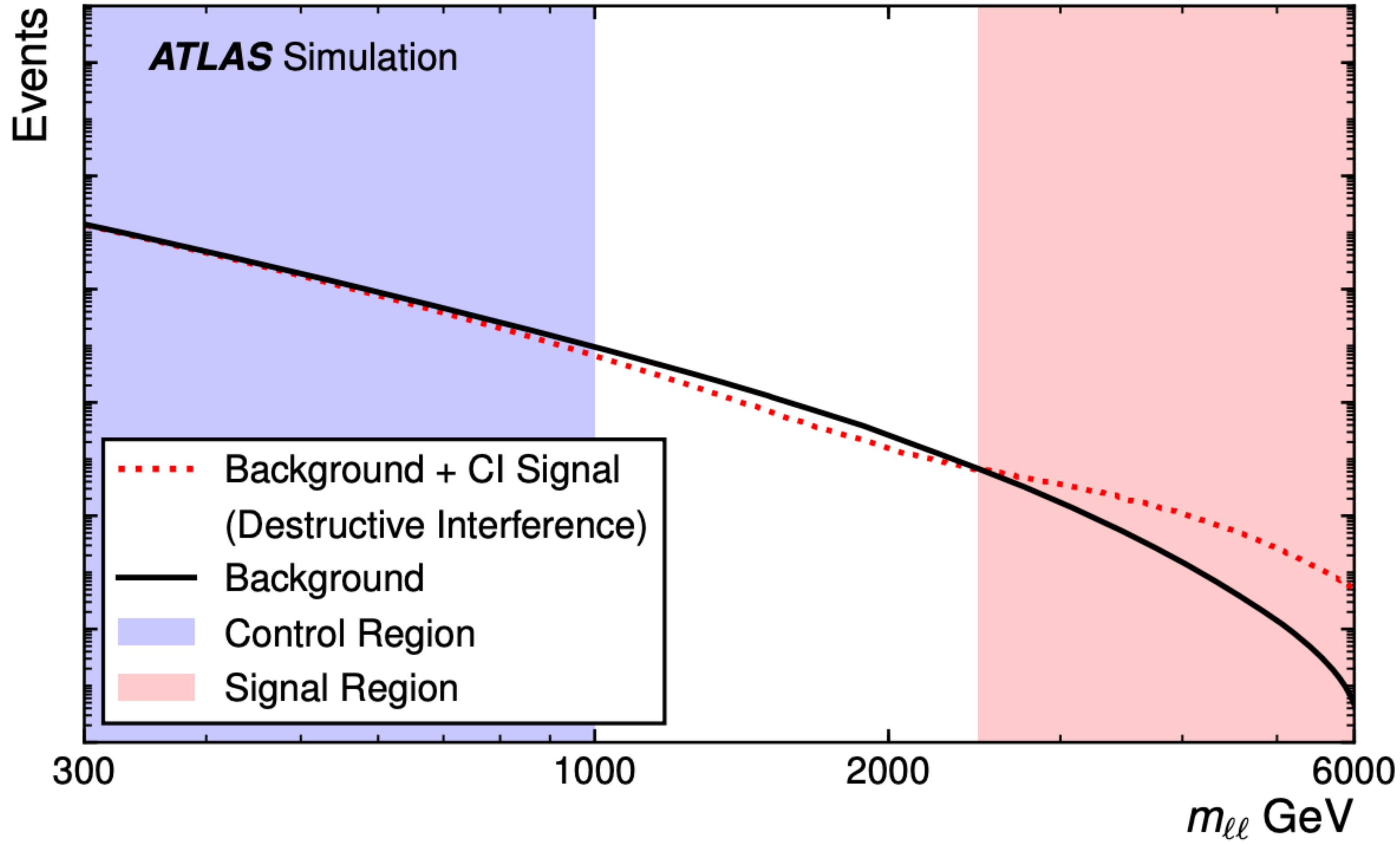


ATLAS dilepton search

background modeling in resonant search

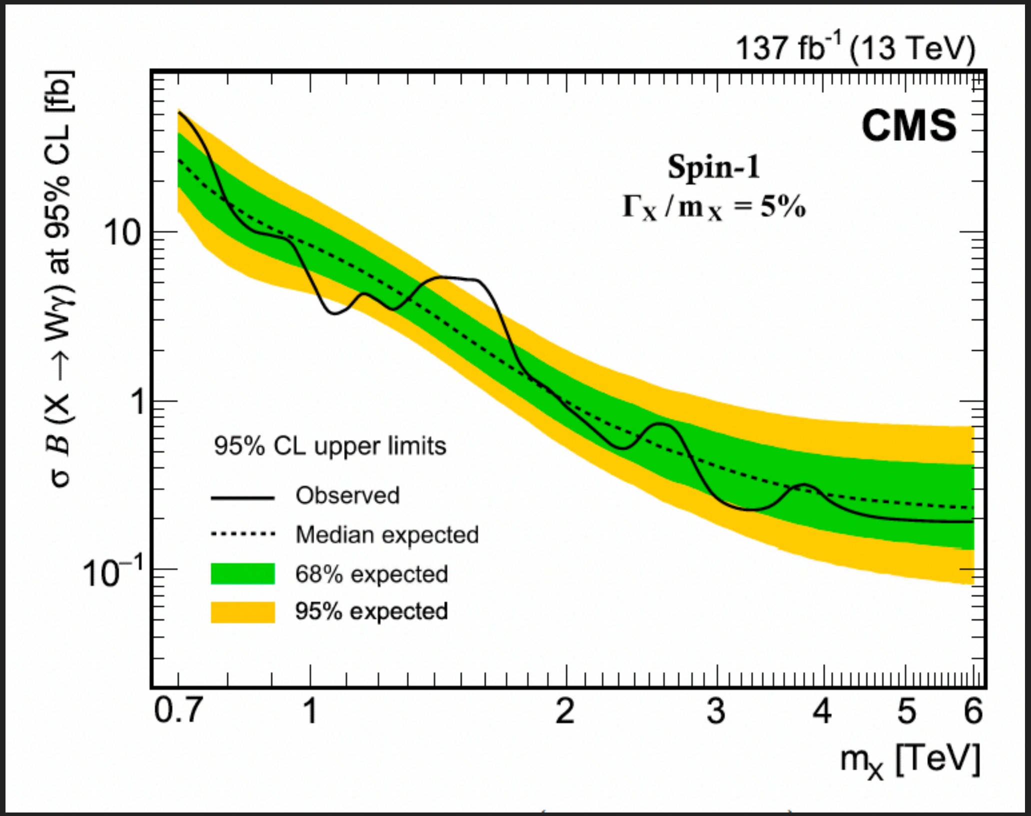
$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW},Z}(m_{\ell\ell}) \cdot (1 - x^{c})^{b} \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i},$$

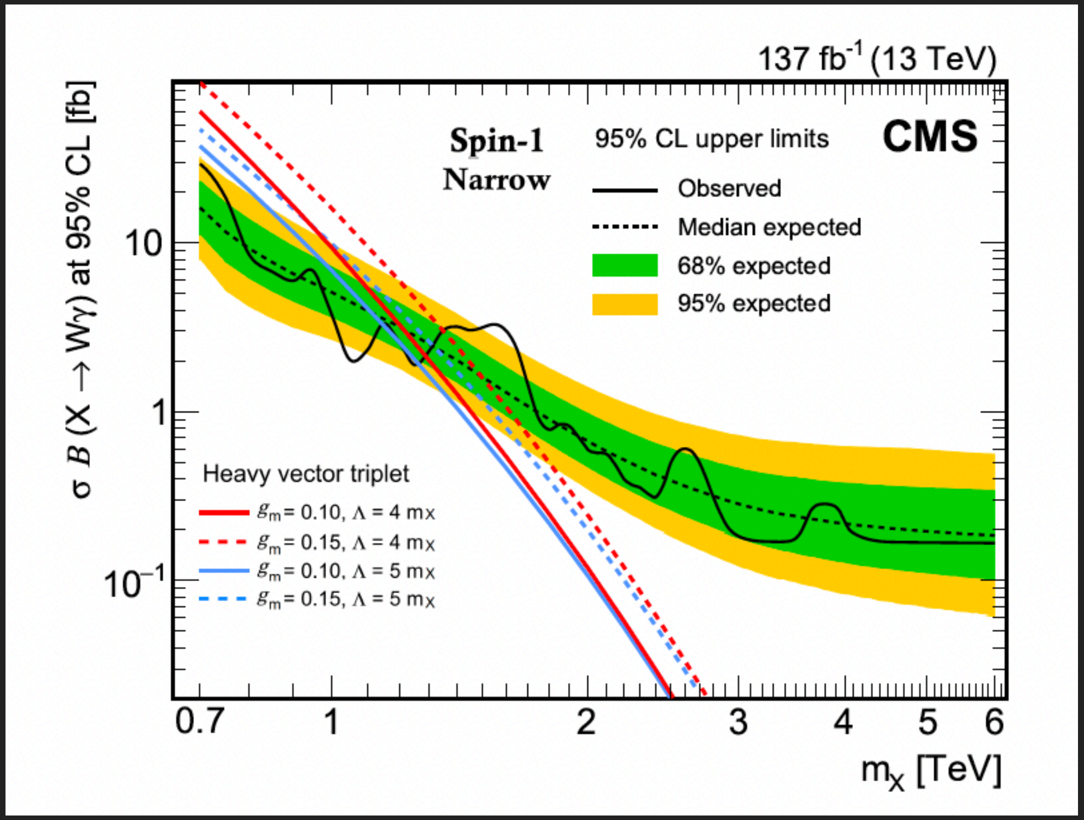
background modeling in non-resonant search



- Fitted in CR and extrapolated to the SR
- In order to avoid any effects of destructive interference arising in the CR, a gap between the CR and SR is allowed

