BSM physics in ATLAS EXPERIMENT and CMS

Masahiro Morinaga
On be half of the ATLAS and CMS Collaborations
Waseda University

BSM Physics in ATLAS and CMS

SUSY
Strong
Electroweak
Long Lived
....

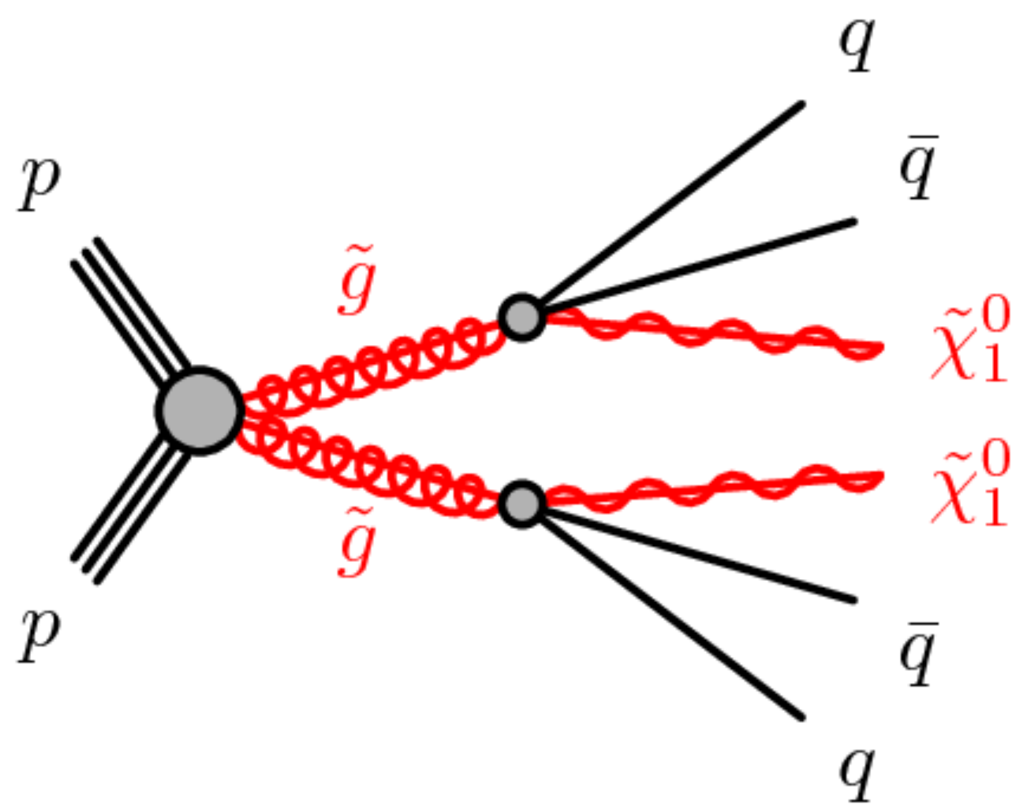
Exotica
Dijet signature
Leptoquarks
Diboson
...

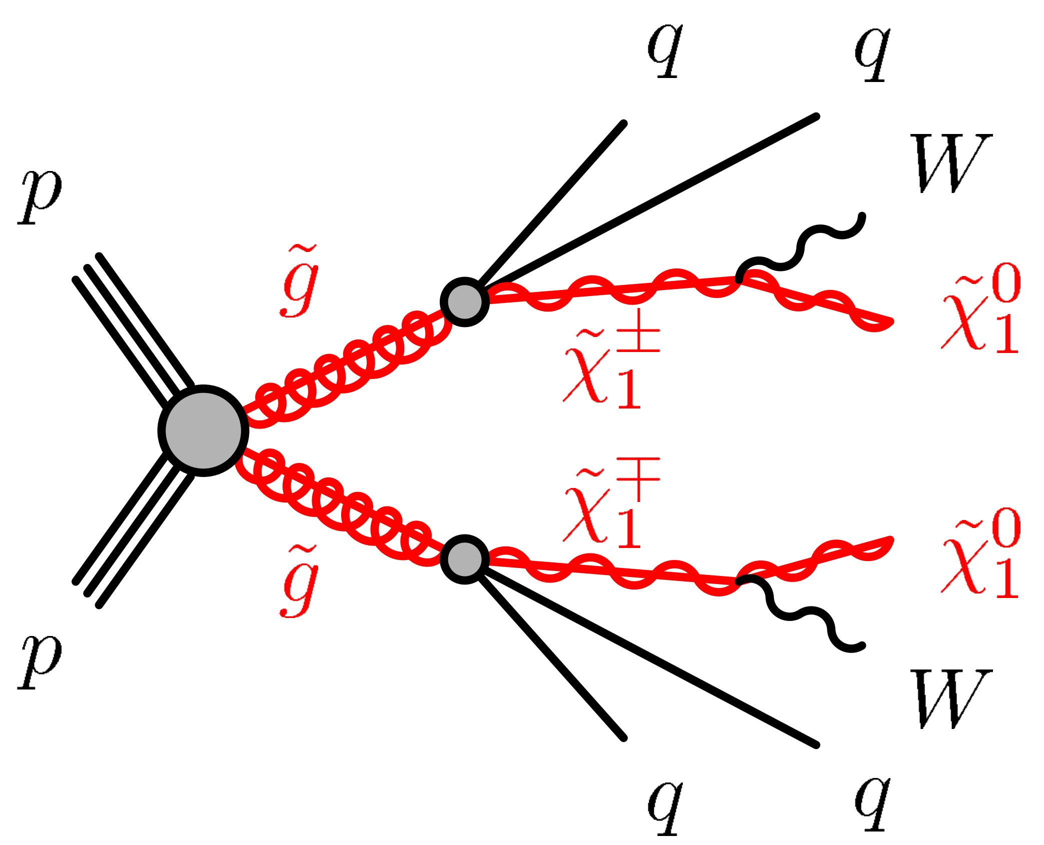
- I will focus on specific topics of interest in
  - SUSY : Several analysis with newer results since Jan.
  - Exotic : Several analysis with really newer results since summer.
- Starting from SUSY search results!!

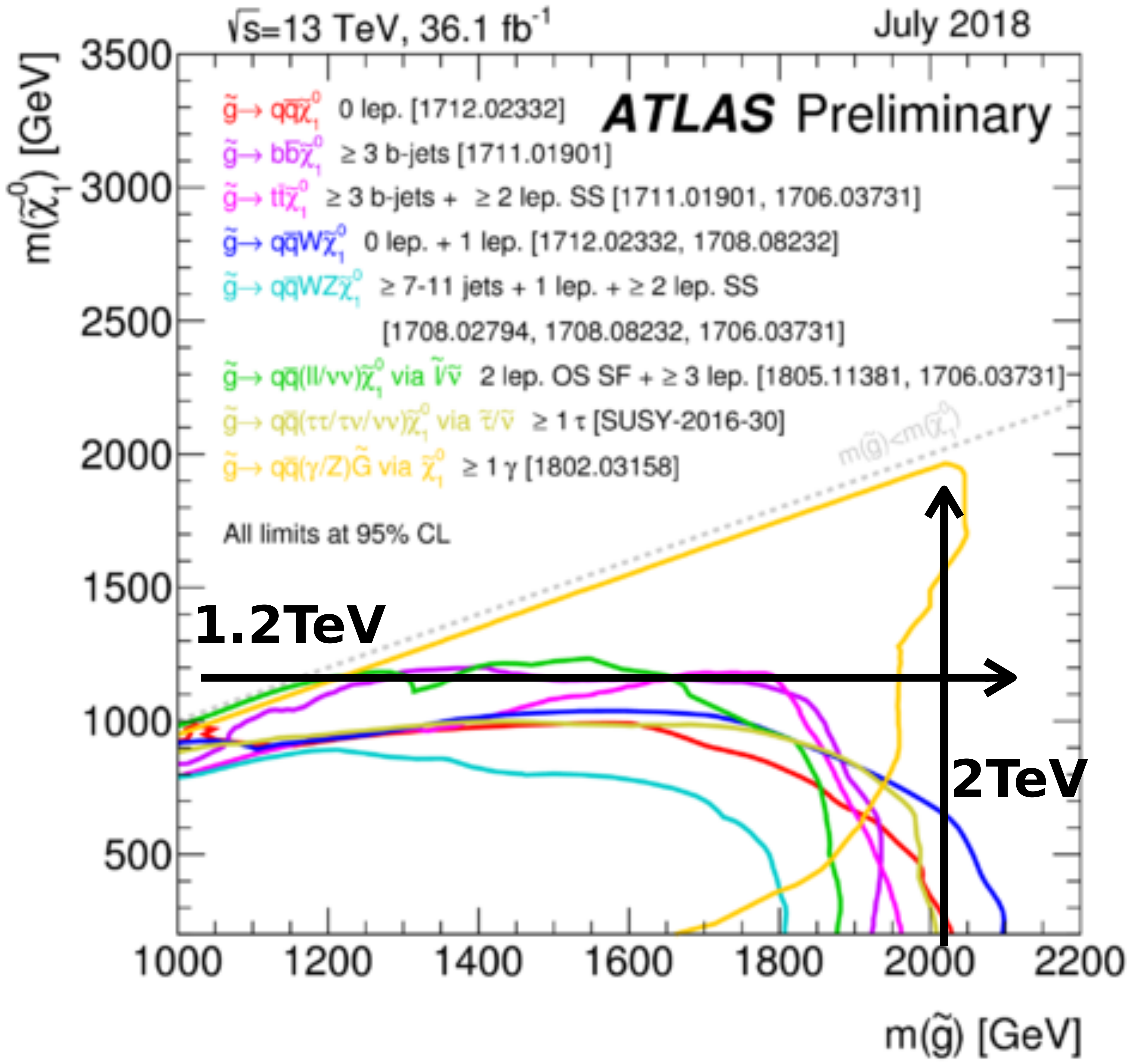
SUSY Analysis

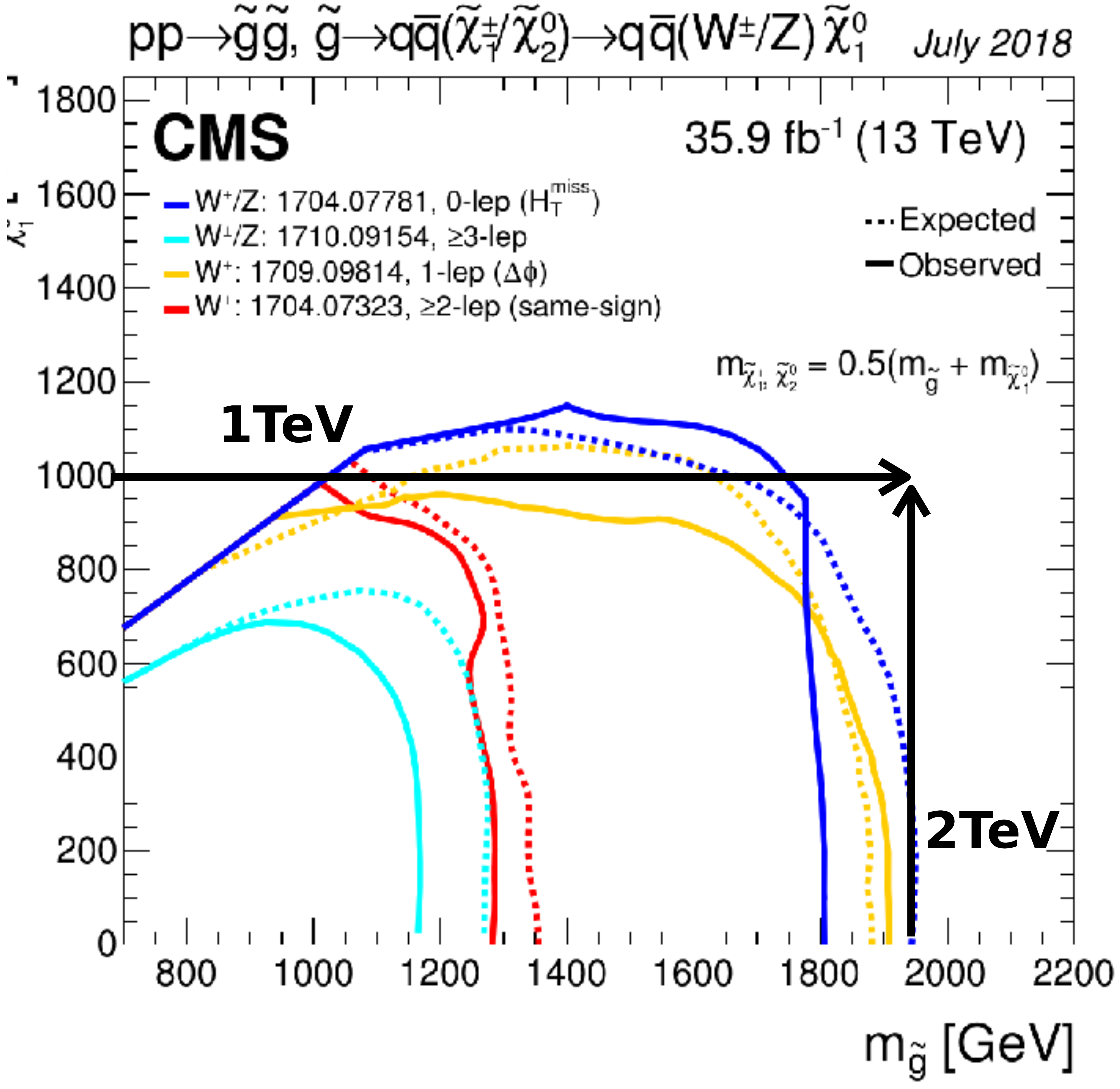
Gluino / Light-flavor Squarks :

- **Royal Road**, large cross section.
  - High pT jets + large E_T^{miss} : Same strategy for light-flavor squark.
  - Large ΔM → hadronic
  - Small → leptonic analysis.



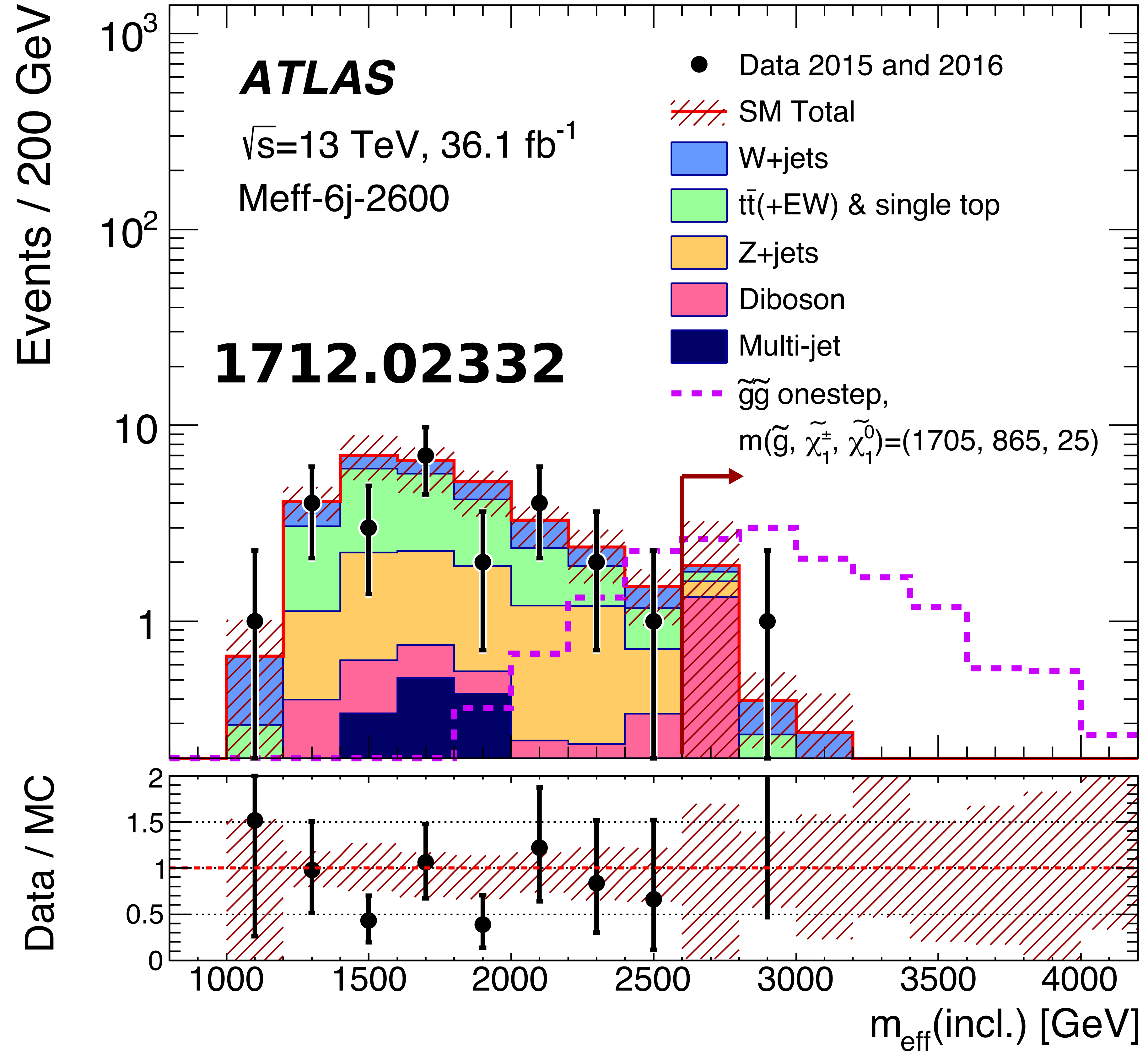


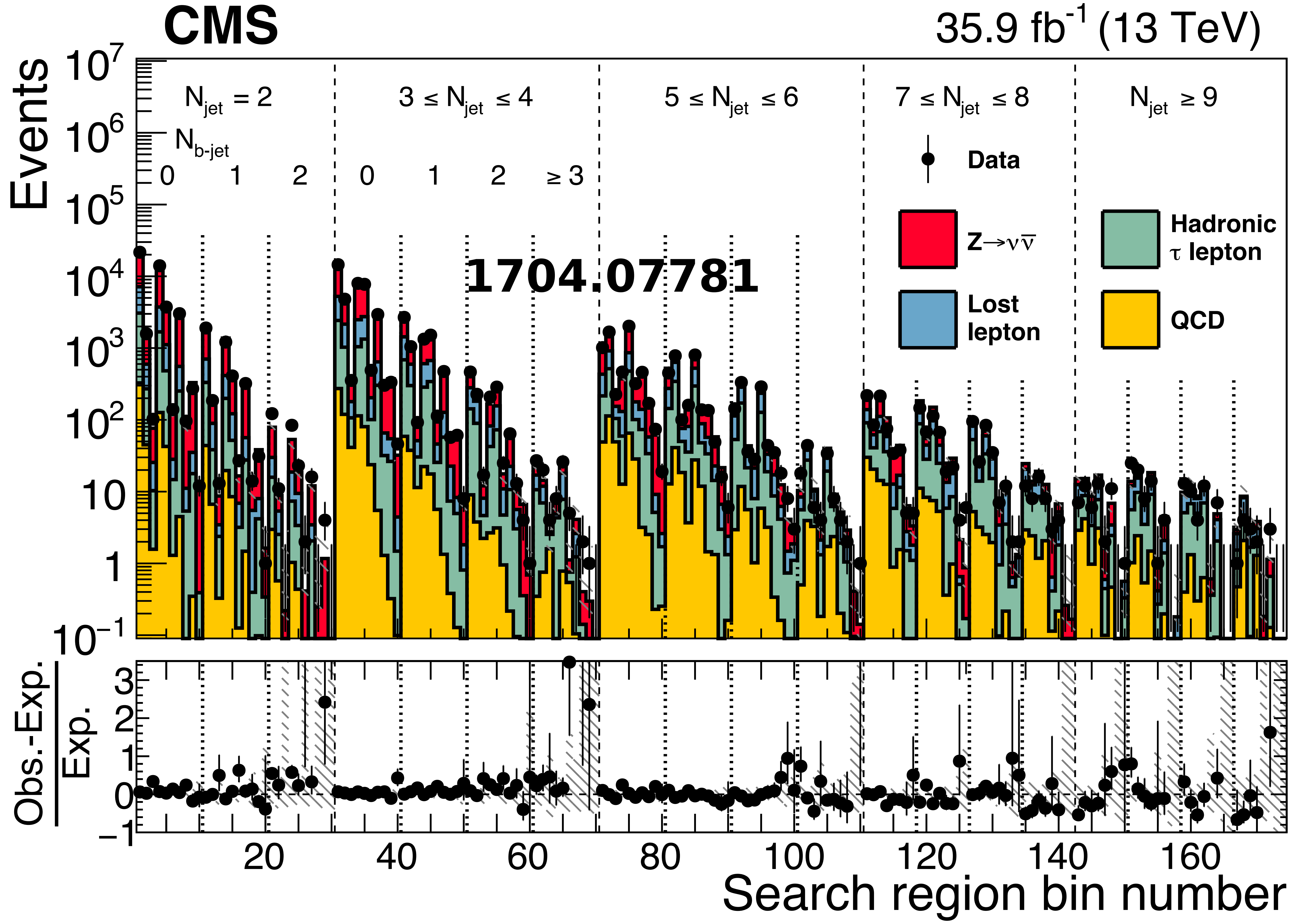




Comparison ATLAS and CMS : e.g. Gluino 0L

- **ATLAS** : Cut & Count(> 40 SRs)
- **CMS** : Inclusive → Multi-bin fit(> 100bins), Specific search → Cut & Count, MVA
- **Background estimation** : Using similar technique, e.g. γ+jets to Z+jets, etc..

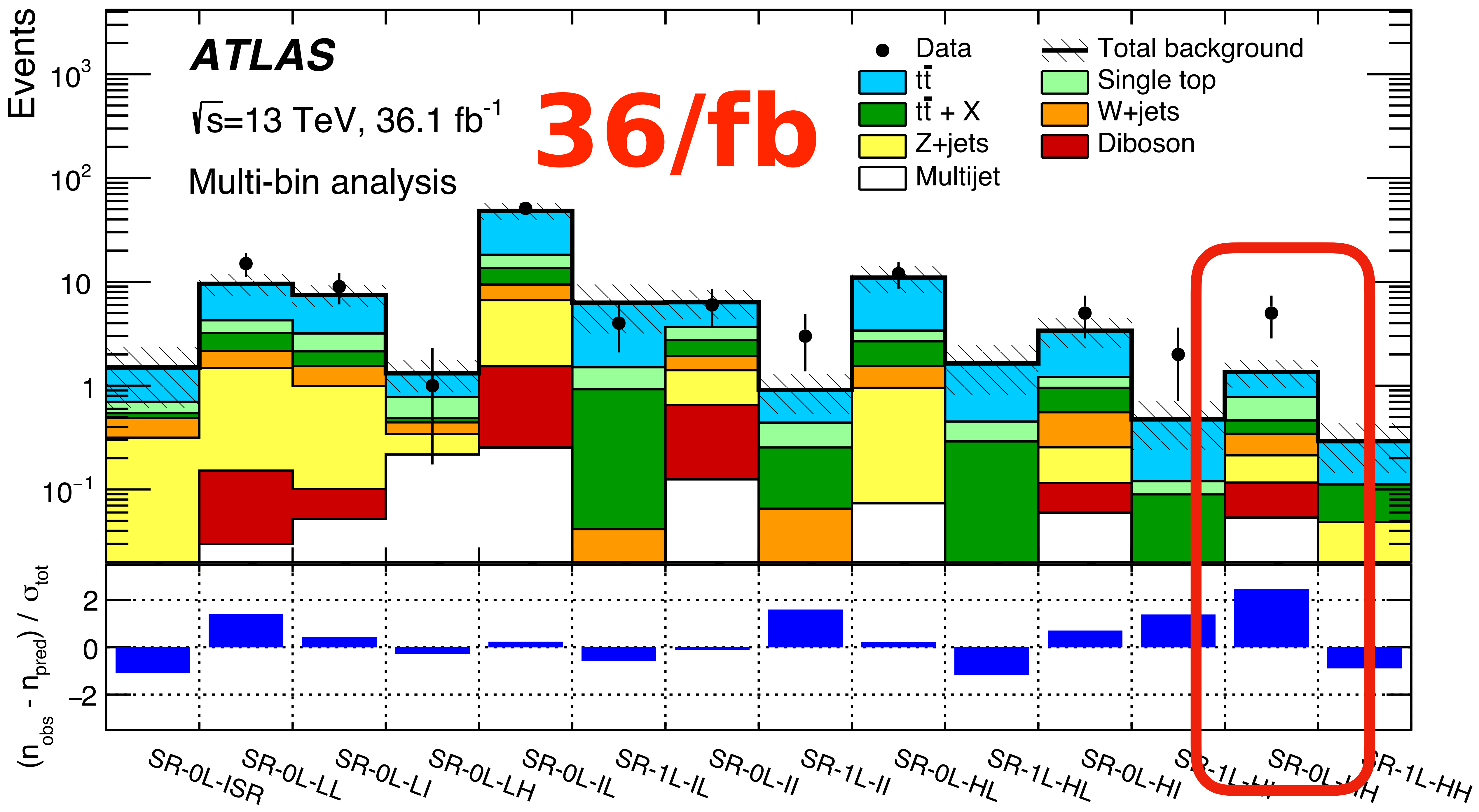


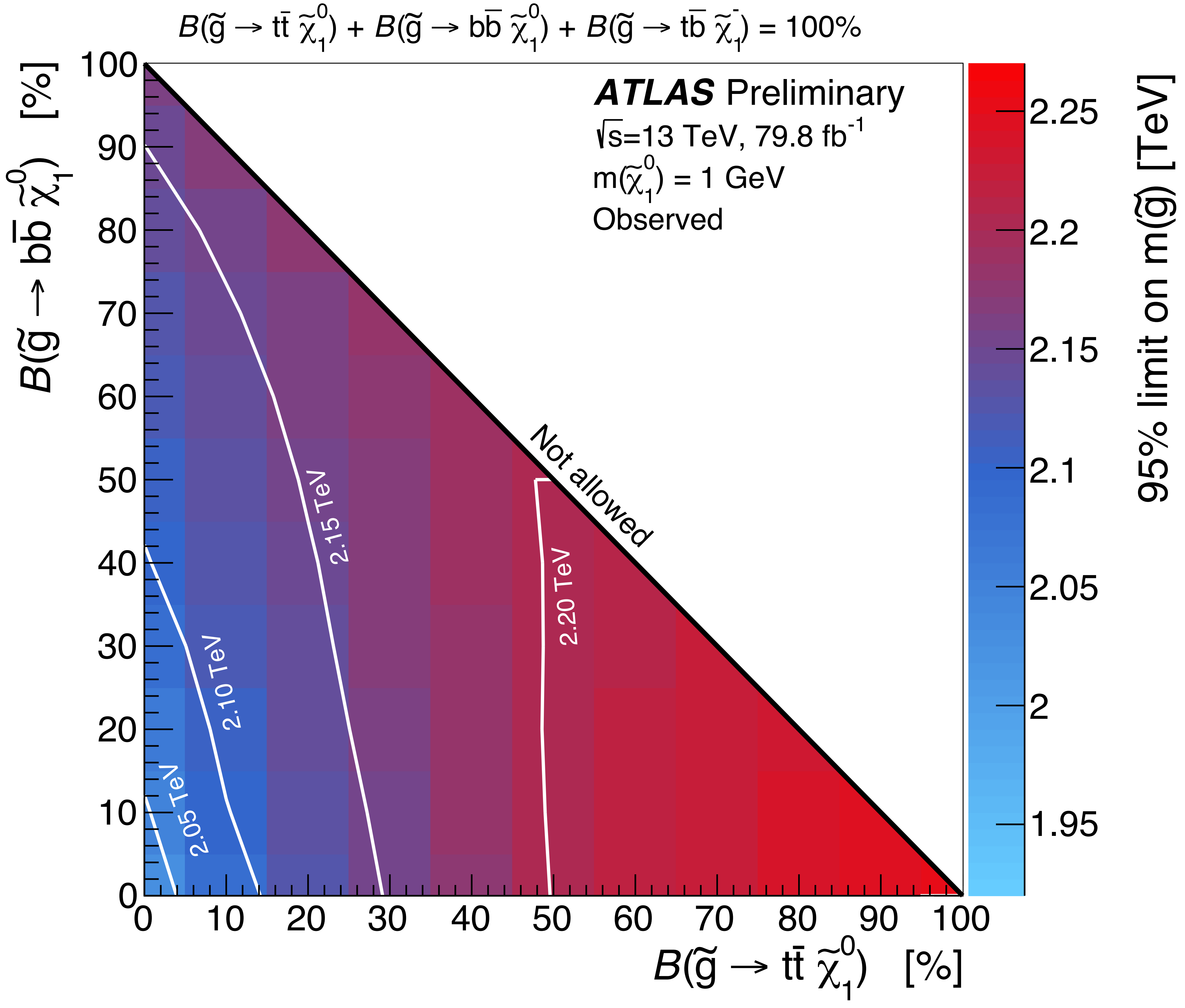


Gluino to multi-b in ATLAS @80/fb

CONF-2018-041

- Benchmark : g→tt/bb
  - > 3 b-jets, main background : ttbar + fake b-jets/tt+bb
  - There was 2.3σ excess @36/fb → disappeared @80/fb
  - New interpretation : simultaneous fit on g→tt/bb
  - More details from Daniela's talk!!