Wγ resonance search in CMS in jet+γ final state

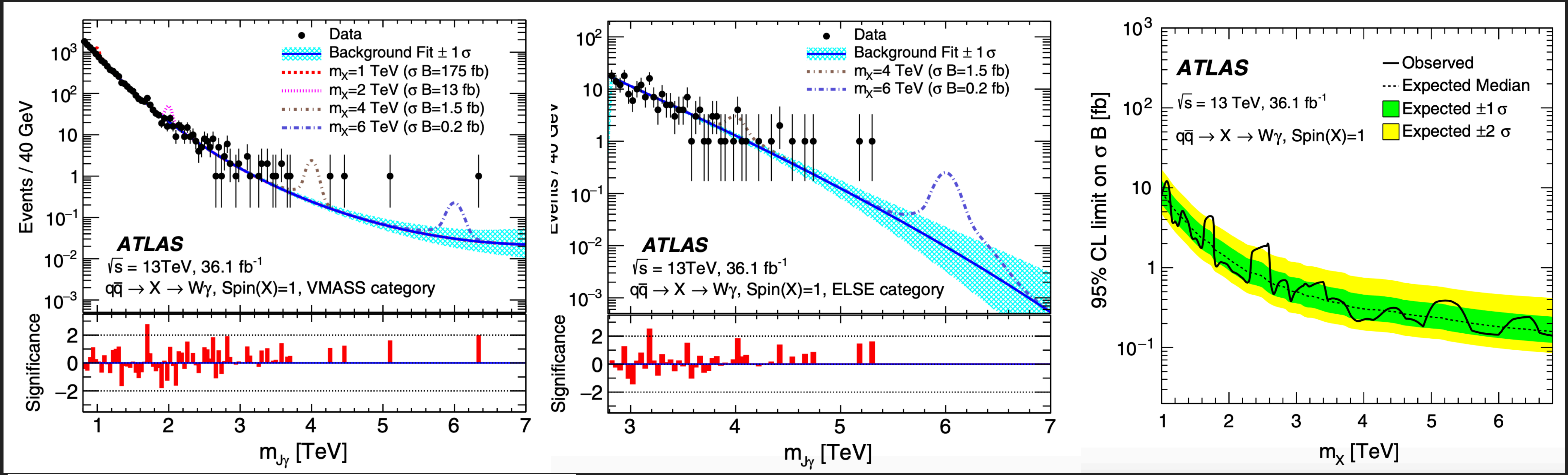


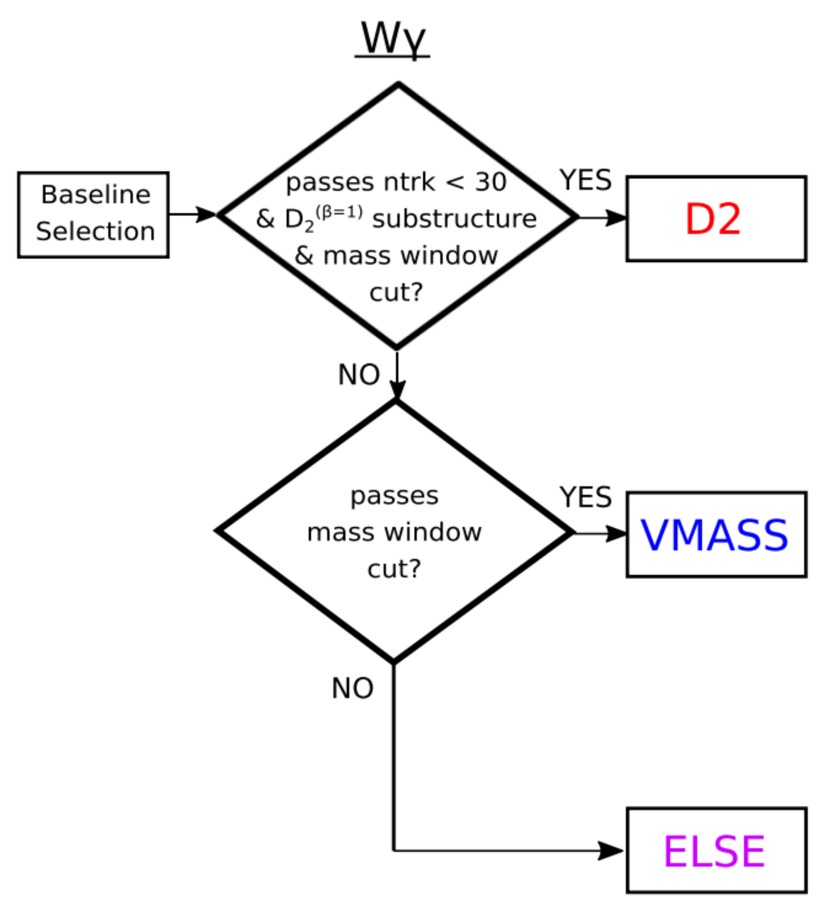


High mass resonance –> Boosted resonance + gluon

- Signal samples generated for ρ_m = 0.1 and 0.2 with G_{kk} masses between 2 and 9 TeV in steps of 1 TeV
- Specific choice of g_{grav} and g_{GKK} does not affect the decay kinematics but only modifies the signal cross-section

Wγ resonance search in ATLAS in jet+γ final state





Wγ

Baseline Selection

passes ntrk < 30 & $D_2^{(\beta=1)}$ substructure & mass window cut?

YES

D2

NO

passes mass window cut?

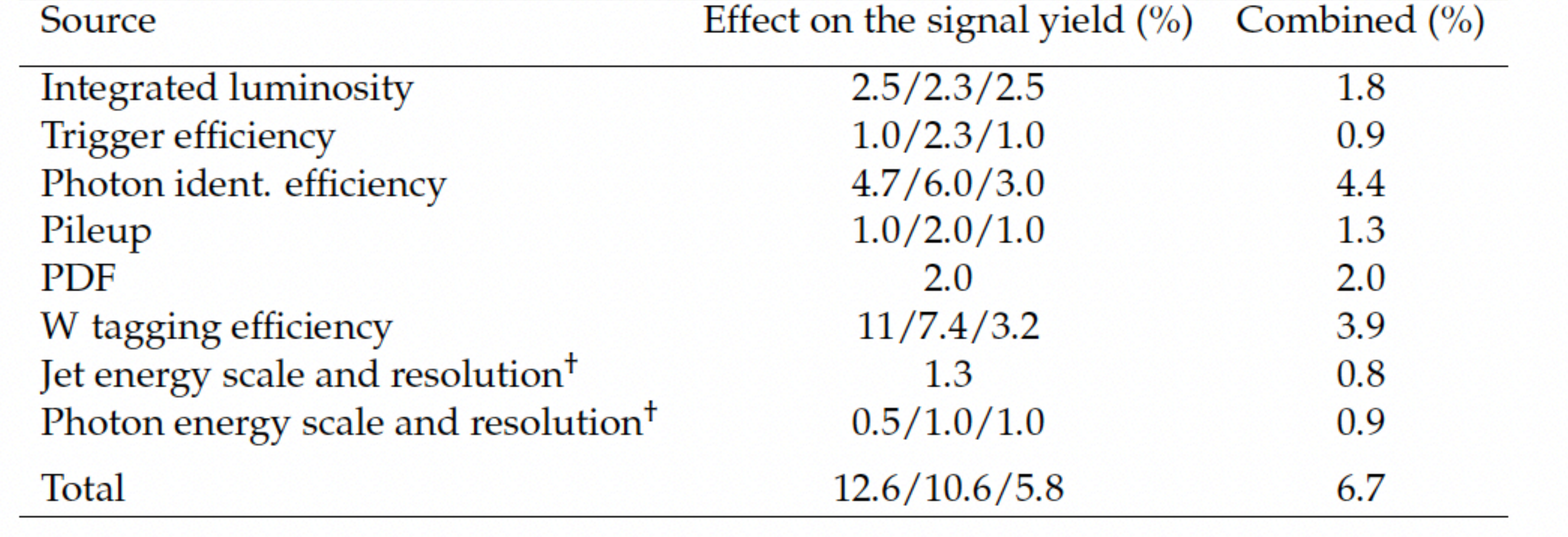
YES

VMASS

NO

ELSE

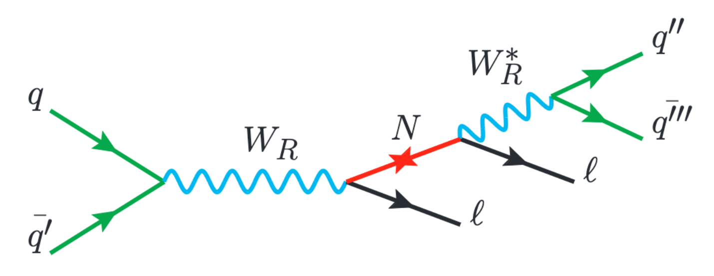
Systematics in Wγ resonance search in CMS



Source	Effect on the signal yield (%)	Combined (%)
Integrated luminosity	2.5/2.3/2.5	1.8
Trigger efficiency	1.0/2.3/1.0	0.9
Photon ident. efficiency	4.7/6.0/3.0	4.4
Pileup	1.0/2.0/1.0	1.3
PDF	2.0	2.0
W tagging efficiency	11/7.4/3.2	3.9
Jet energy scale and resolution†	1.3	0.8
Photon energy scale and resolution†	0.5/1.0/1.0	0.9
Total	12.6/10.6/5.8	6.7

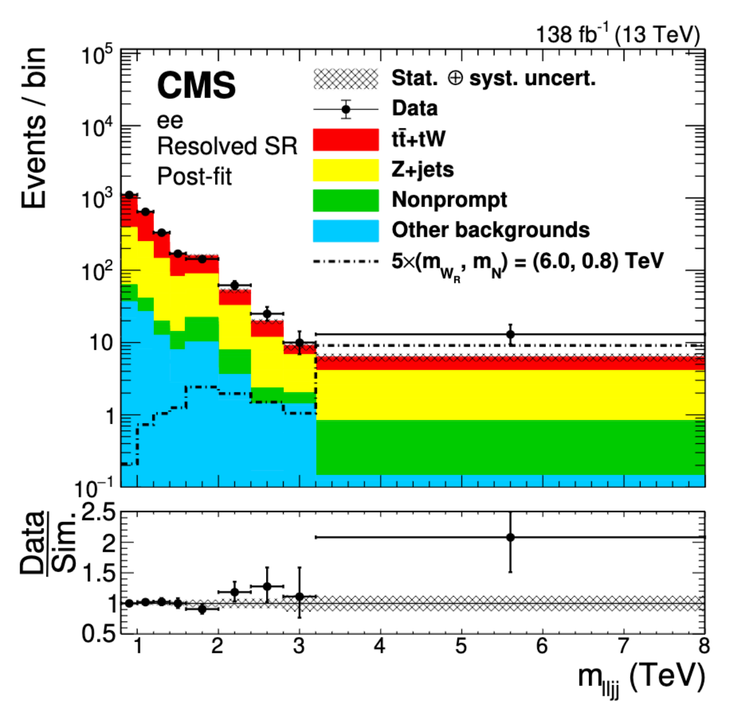
CMS: Search for right-handed W boson and a heavy neutrino

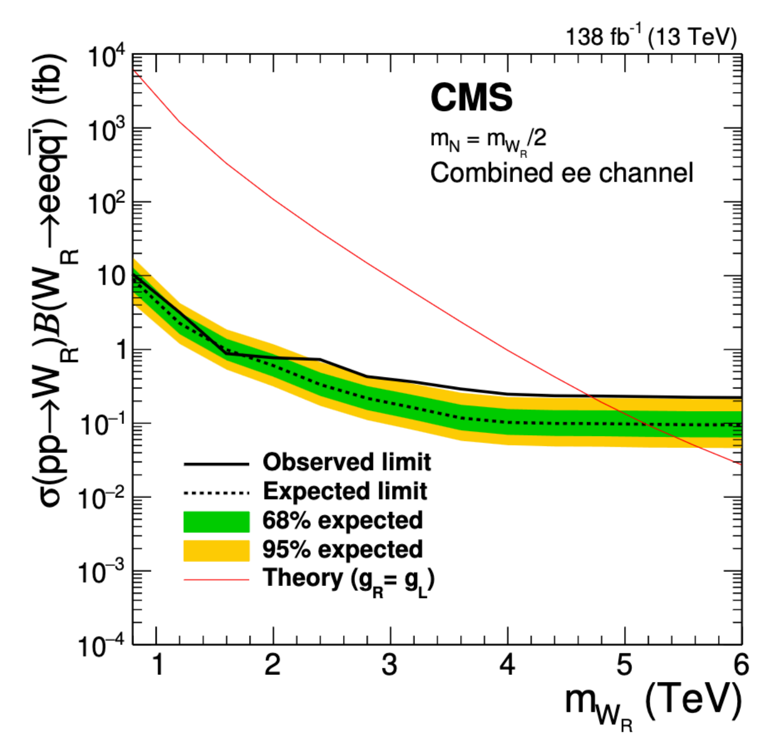
- Final state: 2 same-flavor leptons (ee or μμ) + 2 quarks

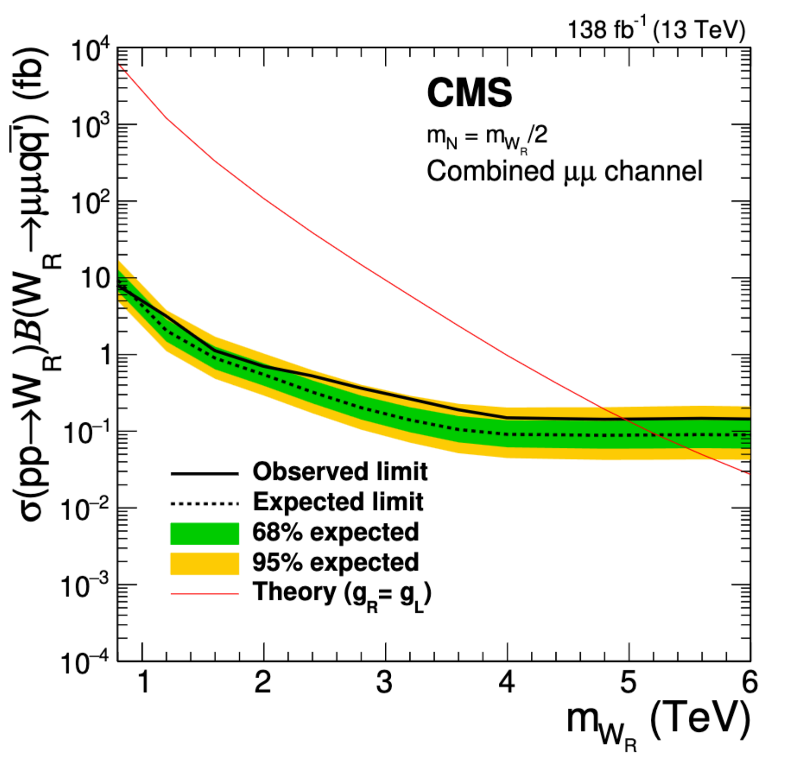


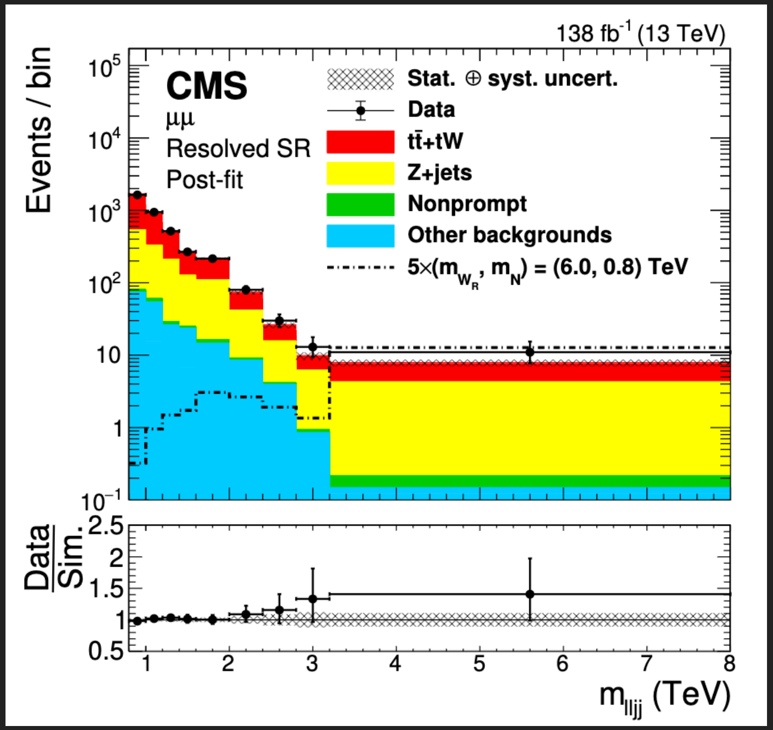
[JHEP04 (2022) 047](https://doi.org/10.1007/JHEP04(2022)047)

- Motivated by Left-Right symmetric models (to explain parity violation, neutrino mass)
  - Predicts a heavy, right handed gauge boson (heavy partner of the SM W boson): W_R
  - Heavy right-handed neutrino for each lepton flavor: N
- Most extreme p-value occurs in the electron channel for (m_{WR}, m_N) = (6.0, 0.8) TeV with a local (global) significance of 2.9 (2.78)σ









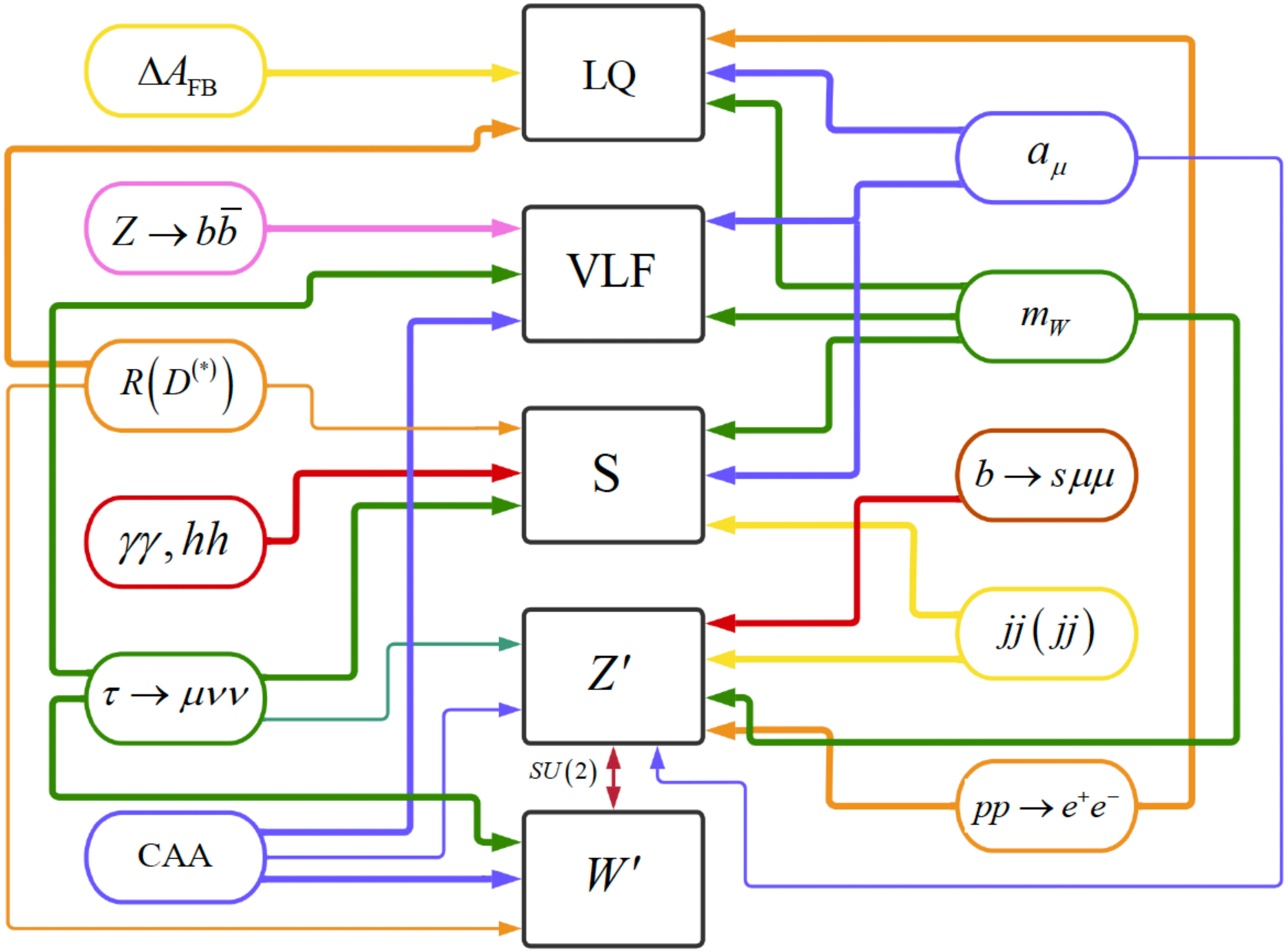


Figure 4: Summary of the anomalies together with the implications for extending the SM with new particles: Leptoquarks (LQ), vector-like fermions (VLF), electrically neutral scalars (S), neural gauge bosons (Z') and charged gauge bosons (W'). Thick lines indicate that full explanations are possible while thin lines mean that only a partial one is or that conflicts with other observables exist.