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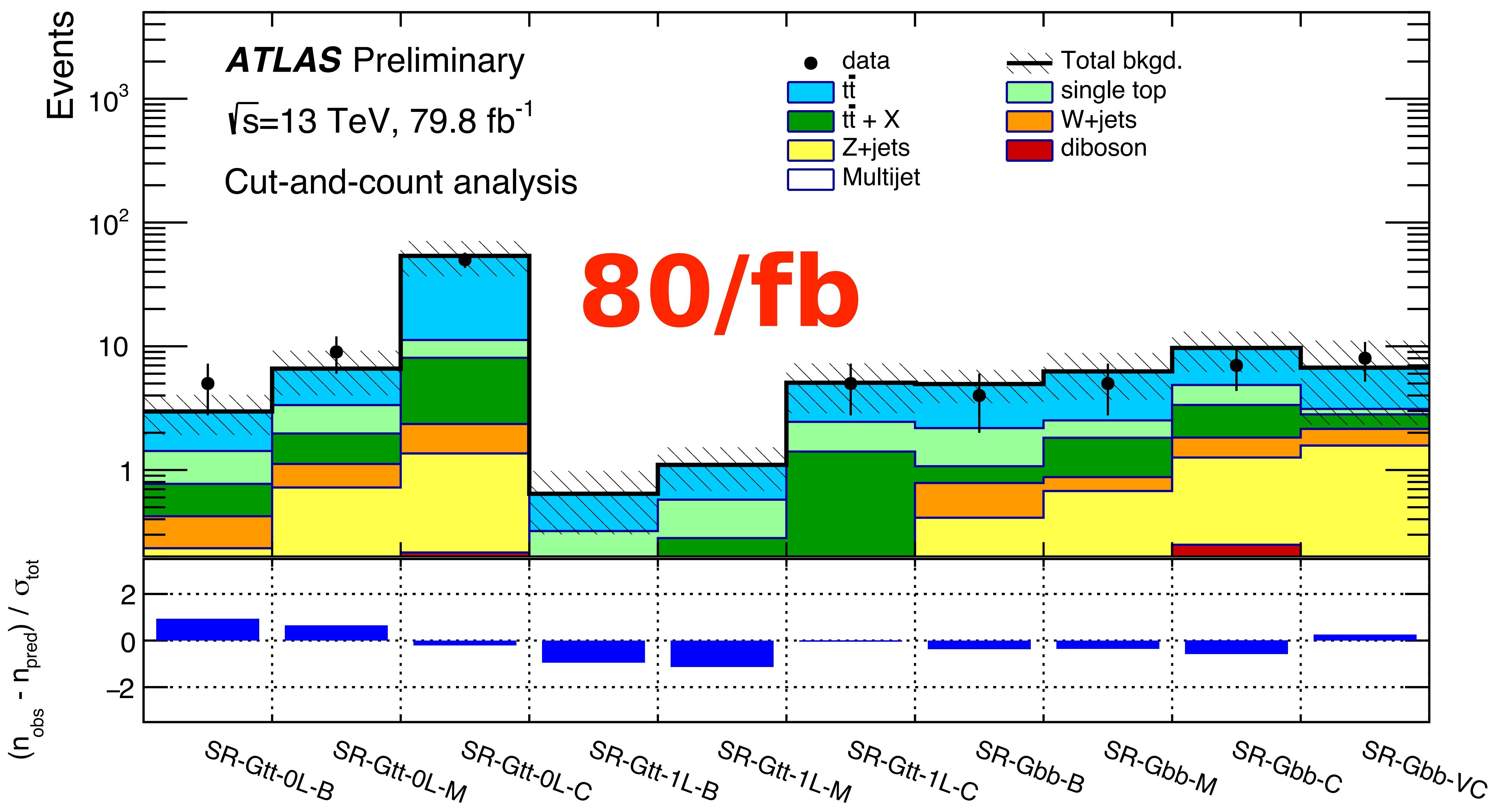
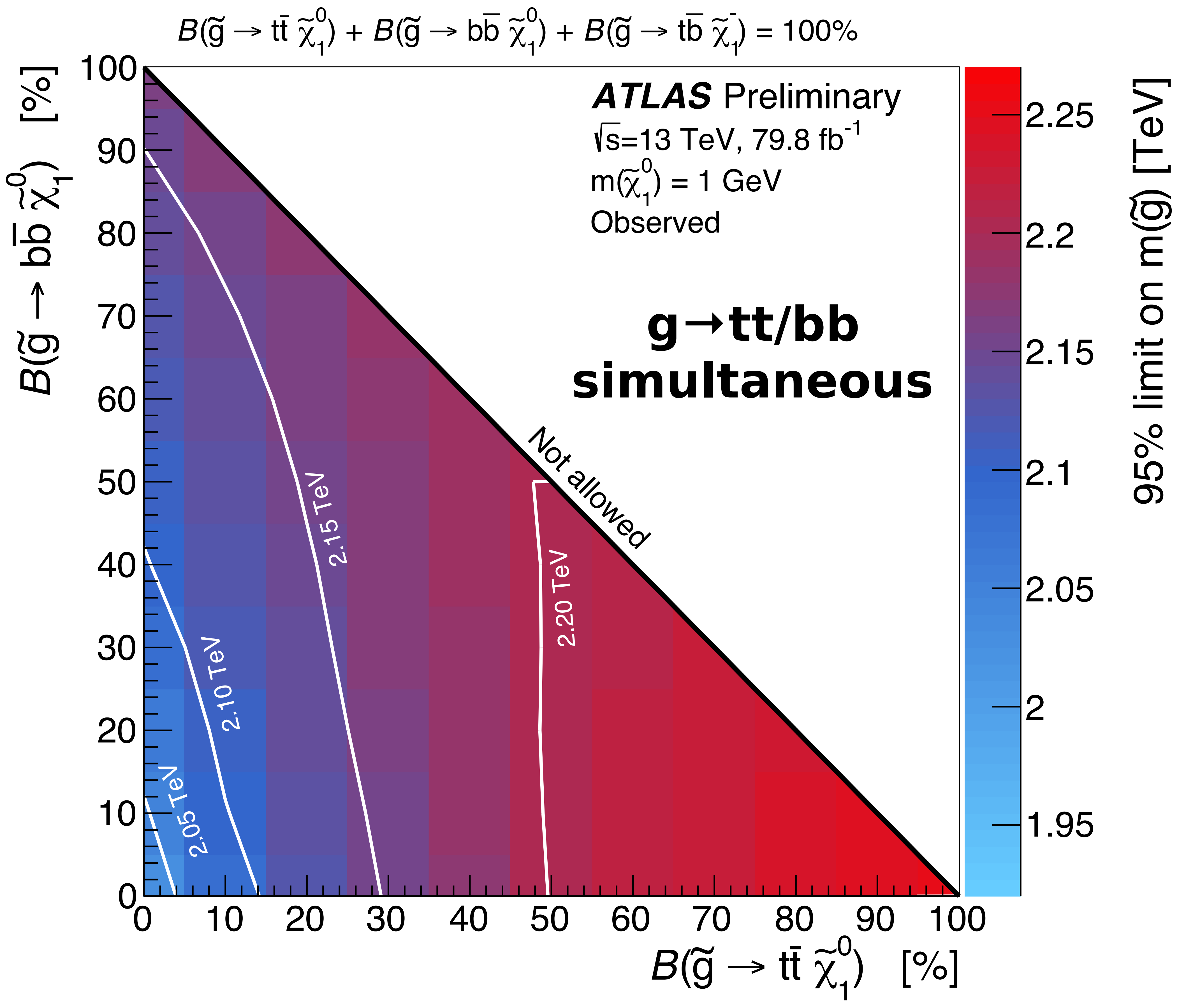
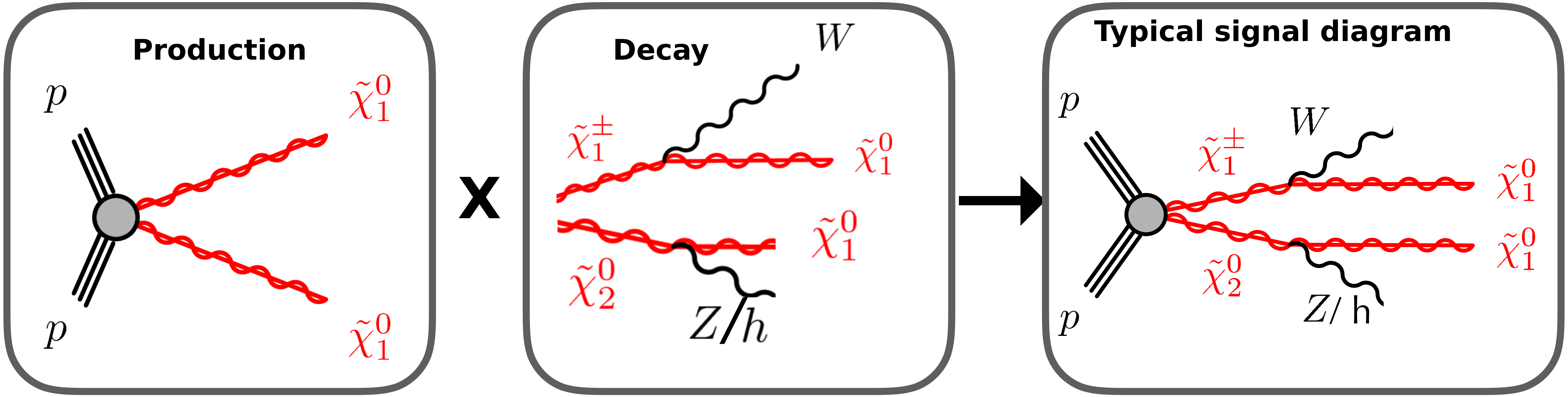




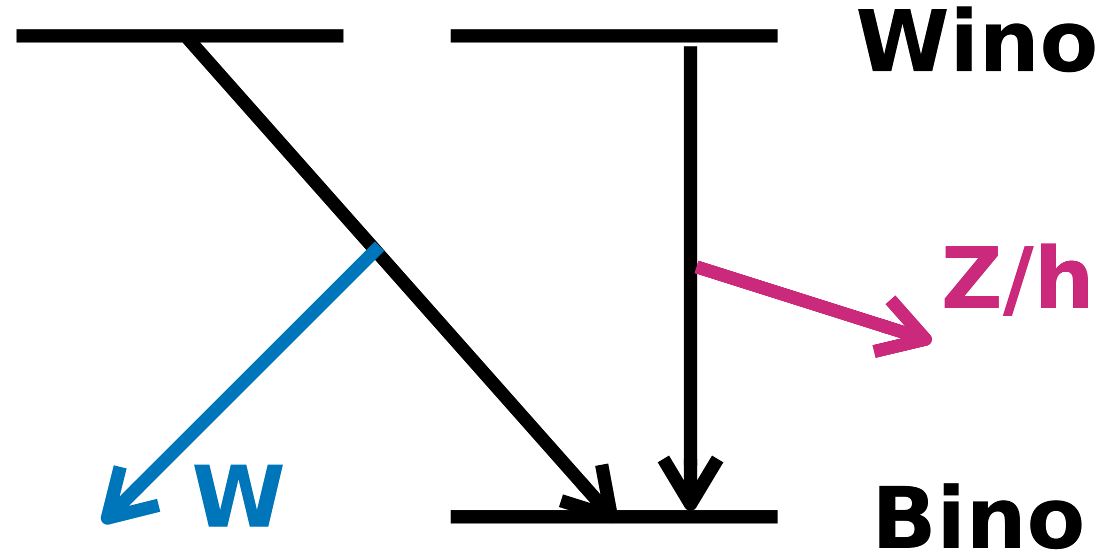
Electroweak Gauginos

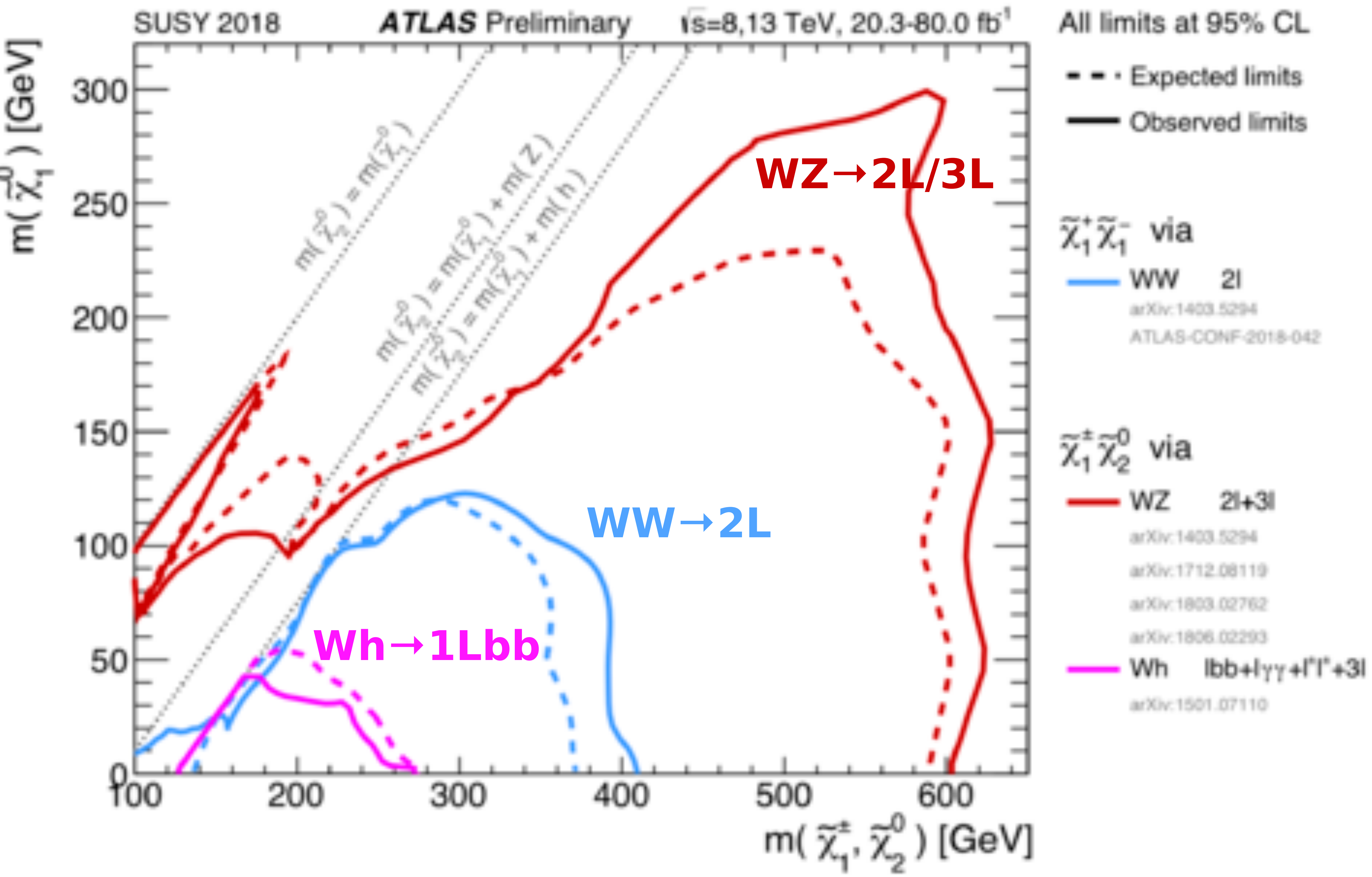
- **Curse loop** : Electroweak production → small cross-section → low mass search → large background → low pT multi-lepton final state → … ??
- How can we avoid this loop?
  - **More stat** → We are in Run2, its' already 80/fb!!
  - **Change strategy** → Use new technique ? Boosted Boson tagging would be powerful on higher mass region.

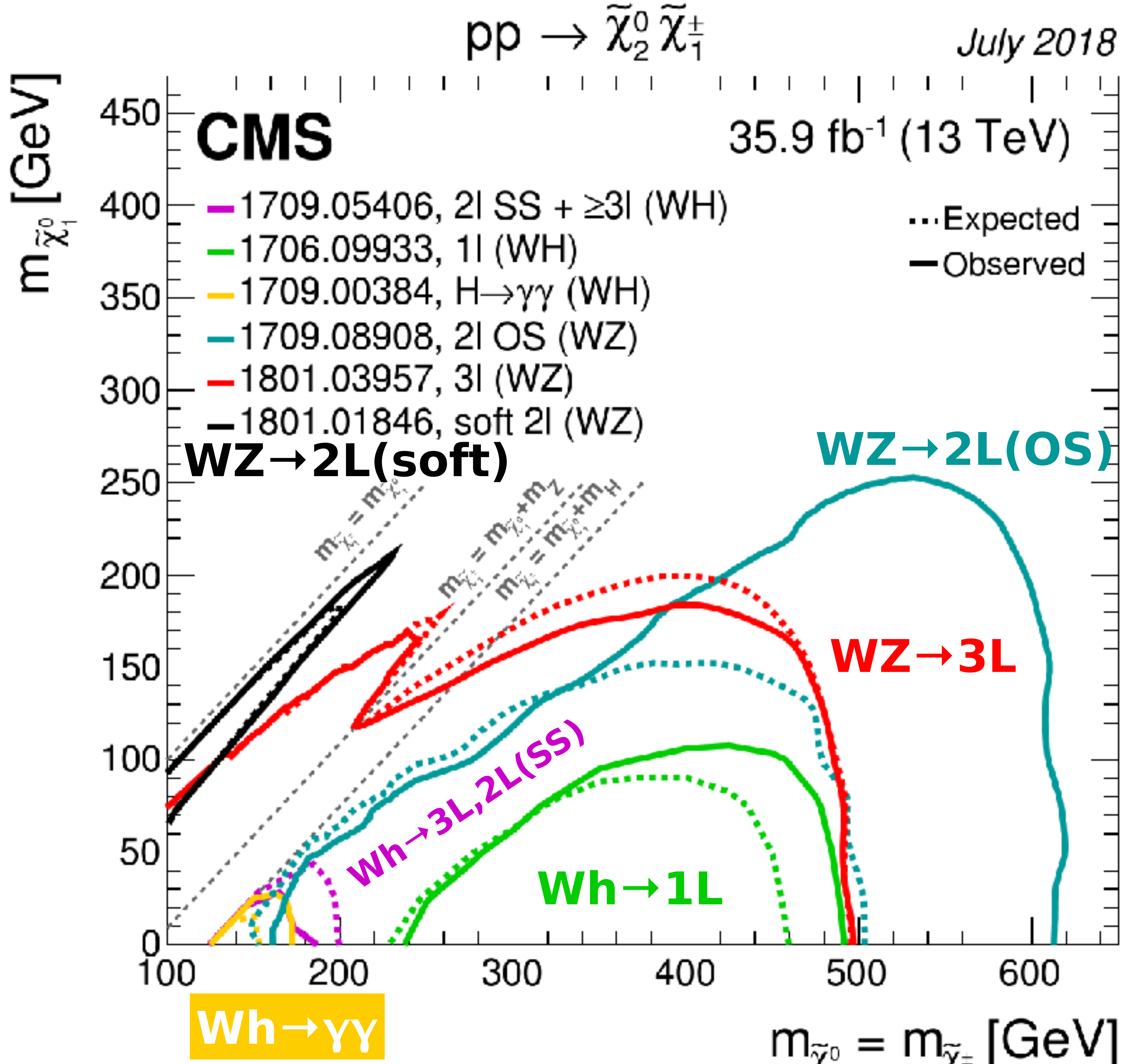


Electroweak Gauginos Searches

- WZ → multi-lepton, Wh → 1L+bb analysis
- Main target is wino production & Bino LSP.
- ATLAS has higgsino LSP direct search.







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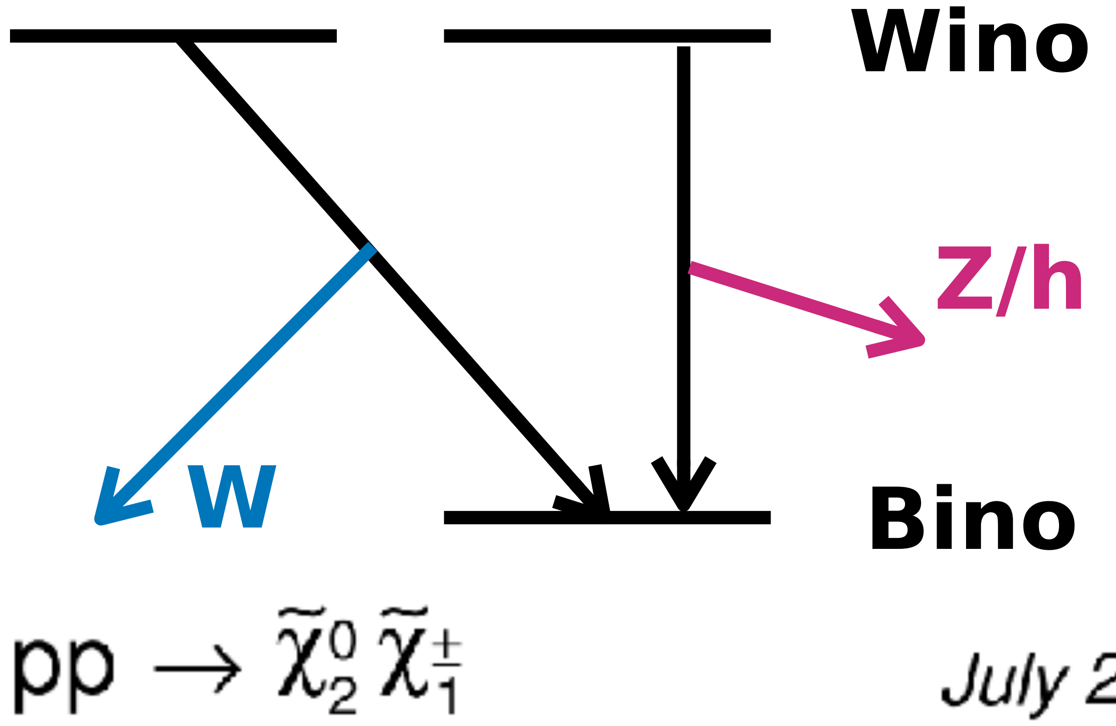
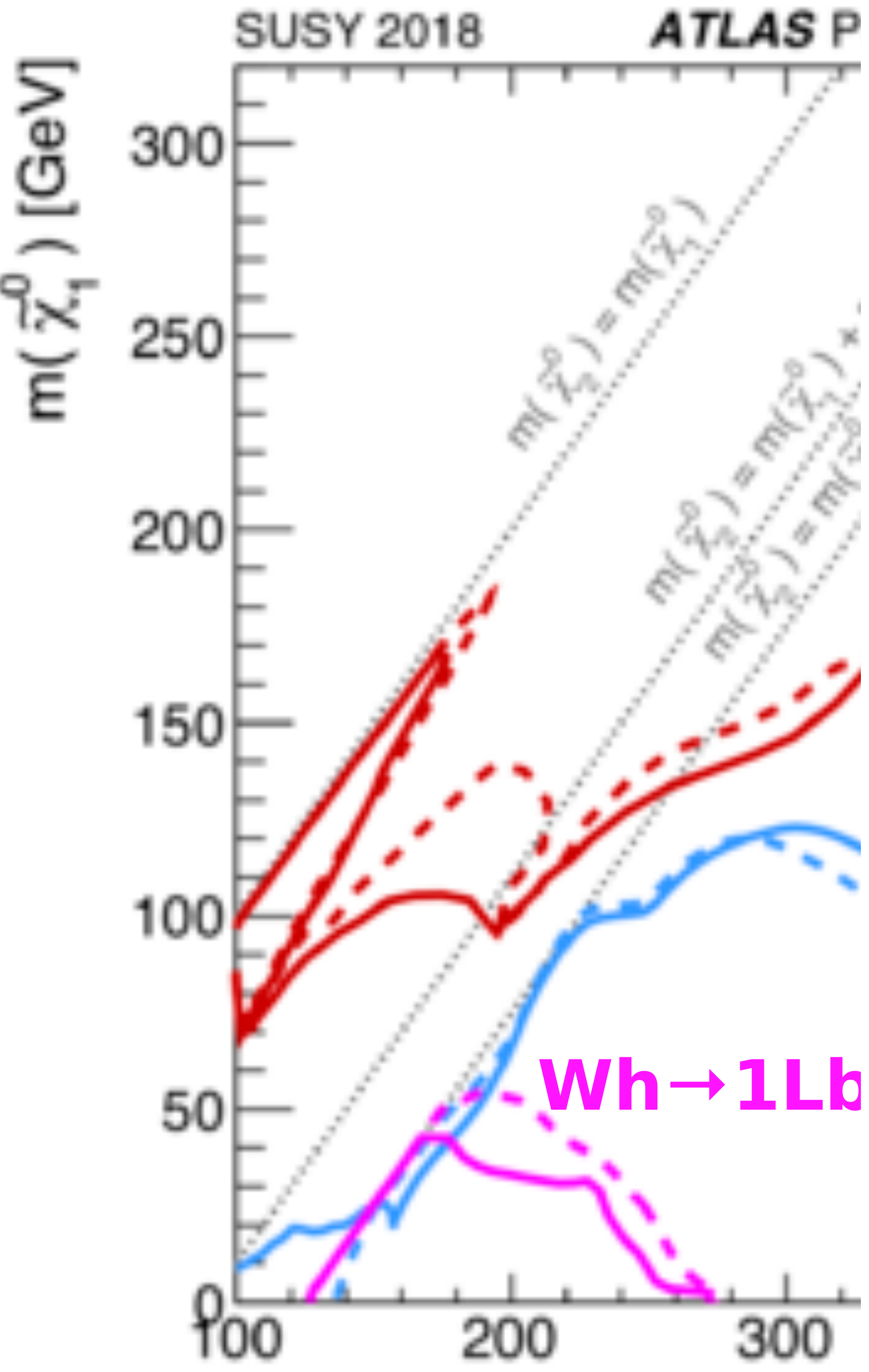
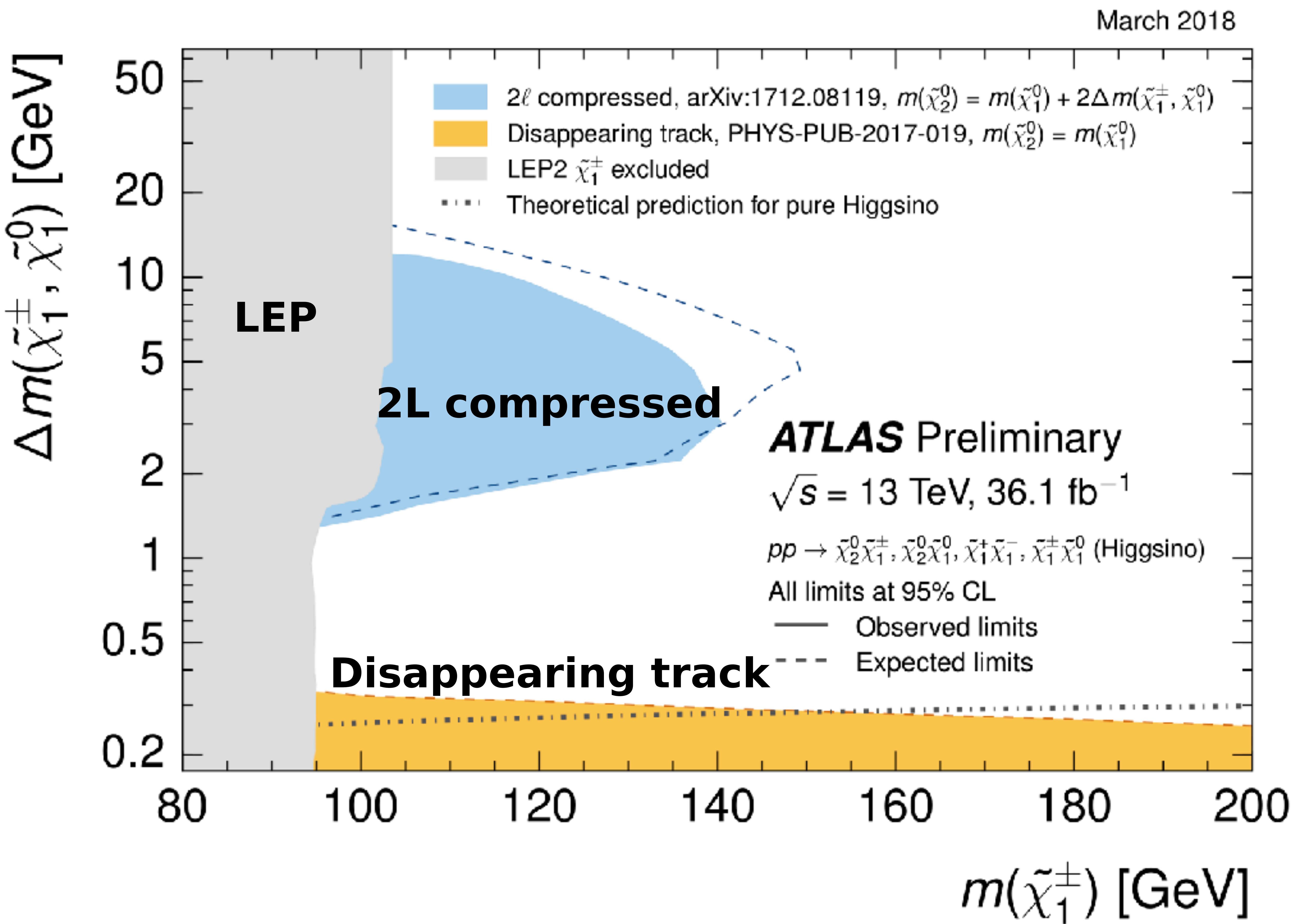
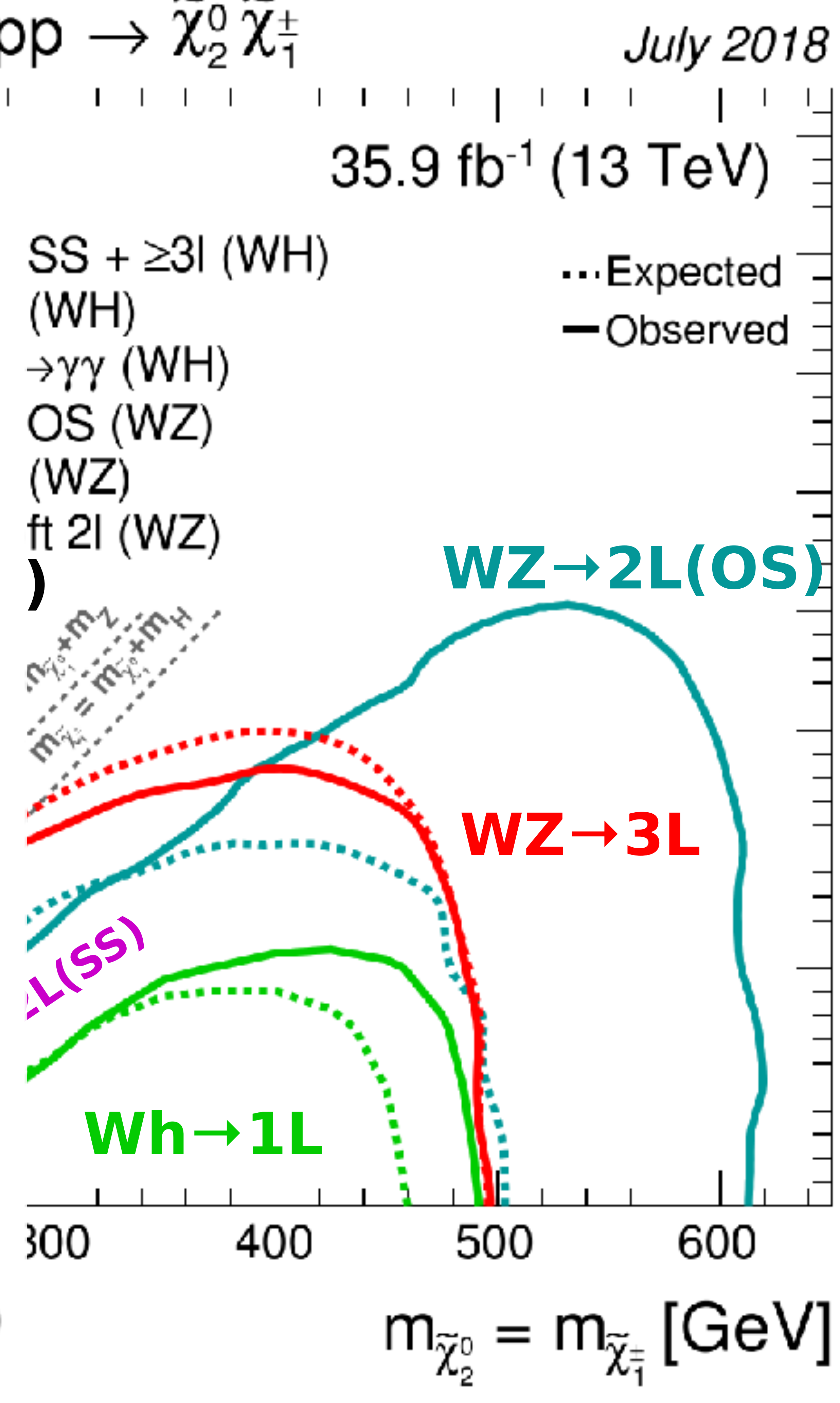