Ref: Andreas Crevellin
arXiv: 2304.01684

Status of charged current LFU

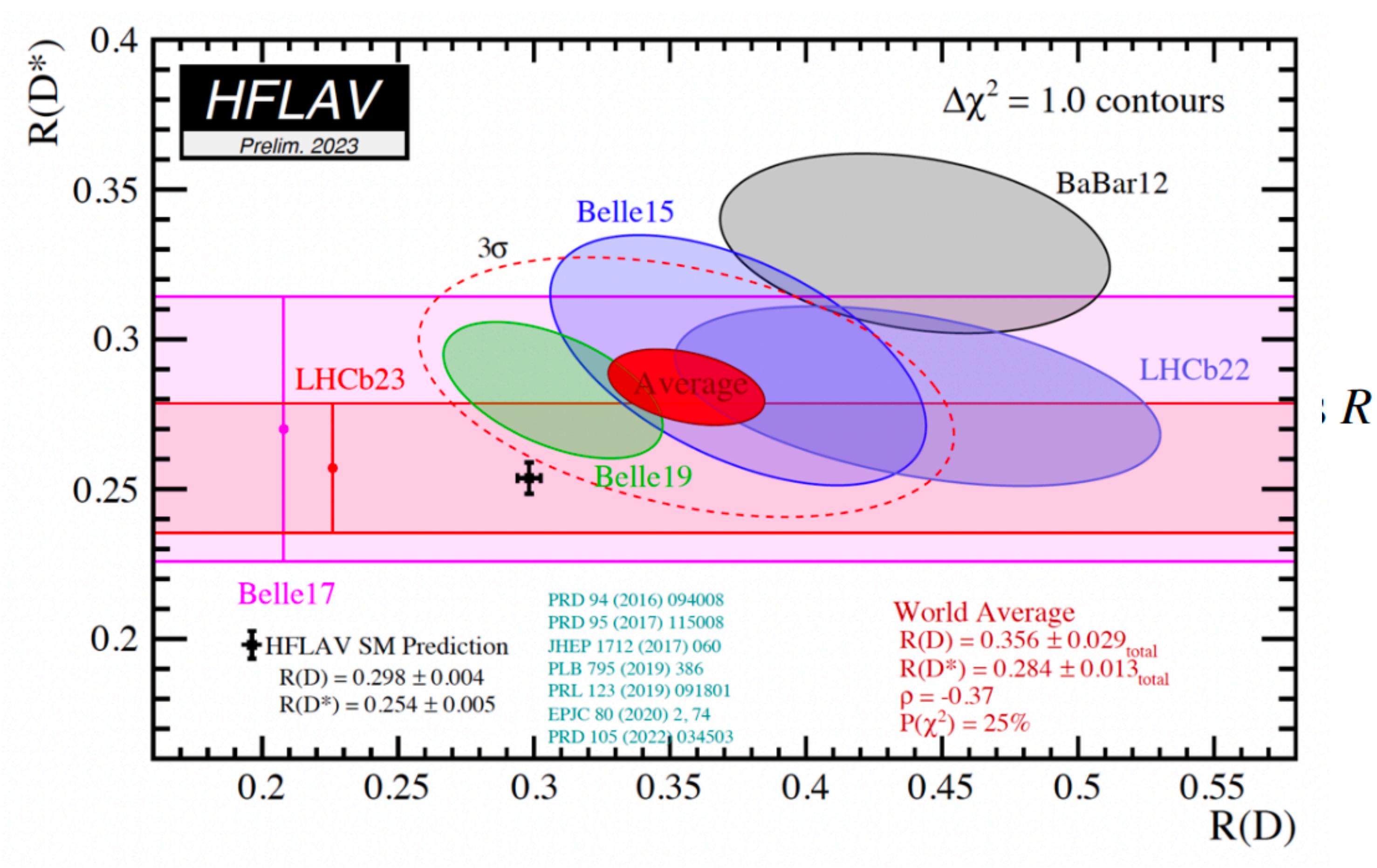


Fig. 1: Status of the charged-current LFU ratios R(D) and R(D*) as of March 2023.

[Source]

$$R\left(D^{(*)}\right) = \mathrm{Br}(B \to D^{(*)}\tau\nu)/\,\mathrm{Br}(B \to D^{(*)}\ell\nu))$$

- Results dominated mainly by BABAR because of cleaner environment (neutrino escapes in the detection) in spite of high statistics at Belle and LHC
- b–>clv mediated at tree-level in the SM have significant BR (O(-3))
- The R(D$^{(*)}$) is bigger than predicted by the SM by around 20% resulting in >= 3σ

Neutral current LFU

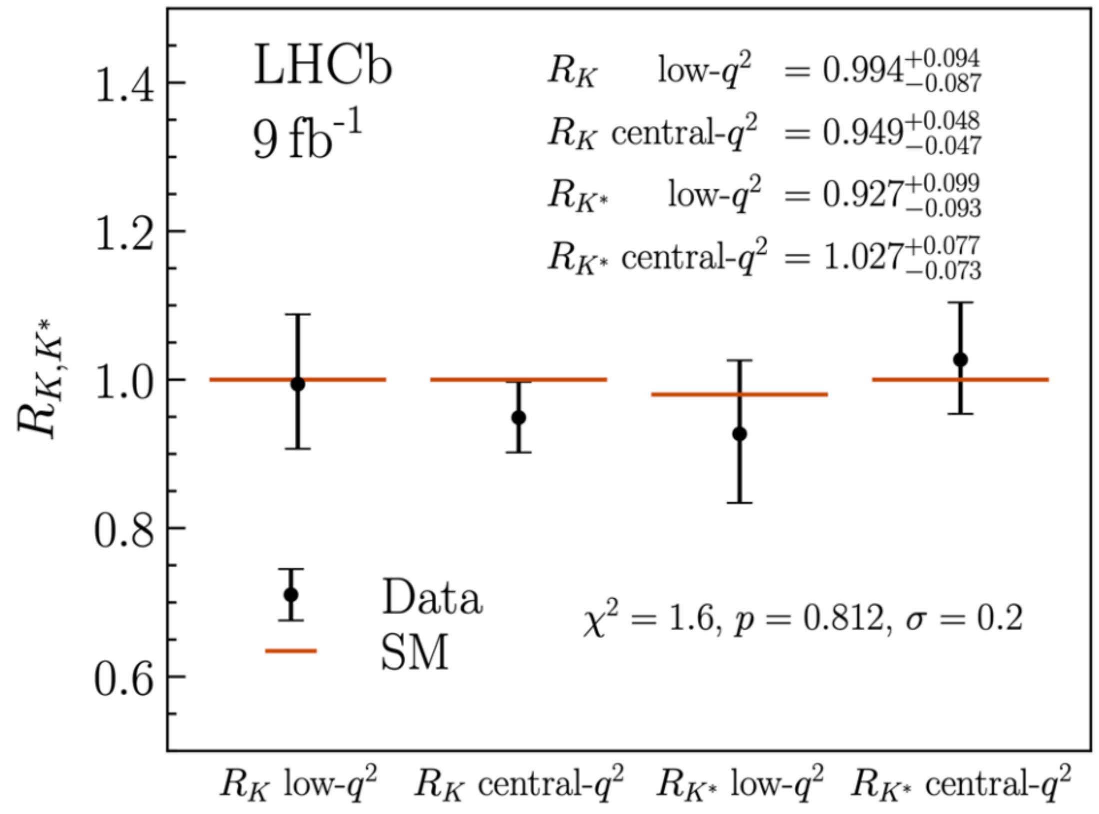
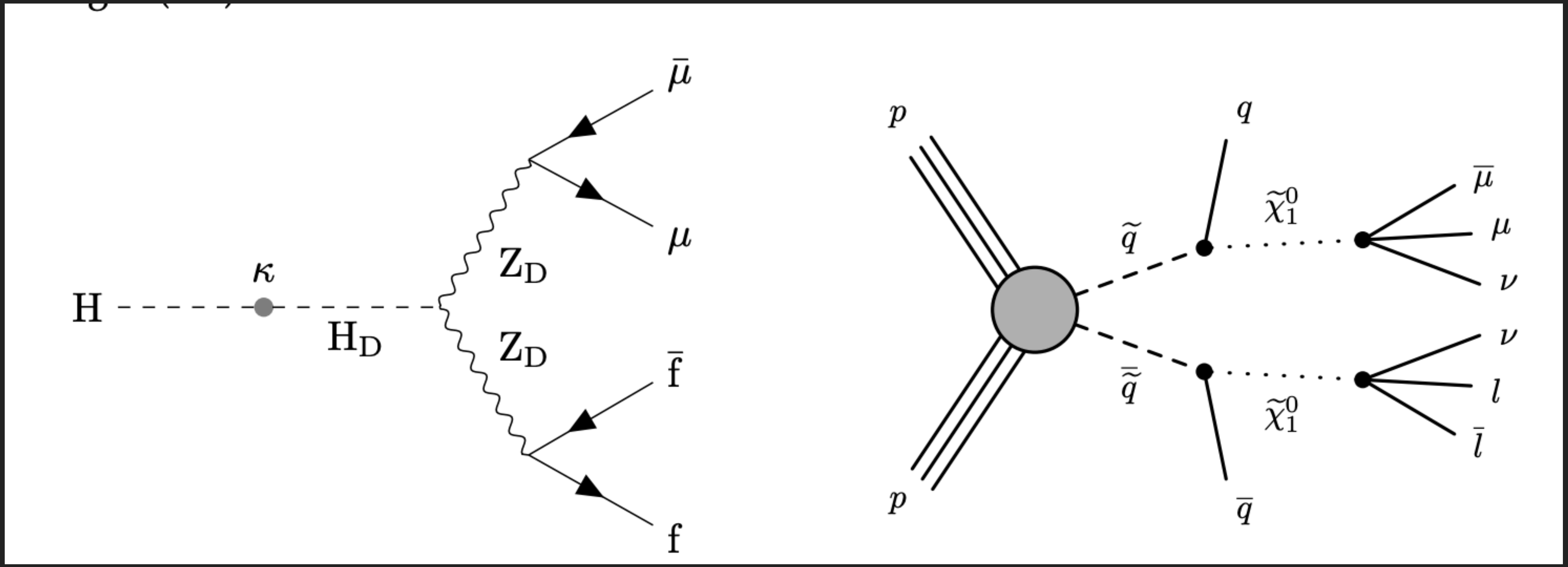


Fig. 2: Measurements of the e/μ LFU rations reported by LHCb in December 2022.