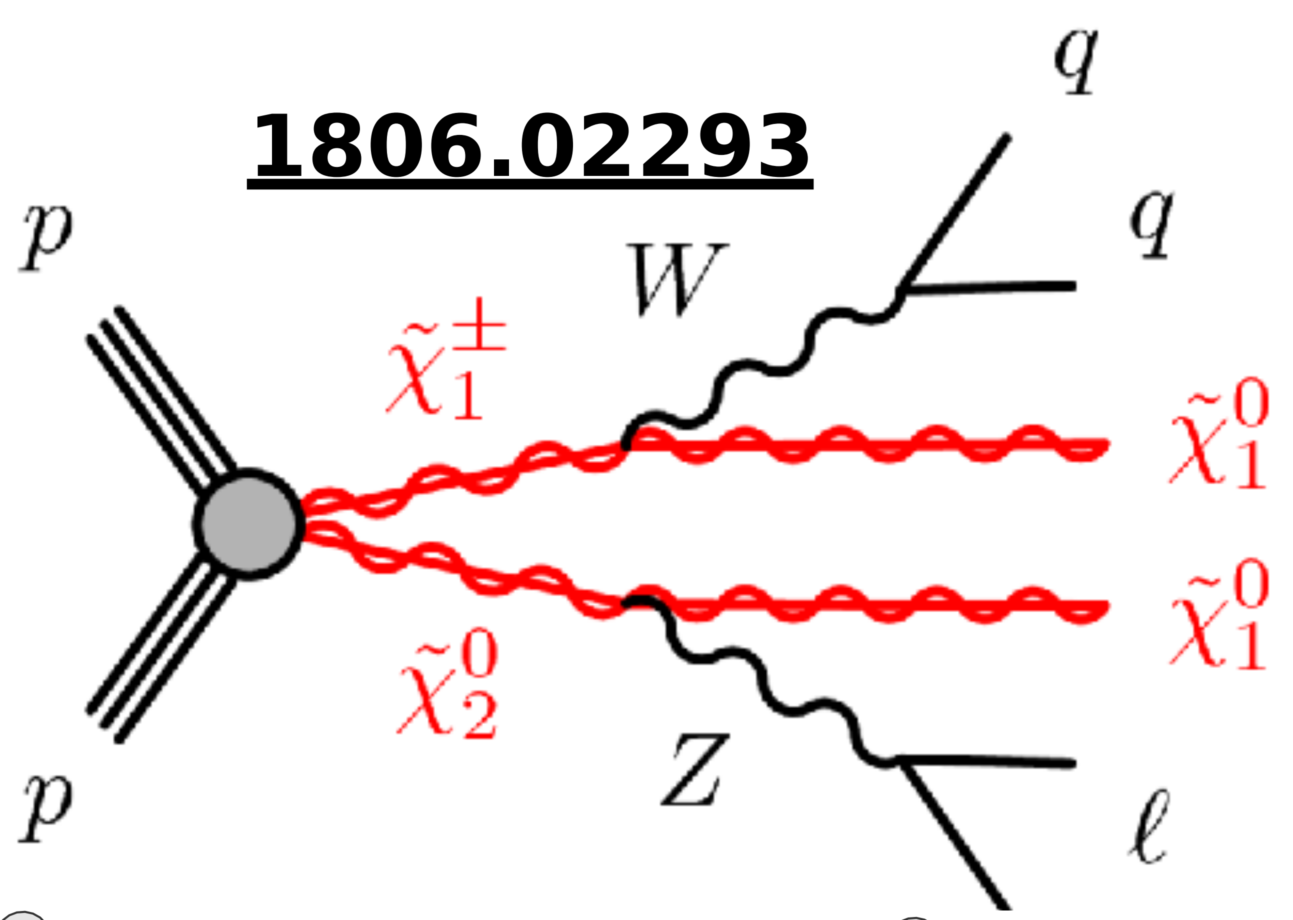




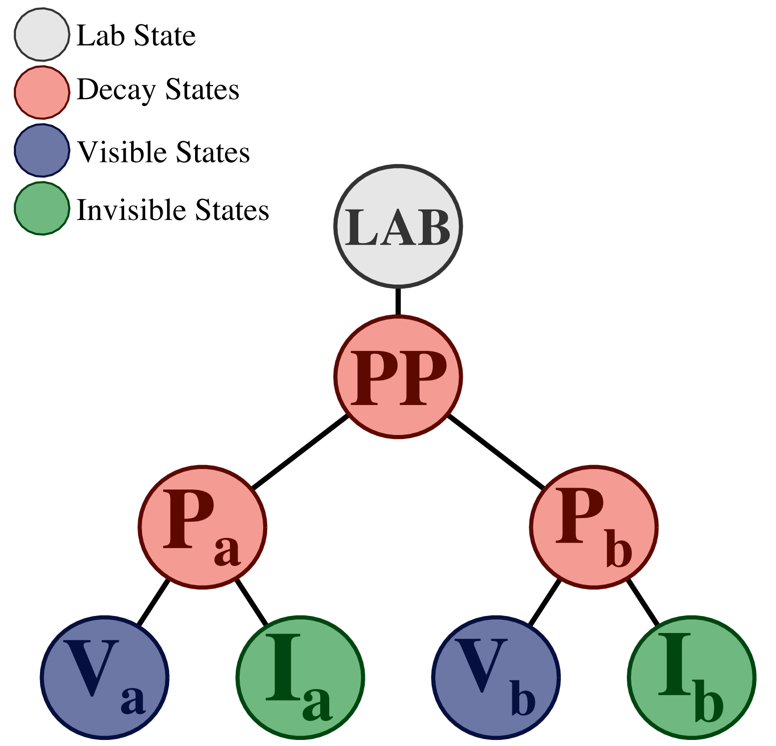


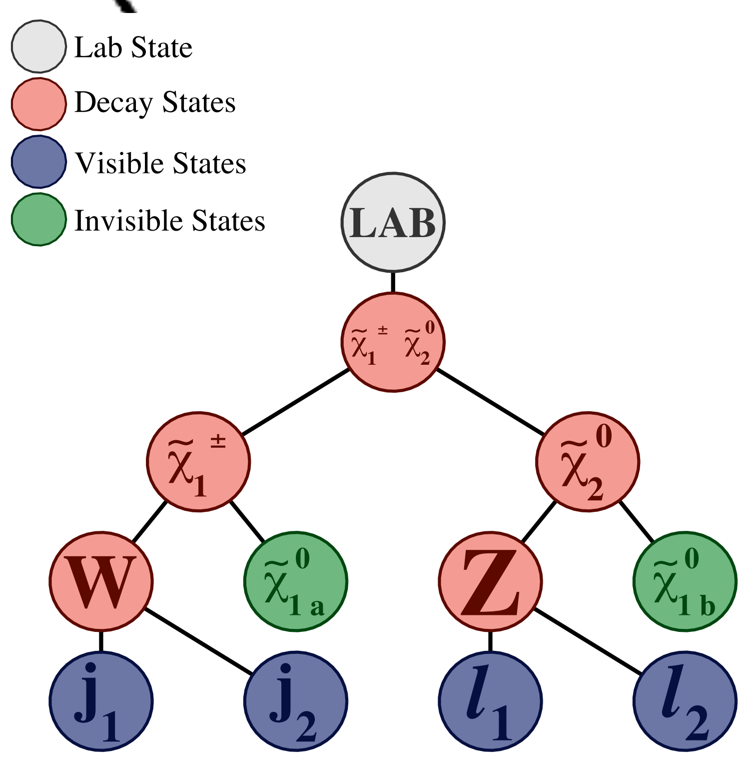
2L/3L RJR Analysis in ATLAS 36/fb

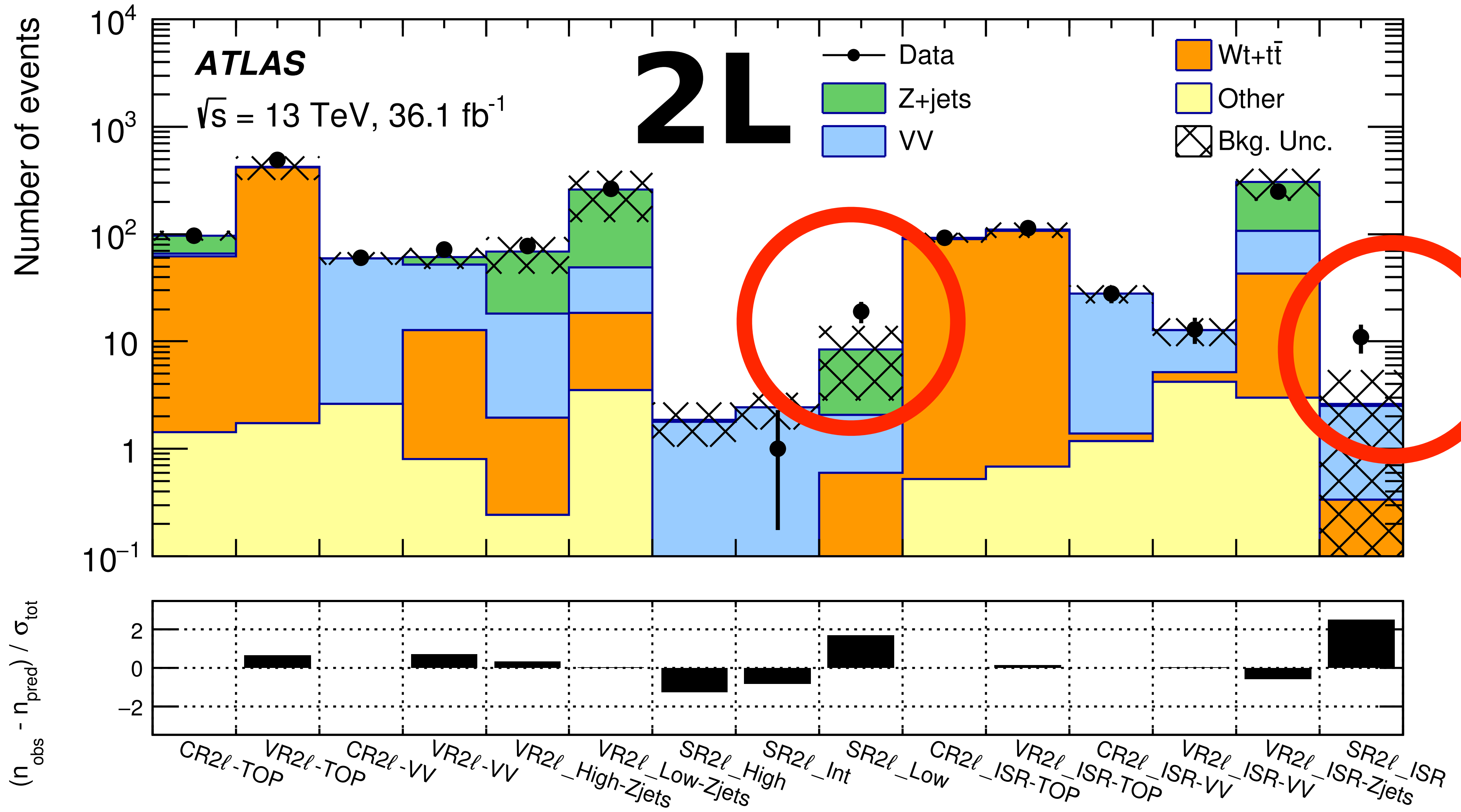
1806.02293

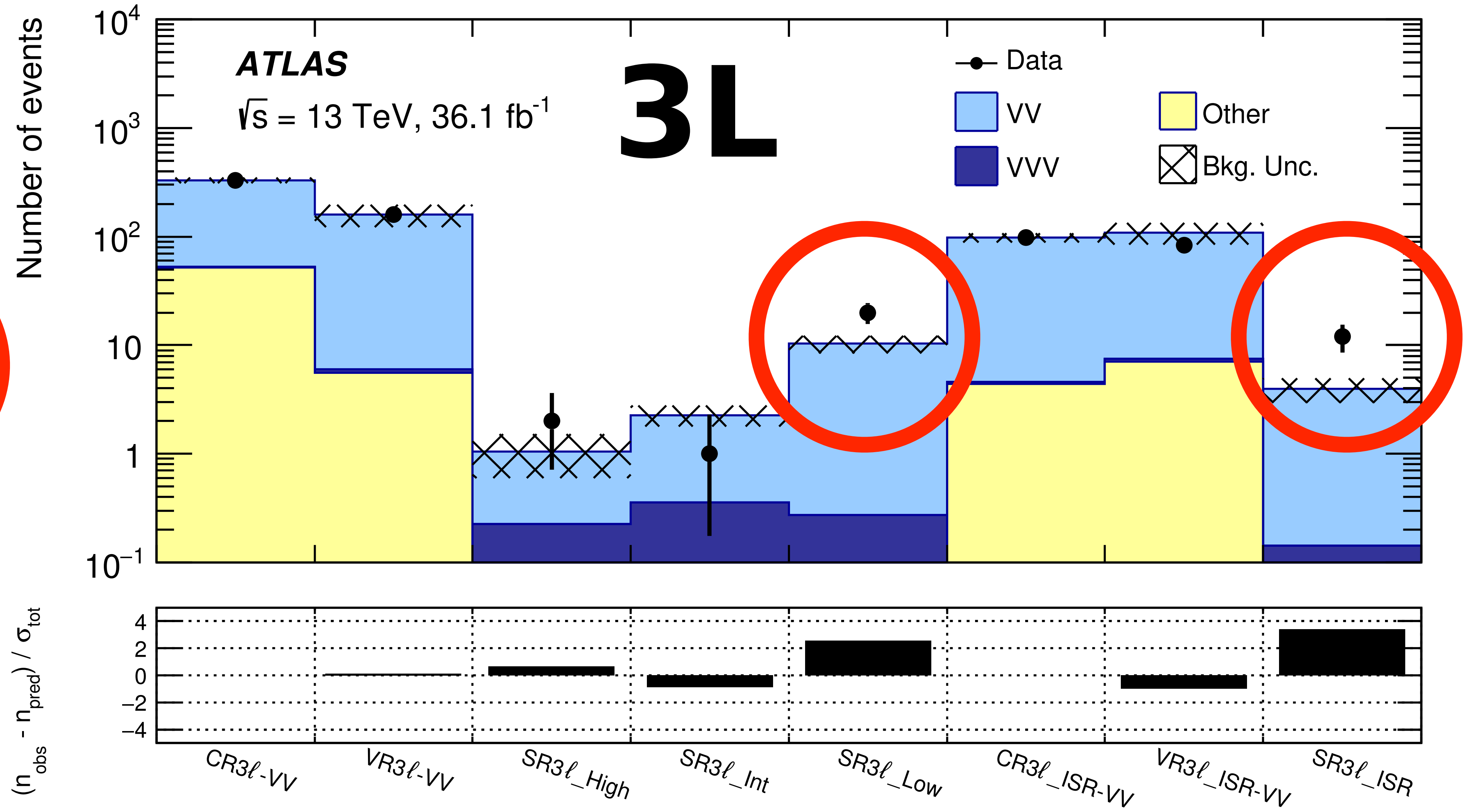


- **Recursive Jigsaw Reconstruction(**RJR, 1705.10733)
  - Extended of RAZOR(1006.2727), reconstruct decay chain
  - Using reconstructed "RJ variable" for kinematic selection
- **Signal Region** : 4 bin(ΔM) x 2L/3L → 8 regions.