- This update in 2022 is attributed to a careful estimation of the background. It was identified that a number of unexpected background especially related to misID of pions and kaons as electrons led to low R_K values initially

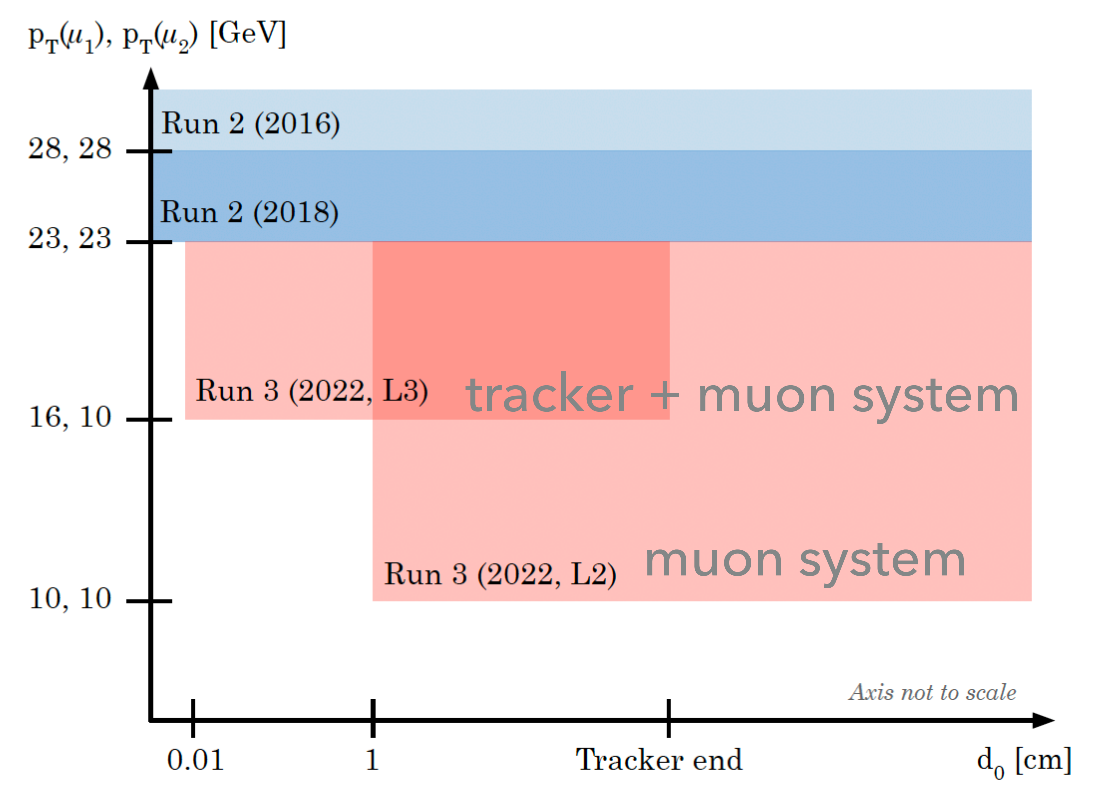
- Concern b–>sμ+μ- and b–>se+e-
- LHCb is the leading one since there is no neutrino that escapes detection
- First deviation observed (not in the context of universality) but deviation in the expected angular distribution of the muon pair in B–>K*μ+μ-
- R_K = Γ(B–>Kμ+μ-)/Γ(B–>Ke+e-) 2.6σ deviation wrt SM.
  - R_K^{exp} = 0.745 +/ 0.097 VS R_K^{SM} = 1 (in 2014 but similar in 2017)
  - In 2021, R_K^{exp} = 0.846 +/ 0.044 –> 3σ deviation
  - In 2022, R_K^{exp} = 0.949 +/ 0.047 –> within 1σ

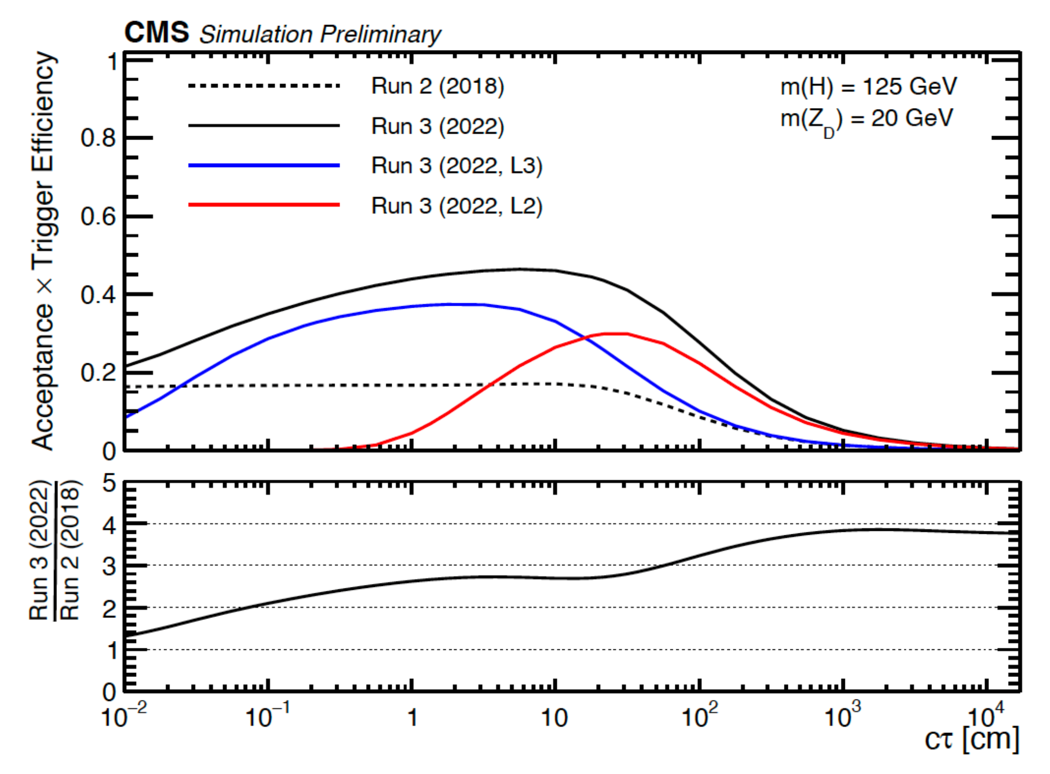
Run 3 (CMS): LLPs to pair of muons



- $\sqrt{s} = 13\ TeV$ using 36.7 fb^{-1} of data
- Experimental signature: Oppositely charged muons originating from a common secondary verctx spatially separated from the pp interaction point by distances ranging from several hundred μm to several meters
- Interpretations:
  - Hidden Abelian Higgs model where H–>Z_D Z_D (Hidden and dark sector)
  - R-parity violating SUSY where LLPs –> μμ+νν

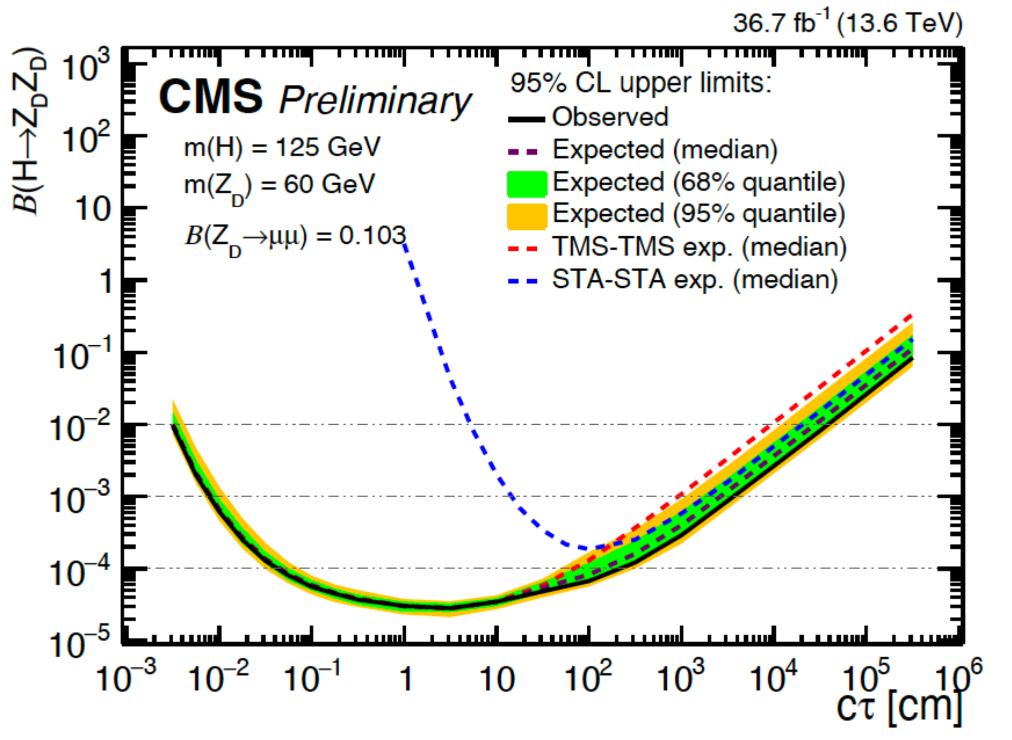
Run 3 (CMS): LLPs to pair of muons

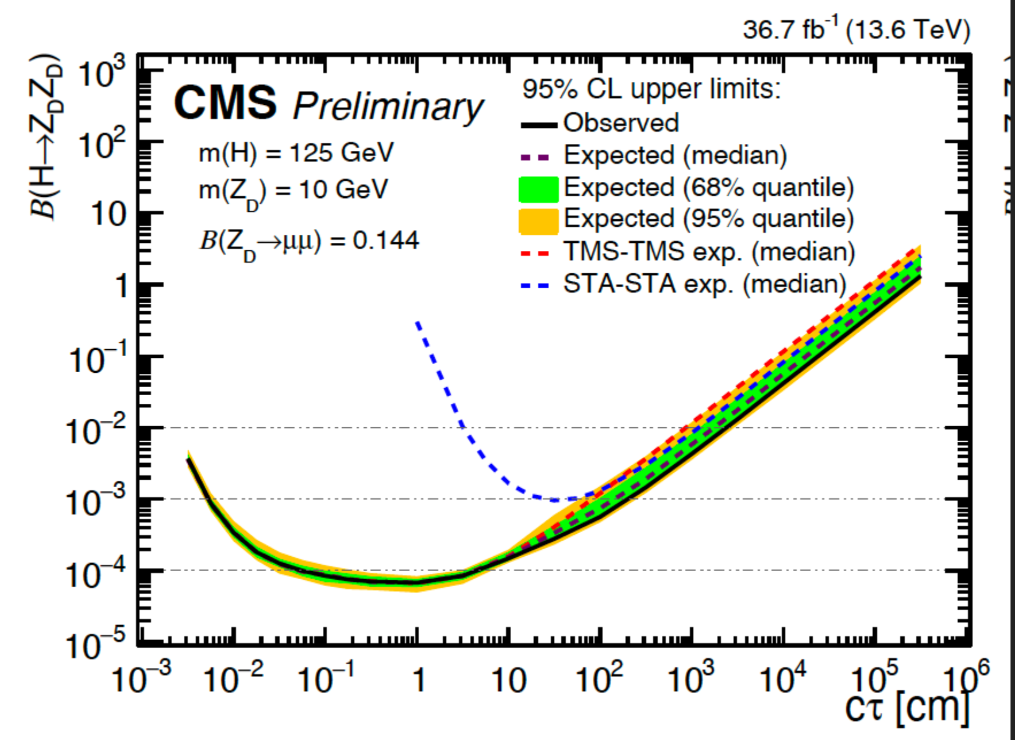


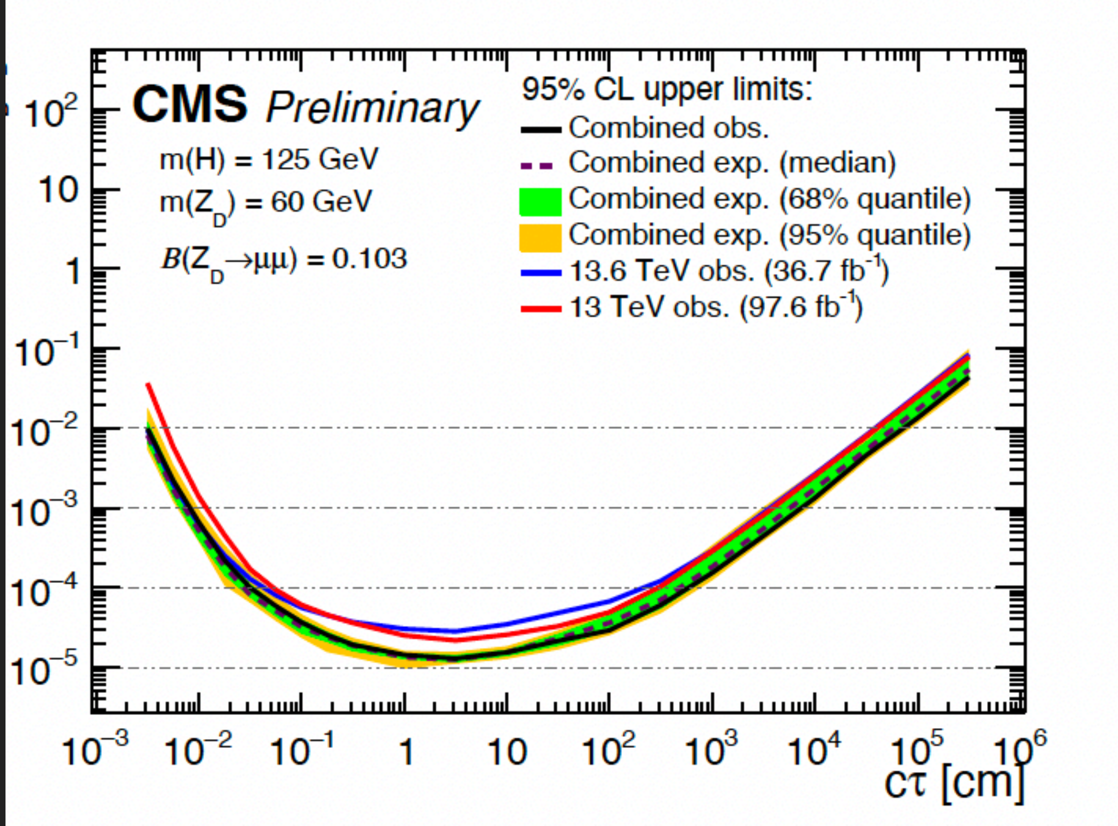


- Analysis strategy: Divide into categories
  - TMS-TMS: Both muons in the tracker and muon system
  - STA-STA: standalone muons
  - STA-TMS
- Improvement in L1 trigger:
  - Run 2: Two muons reconstructed in the muon system alone. pT > 28 and 23 GeV
  - Run 3: Two additional sets:
    - very low muon-pT thresholds, with stringent quality and kinematics requirements
    - New track finding procedure in the L1 muon trigger in the barrel. This reconstructs muon pT without using beam spot constraint

Run 3 (CMS): LLPs to pair of muons

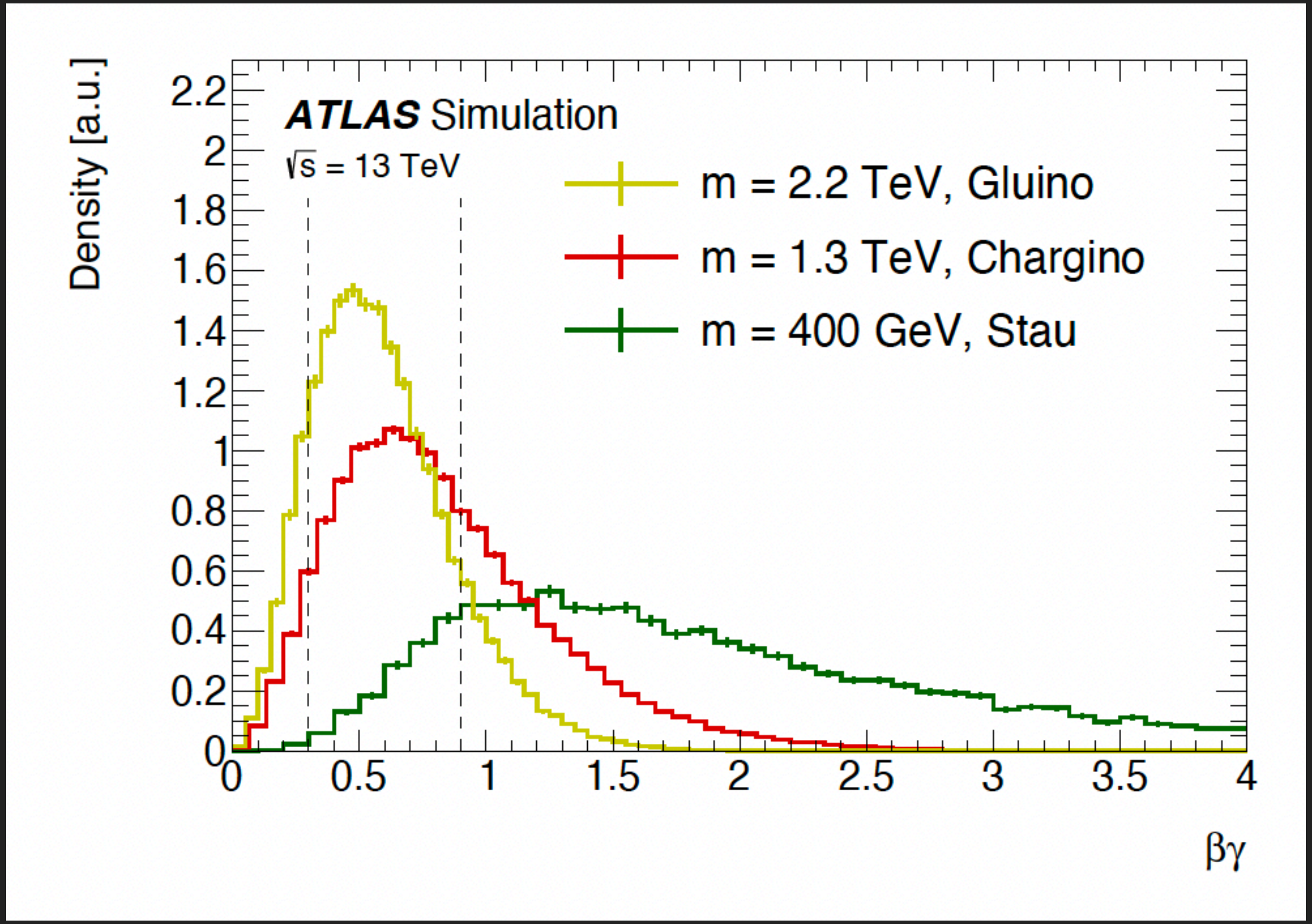






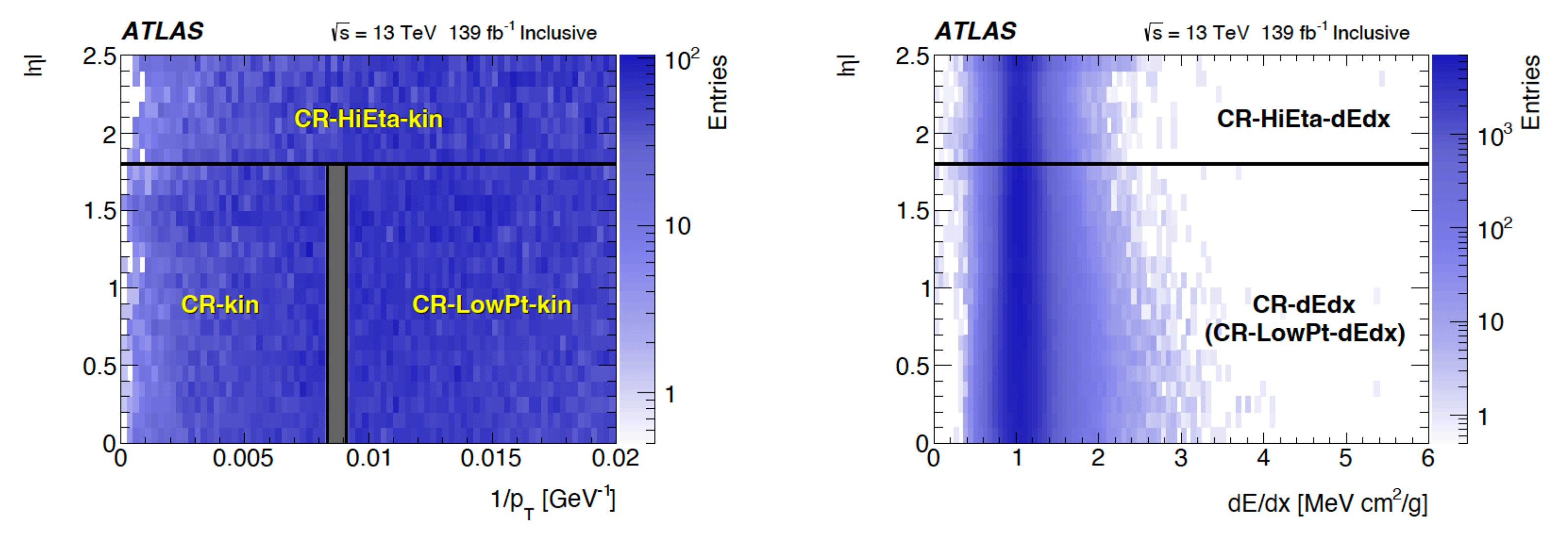
dE/dx: ATLAS

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$



- Studied: 0.3 < βγ < 0.9
- Very well in the range of heavy LLPs
- Strategy:
  - Select isolated tracks with high pT, large specific ionization
  - Reconstruct mass for each track using Bethe Bloch parameterization