- **Background Estimation** :
  - Diboson : Correction from CR extrapolate to SR
  - Z+jets : gamma+jet method(γ replaced to Z)
- **Results** : 2~3σ excess at independent SRs.



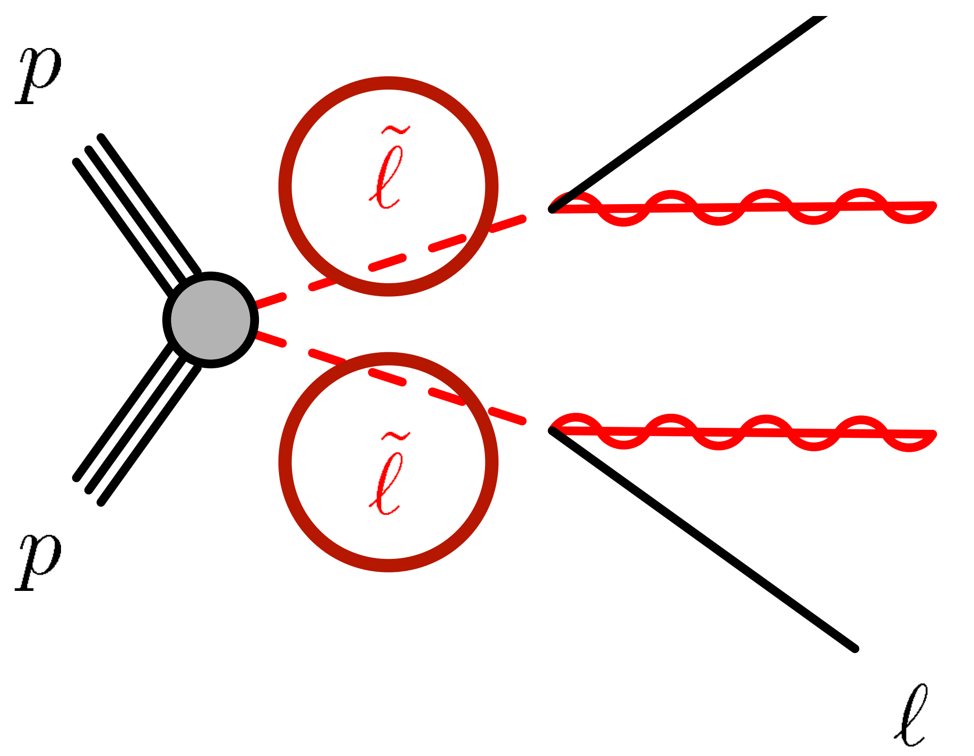


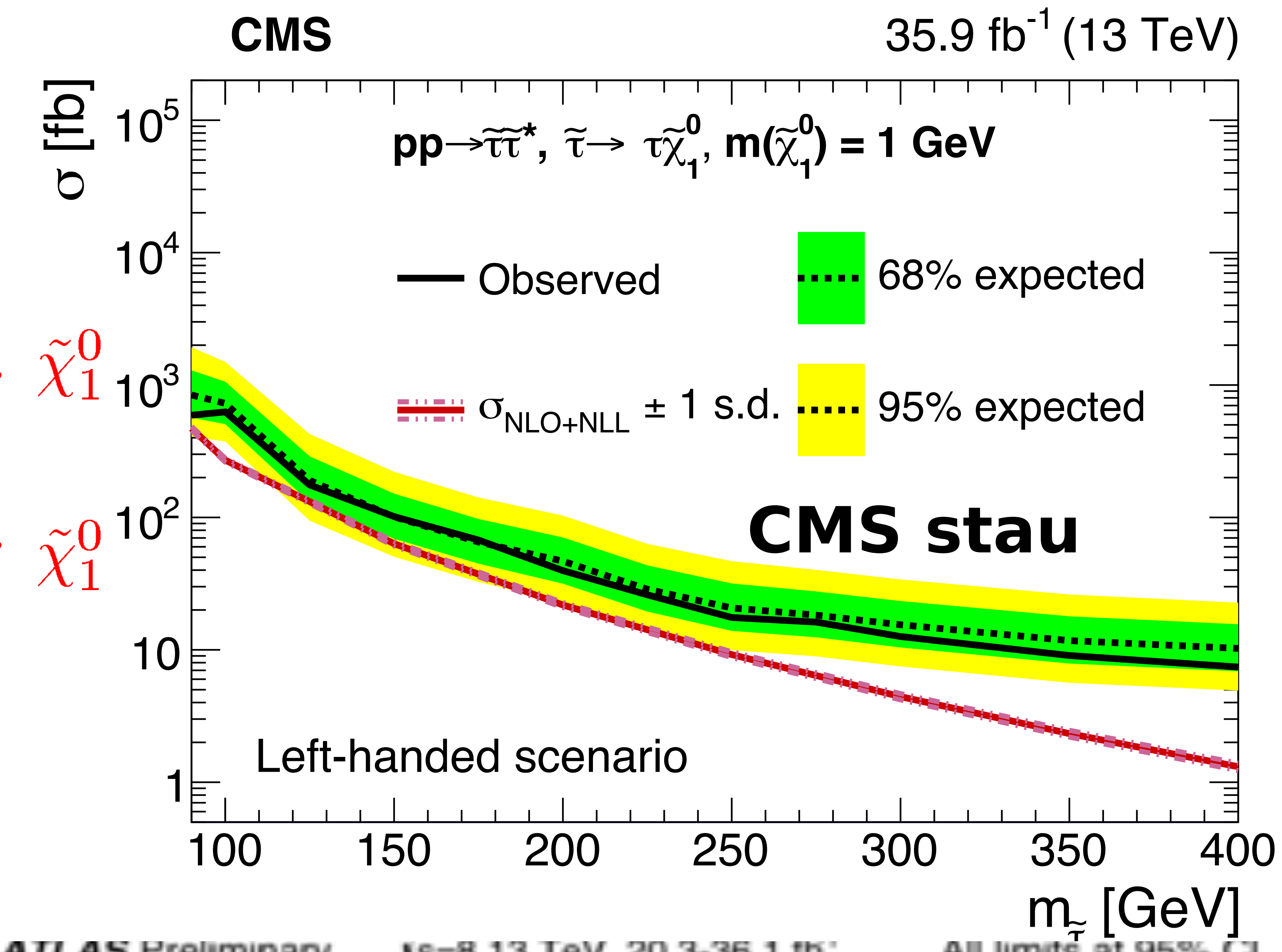




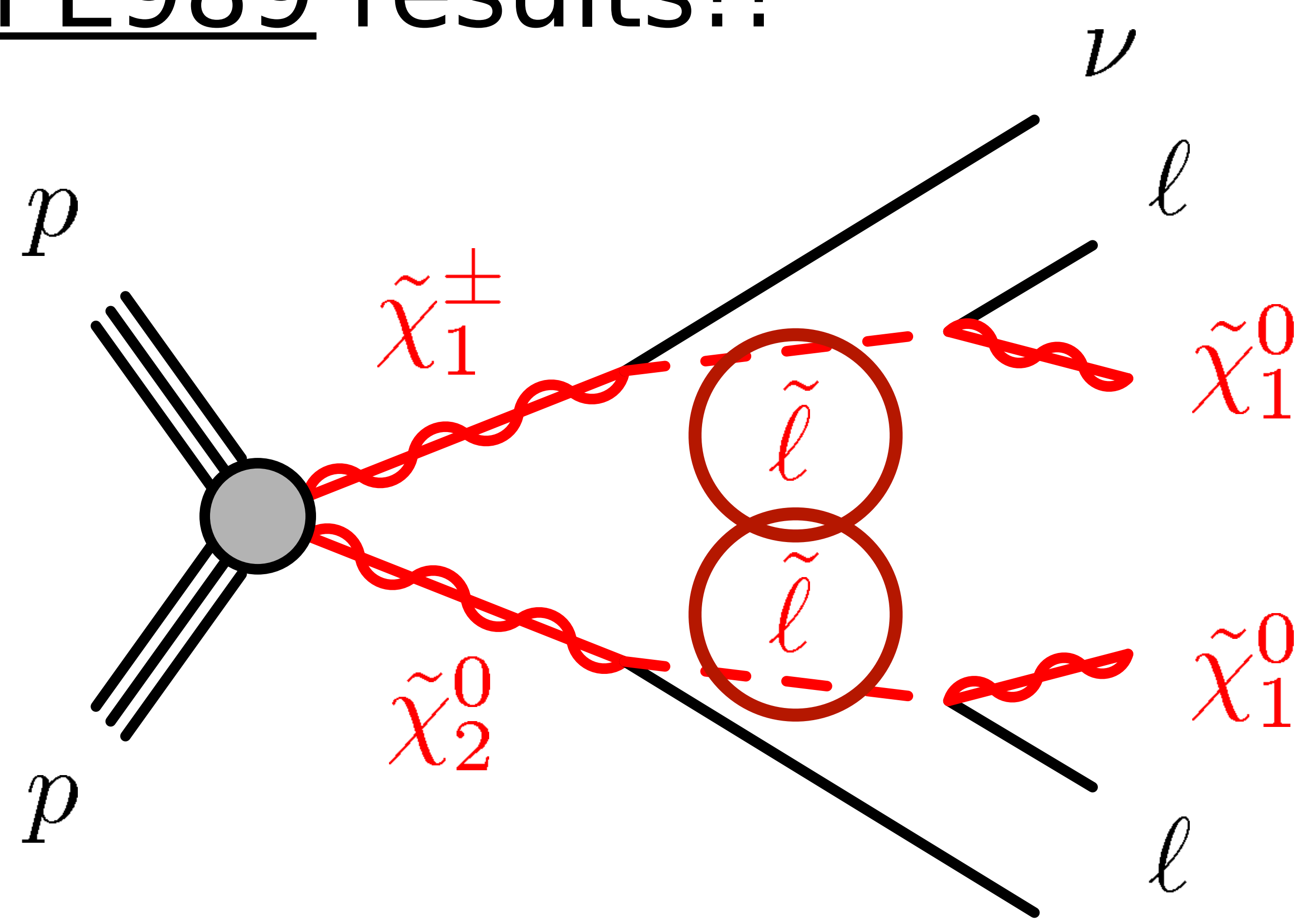
Slepton Search

- **Direct search** : very small cross-section
  - CMS light-flavor slepton(**1806.05264**)
  - CMS stau(**1807.02048**)
  - No significant excess on both analysis..