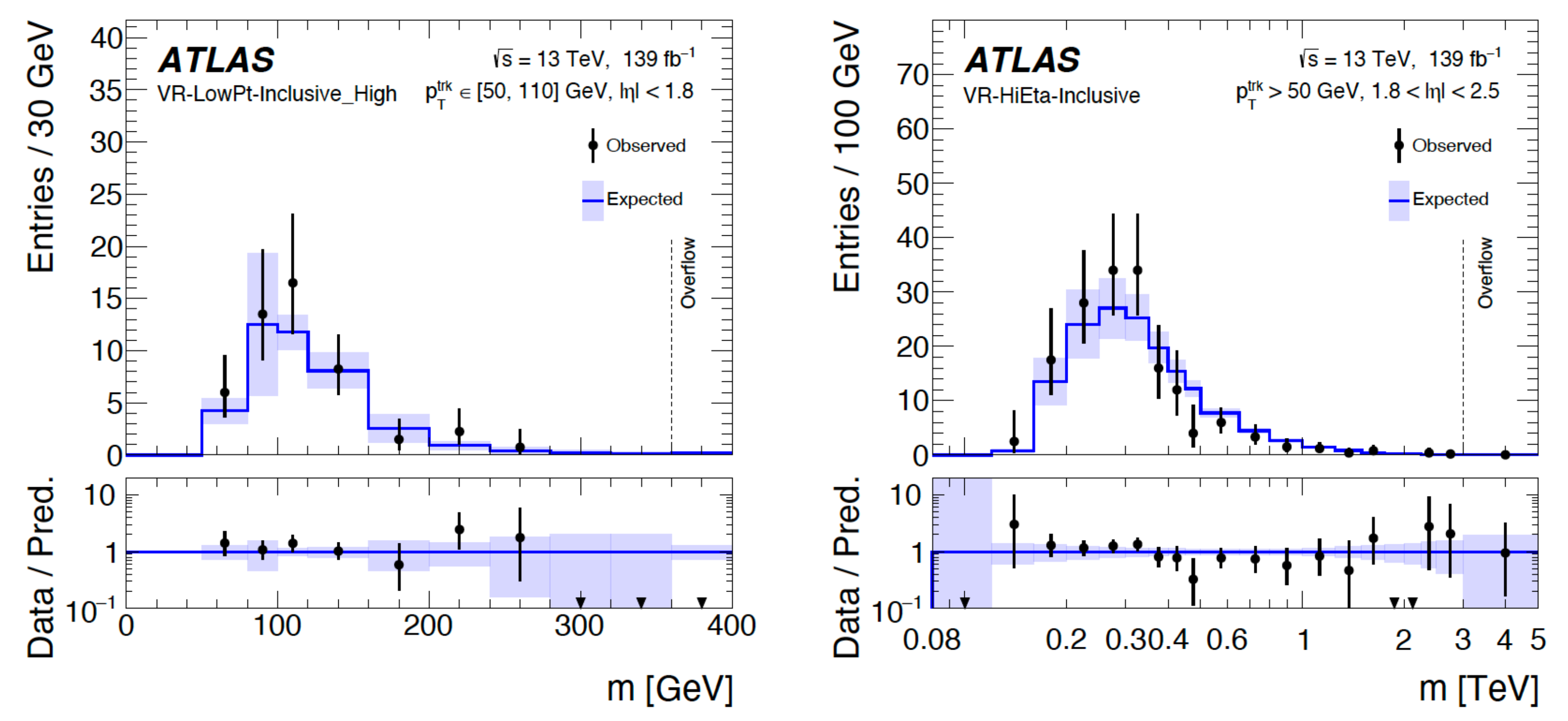
LLPs ATLAS background determination



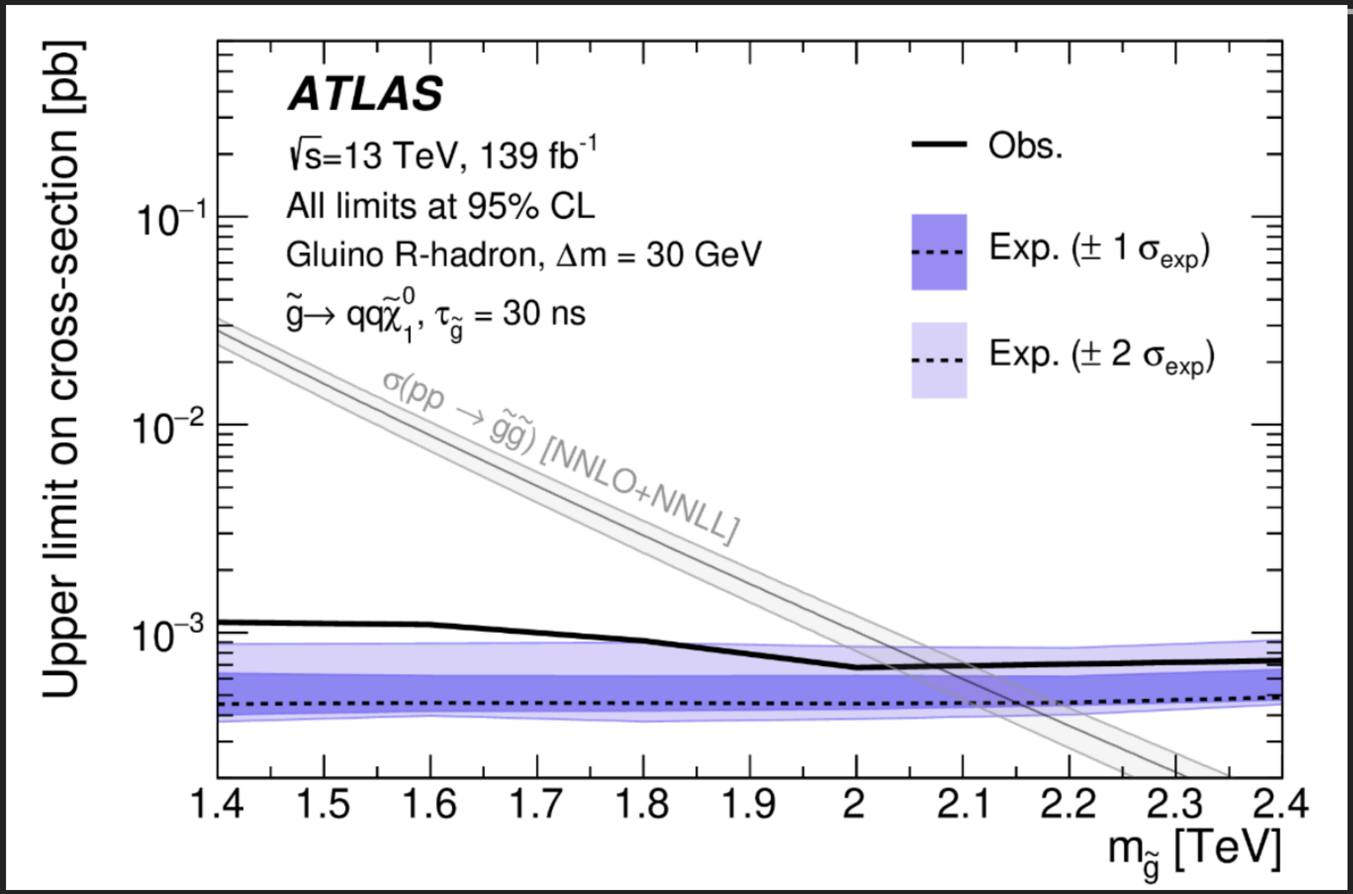
(a) Kinematic control regions (b) dE/dx control regions

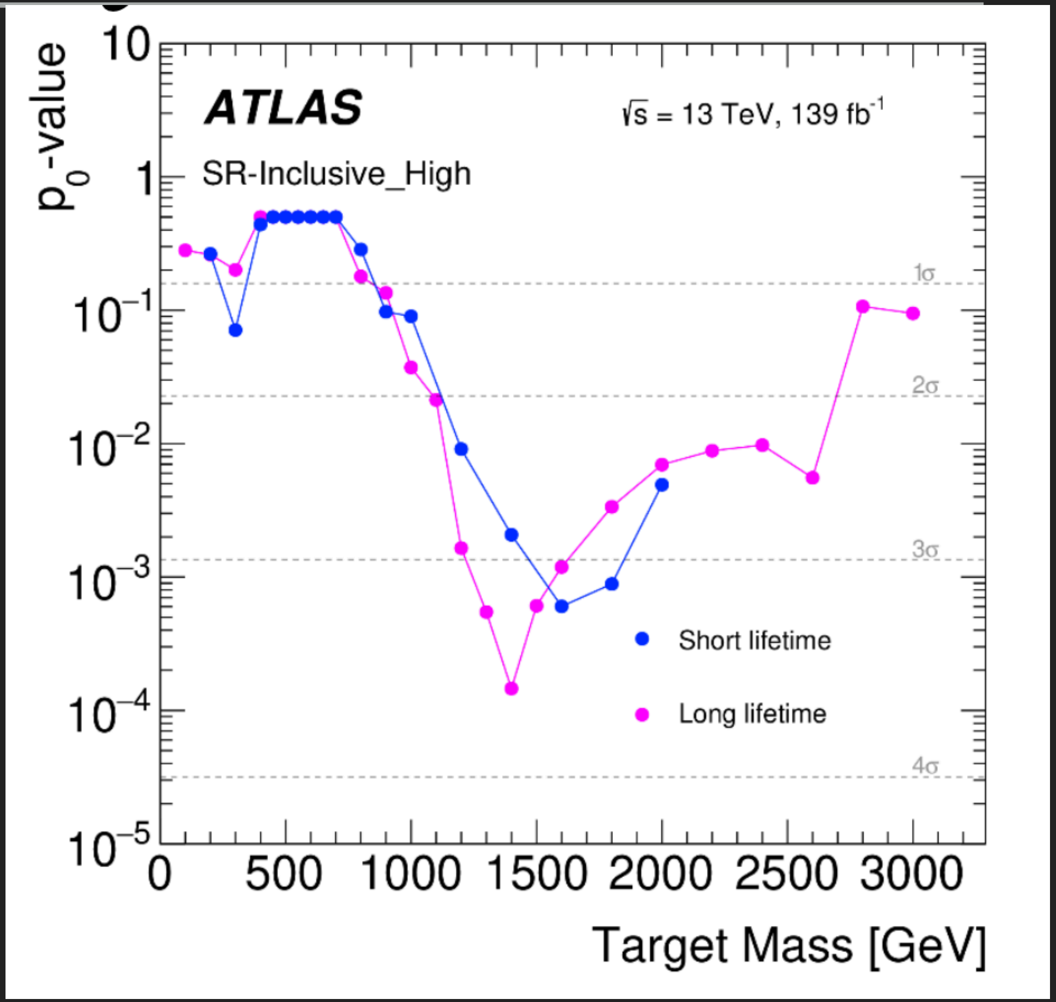
- CRkin: inverting dE/dx requirement in the signal region
- CR-dEdx: inverting E_T^{miss} and removing the dEdX requirement

- Toy track generation
  - Sample 1/pT, η from CR-kin
  - Sample dE/dx from the corresponding η bin of CR-dEdx
  - Compute m using dEdx and β
  - 10-40M toy tracks sampled
  - Validation done in validation regions



Statistical Analysis





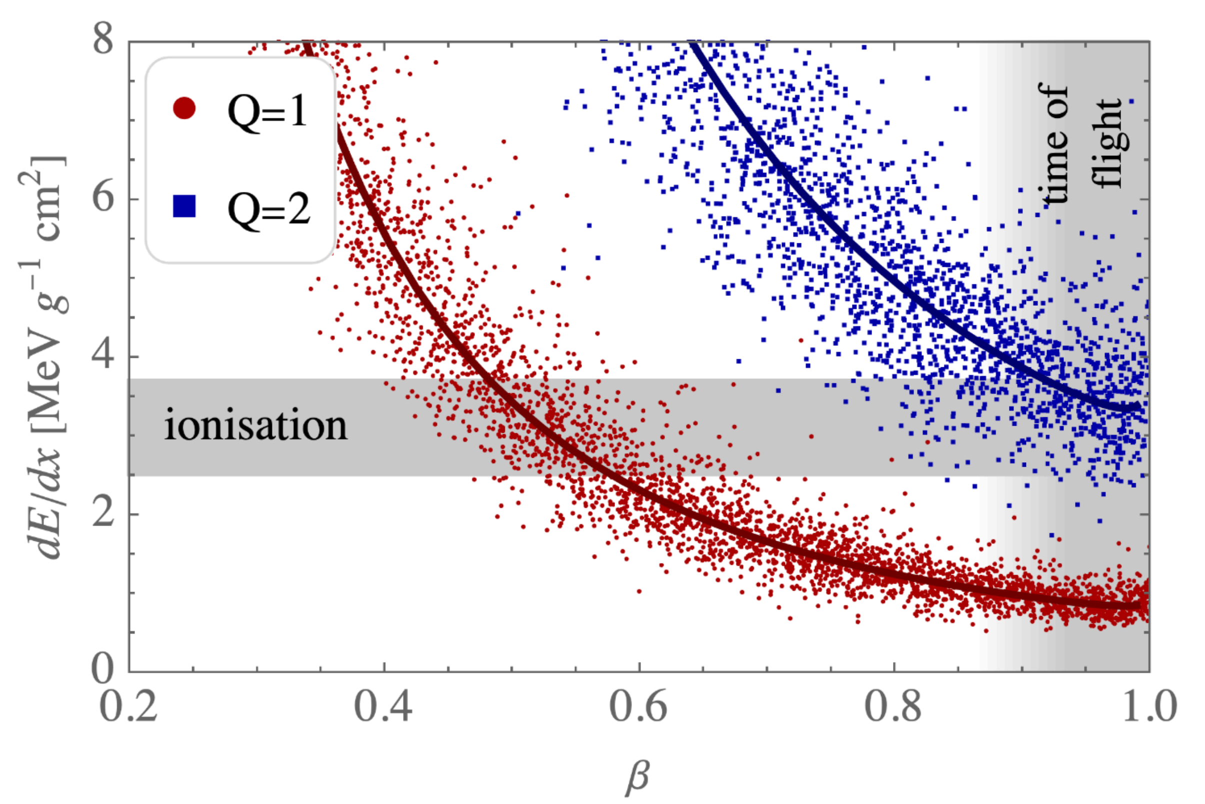
CMS analysis in progress

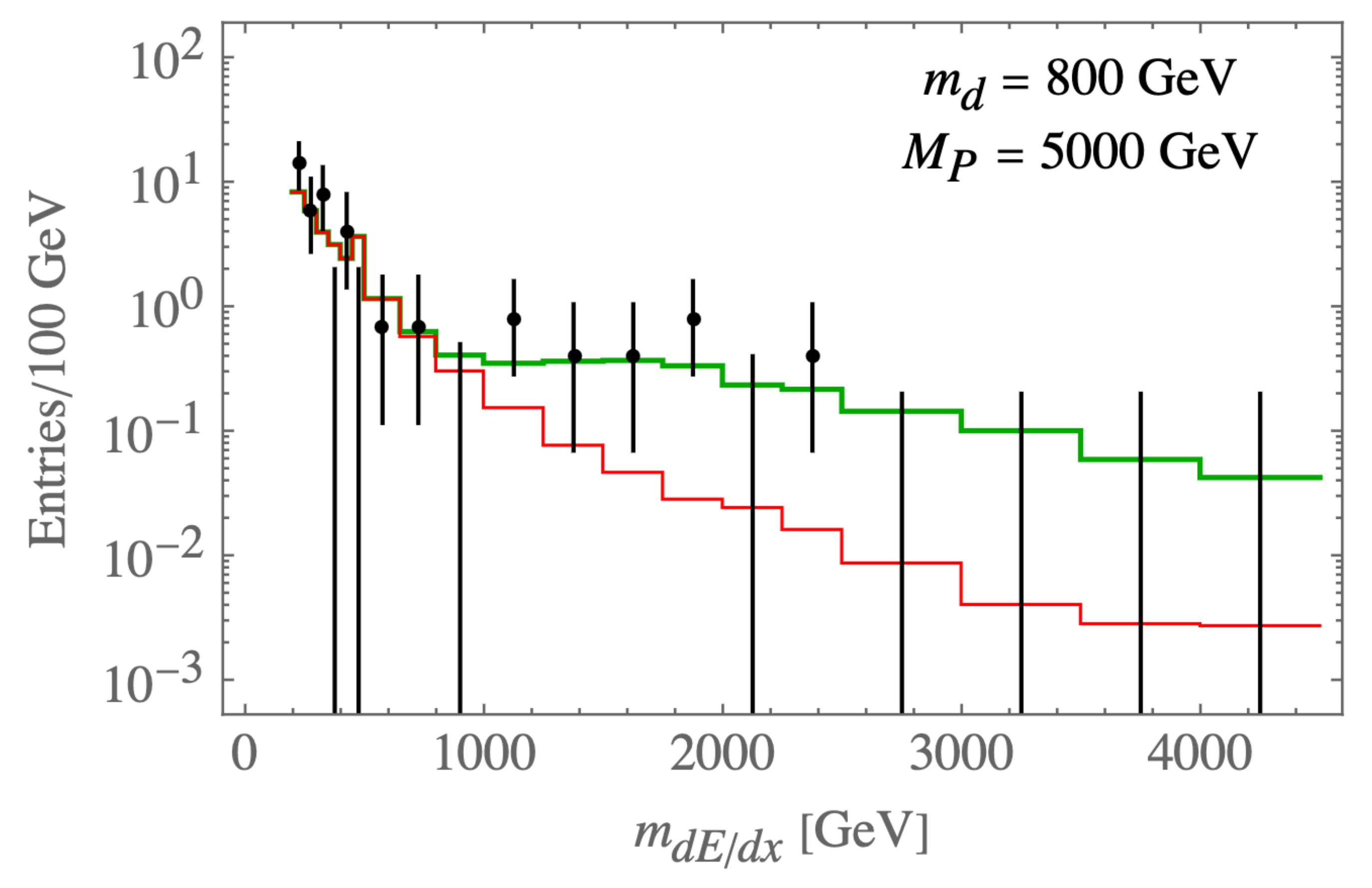
- 7 excess events with $1100 < m < 2800$ GeV (expected 0.7 +/- 0.4). p-value ~3.6σ for signal mass = 1.4 TeV(global is ~3.3σ)
  - 2.4 <= dE/dx <= 3.7 MeV $g^{-1}cm^{2}$
    - Predicted β = 0.5–0.6, but measured β ~ 1 (from ToF, MS, Calo)
  - Not consistent with the heavy (and hence slow) LLP hypothesis

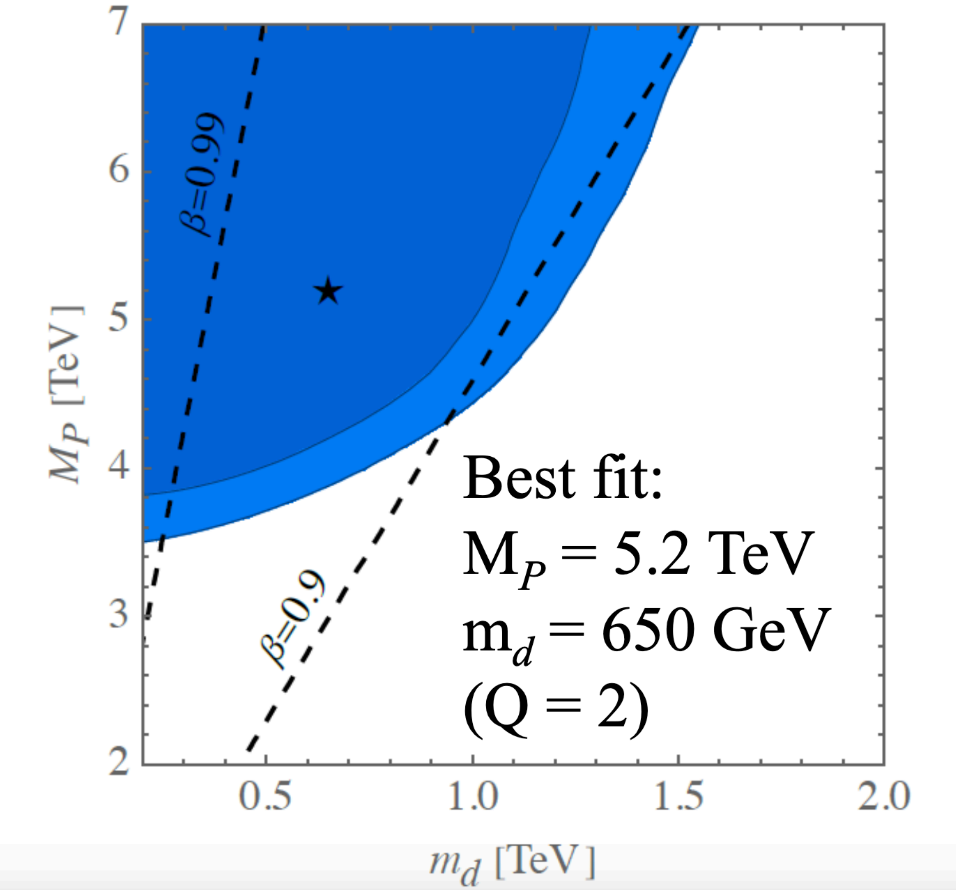
Another Interpretation

- Doubly-charged LLPs have β values compatible with measured dE/dx!
- Resonant production of relatively light daughter particles d from massive particle P –> boosted
- Good match for kinematic properties of excess events

arXiv: 2205.04473







Best fit:
M_P = 5.2 TeV
m_d = 650 GeV
(Q = 2)

Improvements in Run 3 for Dijet

- Current analysis is model dependent. But the nature may not have this BSM scenario that we test
- Idea is to be model independent
  - But such an analysis may have sensitivity penalized when the search is performed in large number of bins due to look elsewhere effect
- Anomaly detection based analysis.
  - Train model on background enriched sample of data to learn the background typical distribution and thus detect out-of-distribution examples when tested on an independent data sample
- A total of 5 anomaly detection methods which are model agnostic are in place