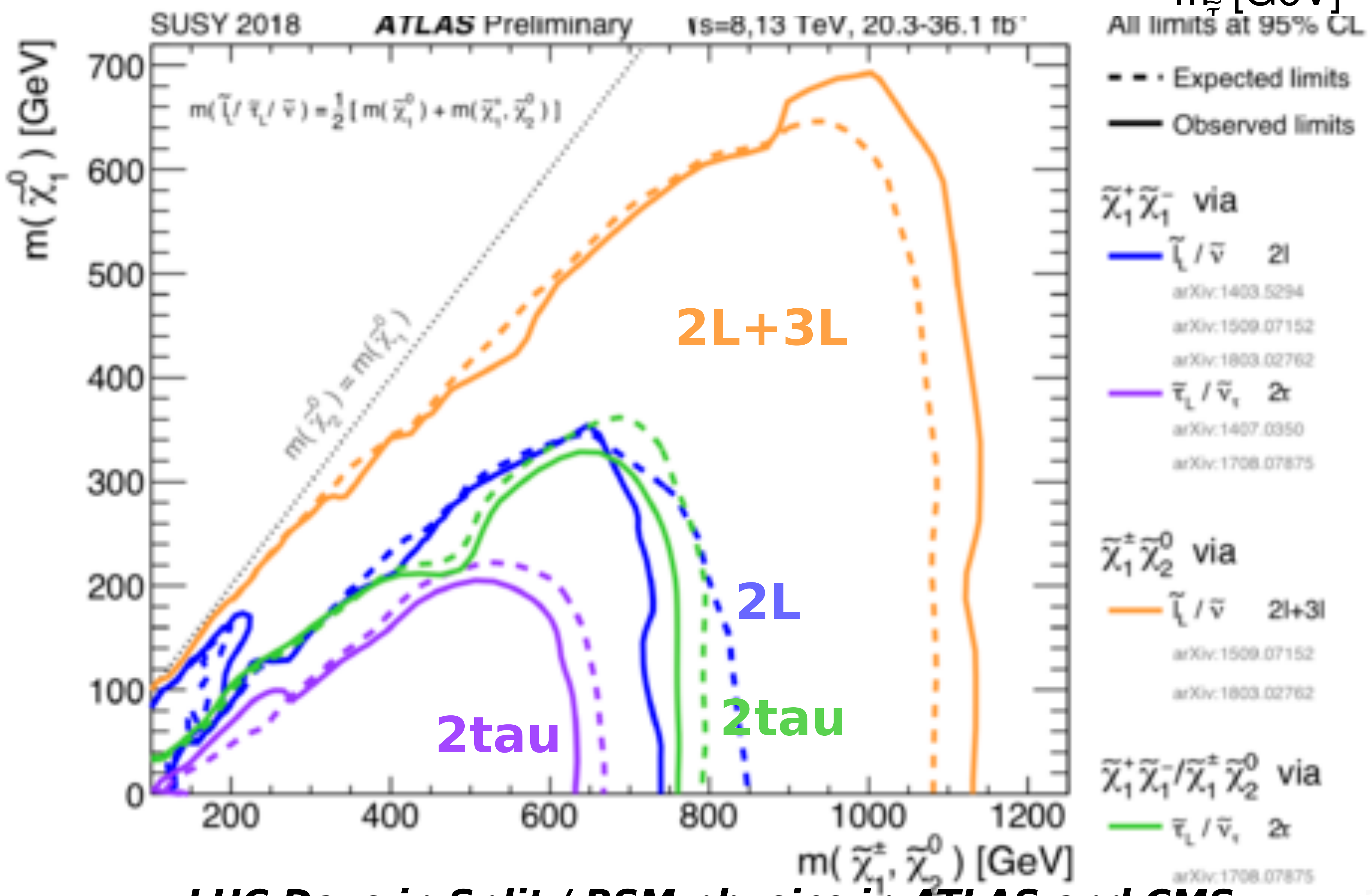




- **Gaugino to slepton** : well motivated from g-2 anomaly(1309.3065)
  - Will be (possibly) interesting topic depending on Fermi E989 results!!

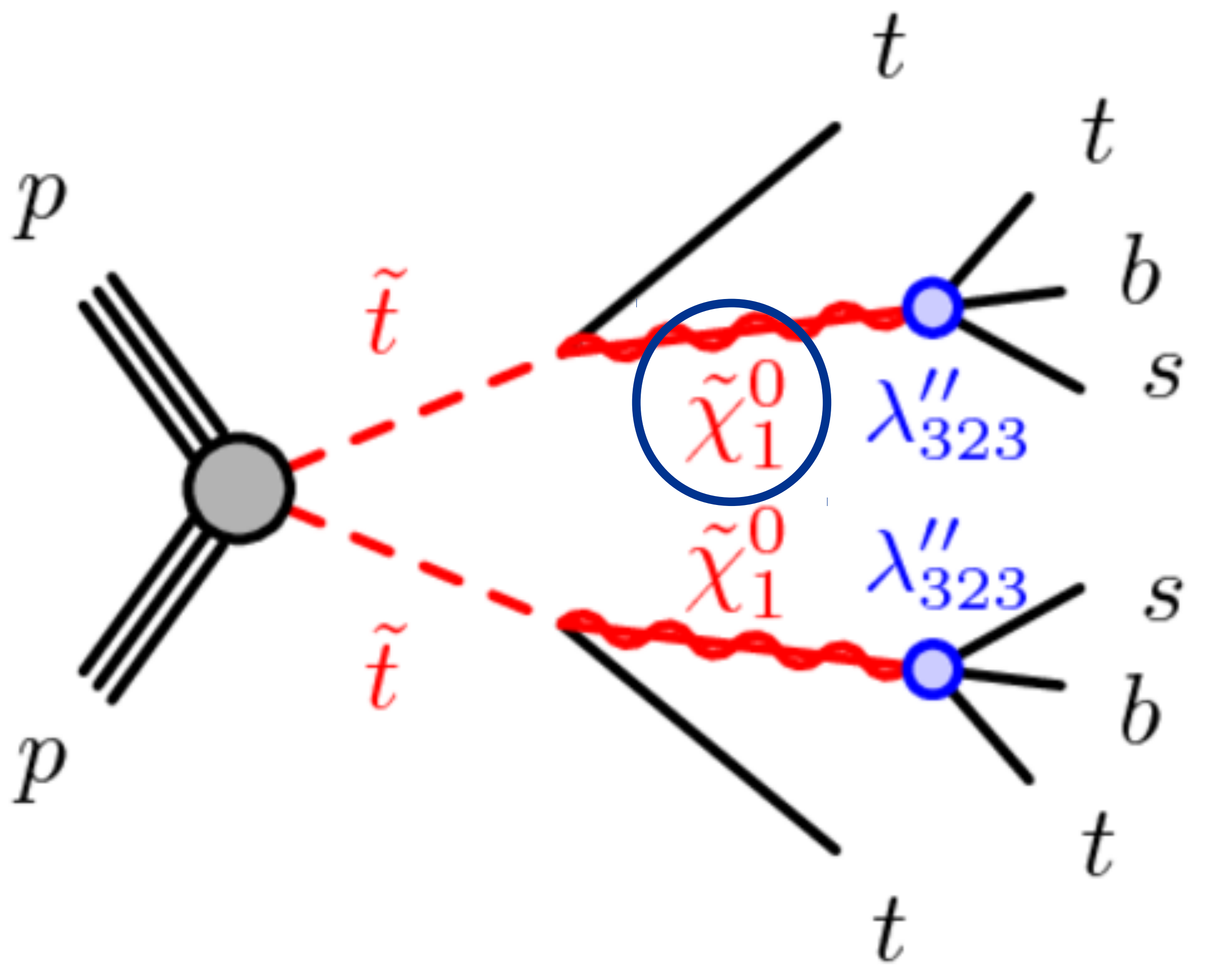


Leptonic BR 100%
(c.f. WZ mediated 2%)



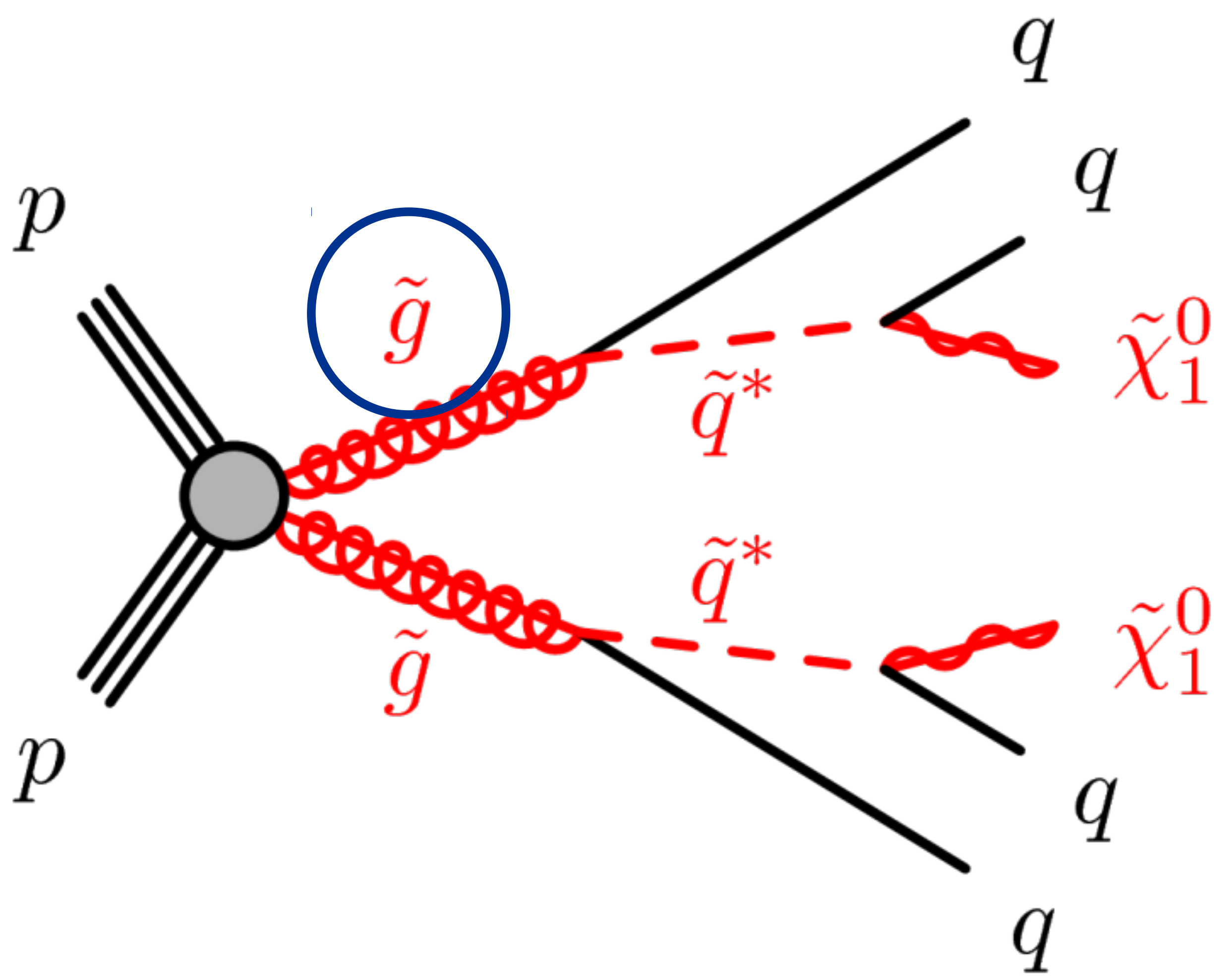
Long-Lived SUSY Searches

- Why long-lived SUSY particles are long lived?



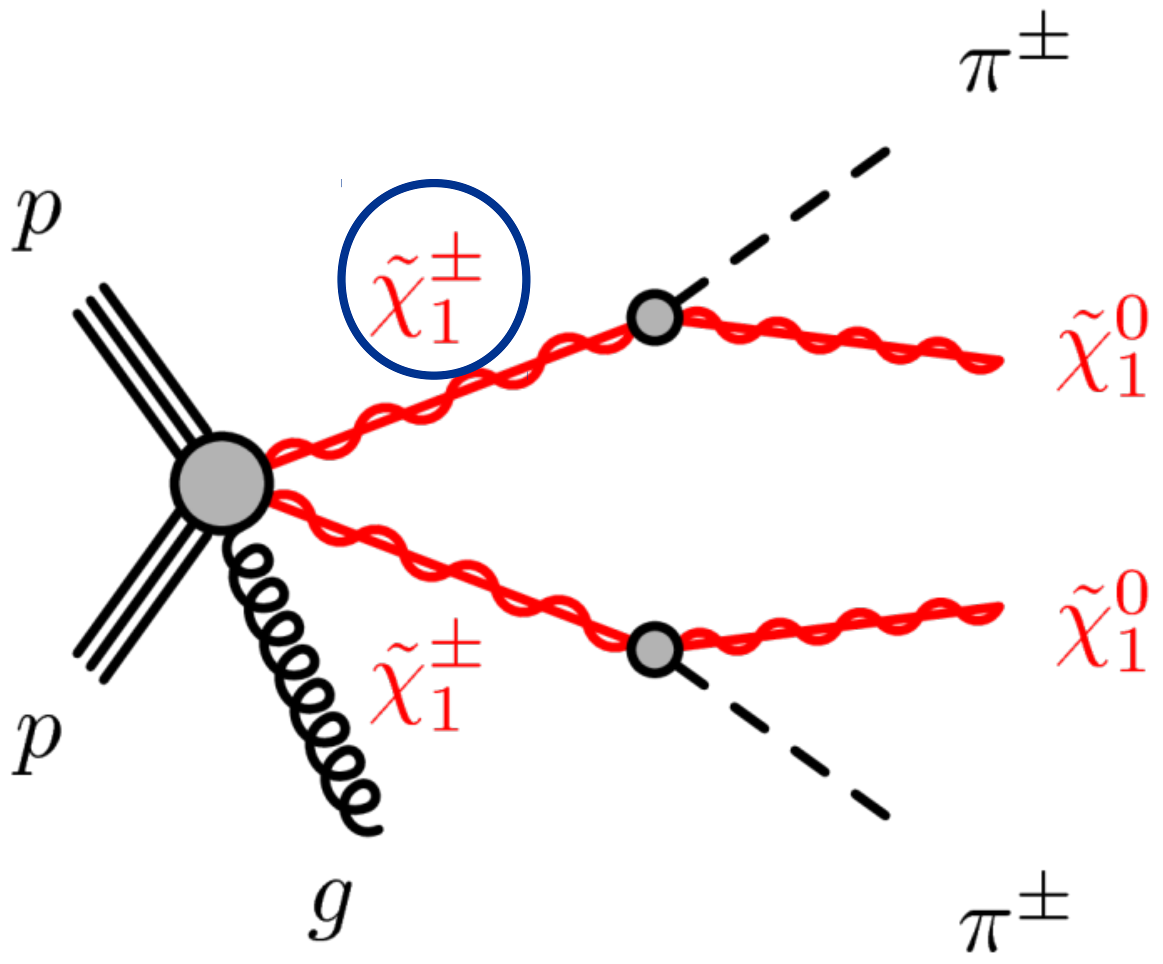
Small Coupling Case

- e.g. Small RPV coupling
- e.g. Gravity(into gravitino)



Heavy intermediate particle

- e.g. 10TeV squark → gluinos
- e.g. 100TeV higgsino → wino/bino



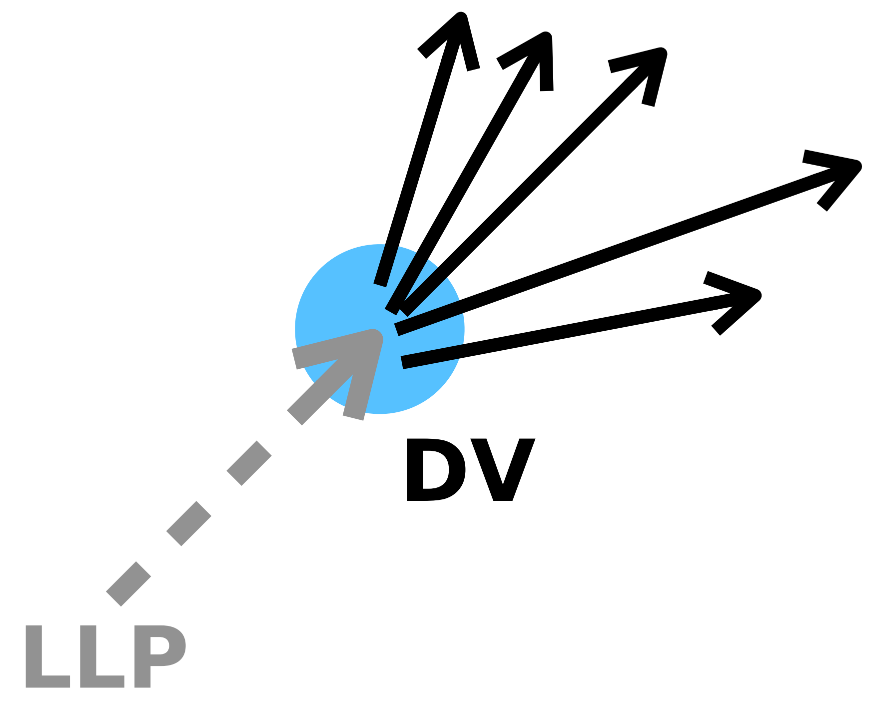
Small ΔM

- e.g. pure wino LSP(ΔM~160MeV)

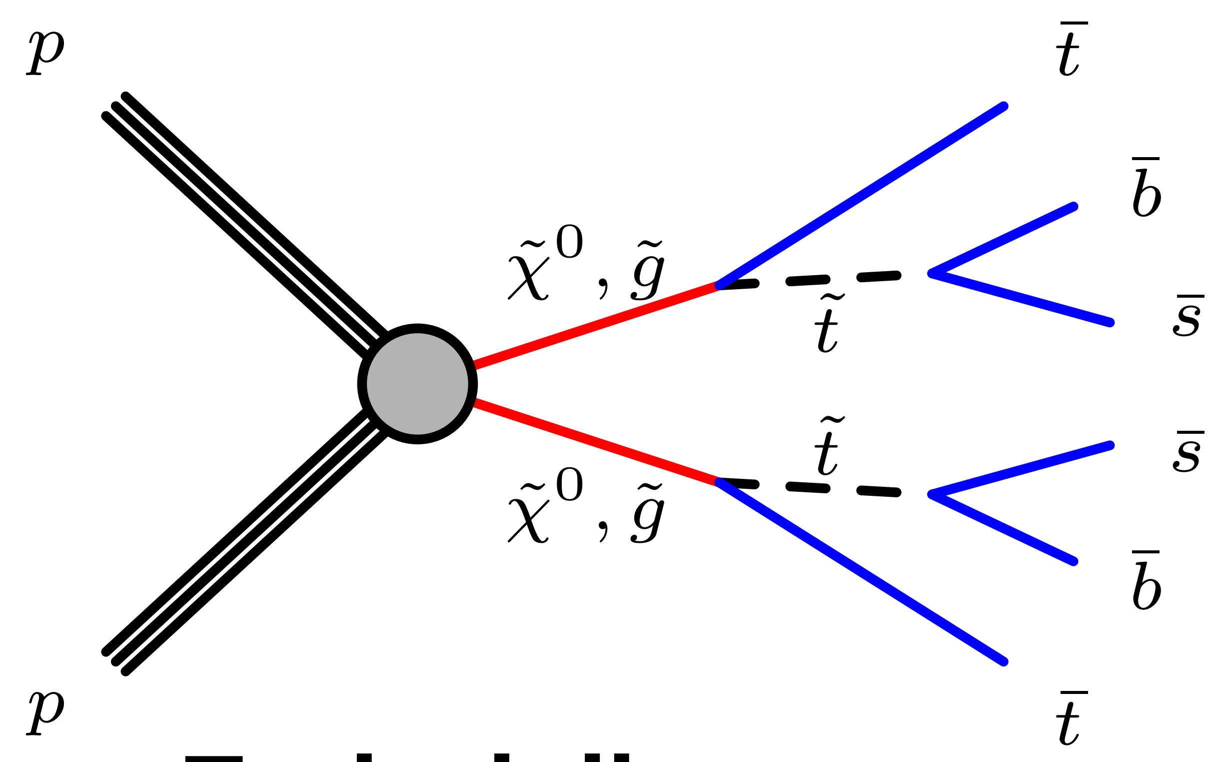
- How can we detect long-lived particle(LLP)?
  - Detect LLP itself at detector → Large dE/dx, disappearing track
  - Detect SM particle from LLP decay → Displaced vertex, displaced late photon…

Displaced Vertex(DV) with jets in CMS @38.5/fb

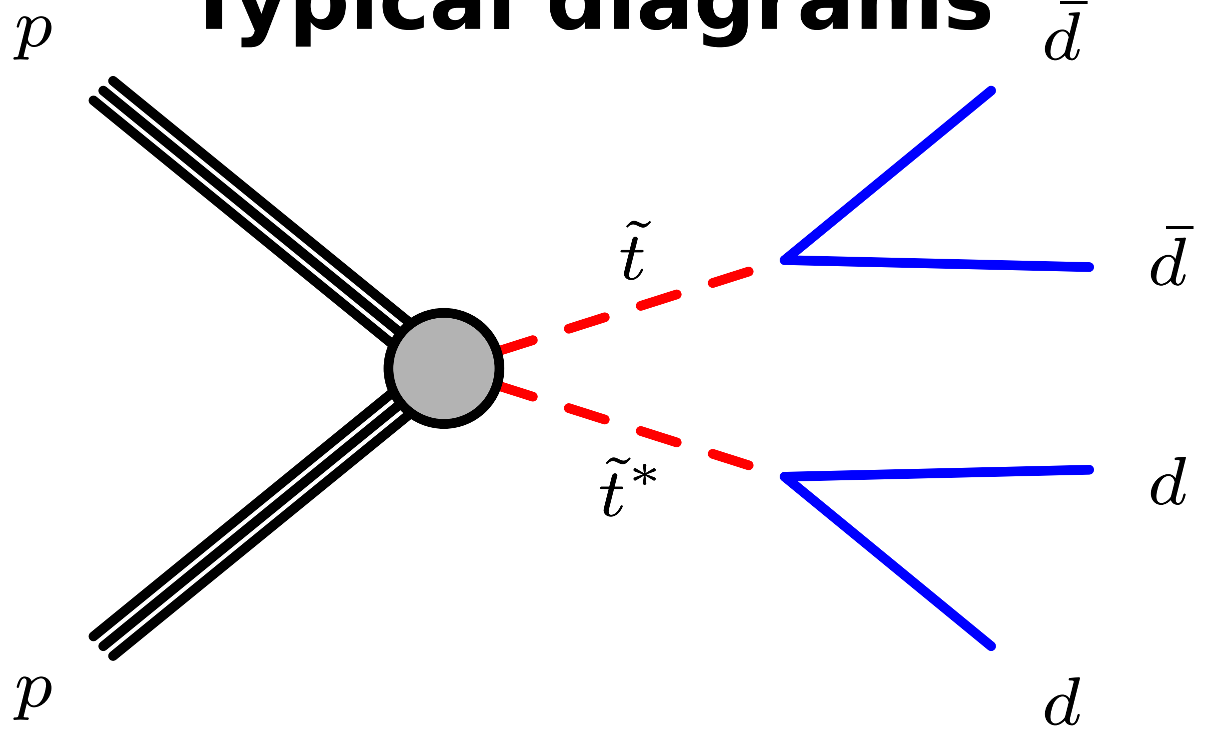
PAS-EXO-17-018

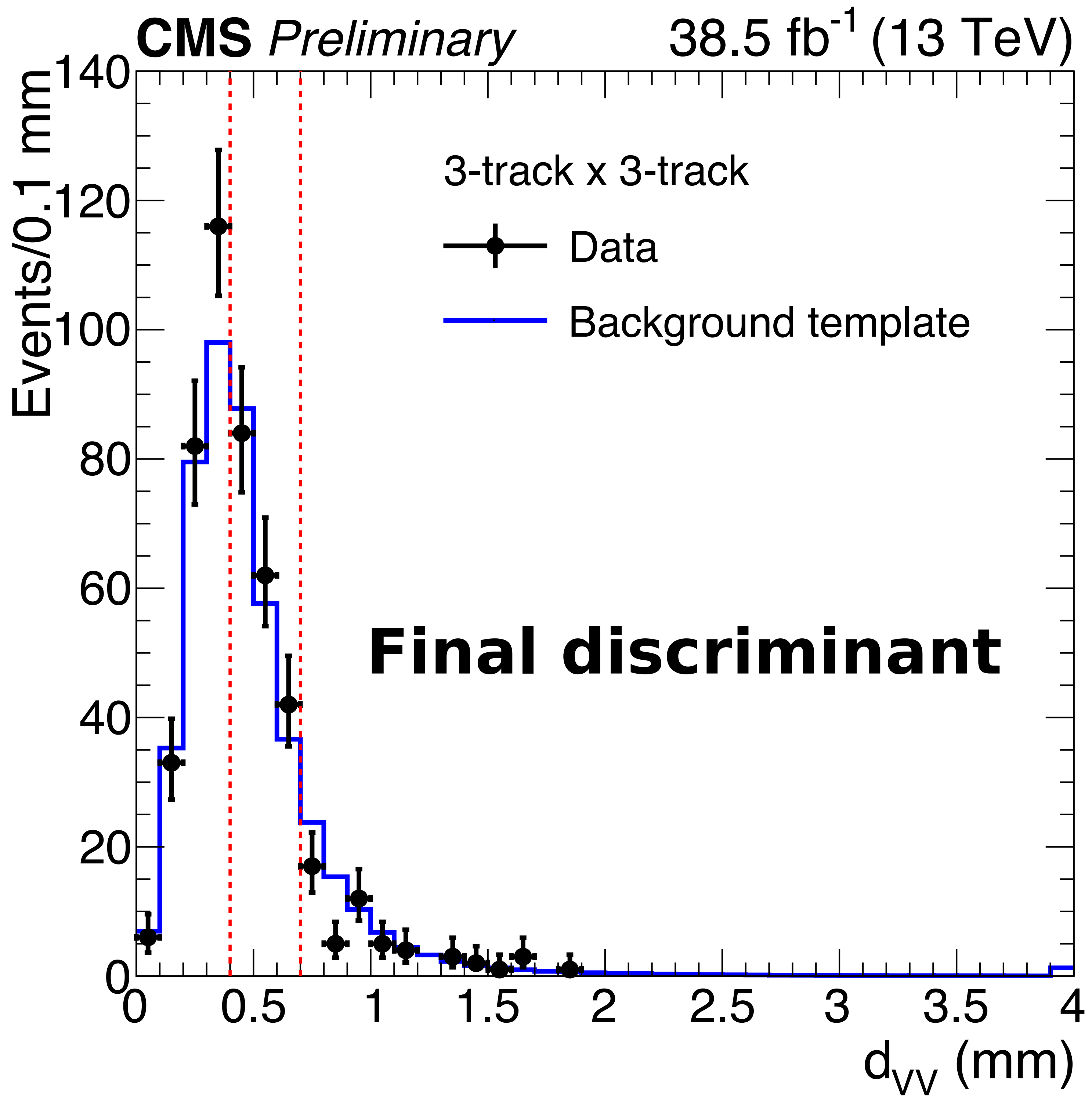


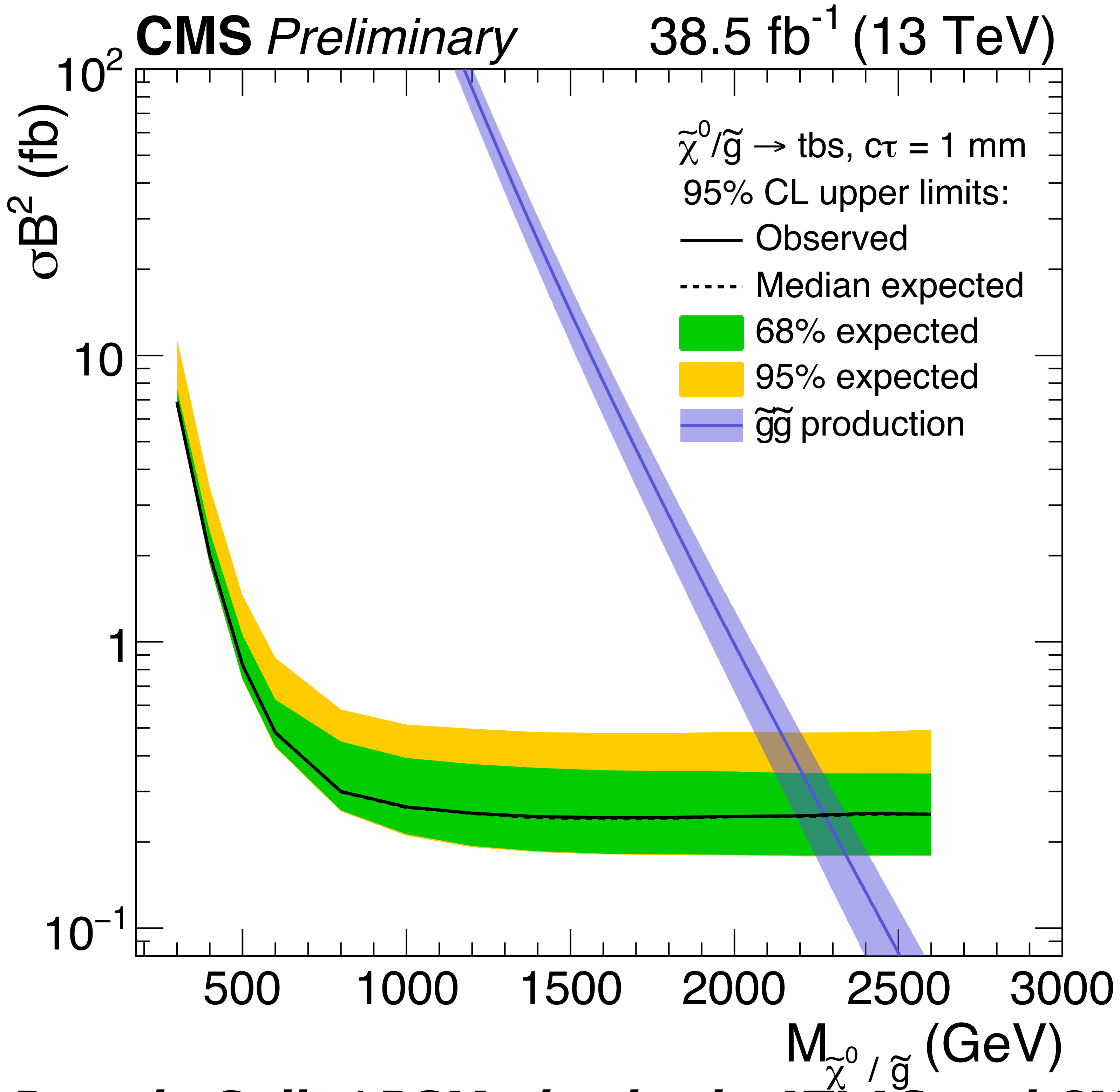
- **LLP pair production → 2 DV at event !!**
  - DV : at least 5 tracks(pT>1GeV, σ_{d0}>4, d_0 < 20mm)
  - Final discriminant : distance between two DVs
- **Background** : random crossing → Using data template
  - Add track randomly to 1DV data sample
- No significant excess…



Typical diagrams



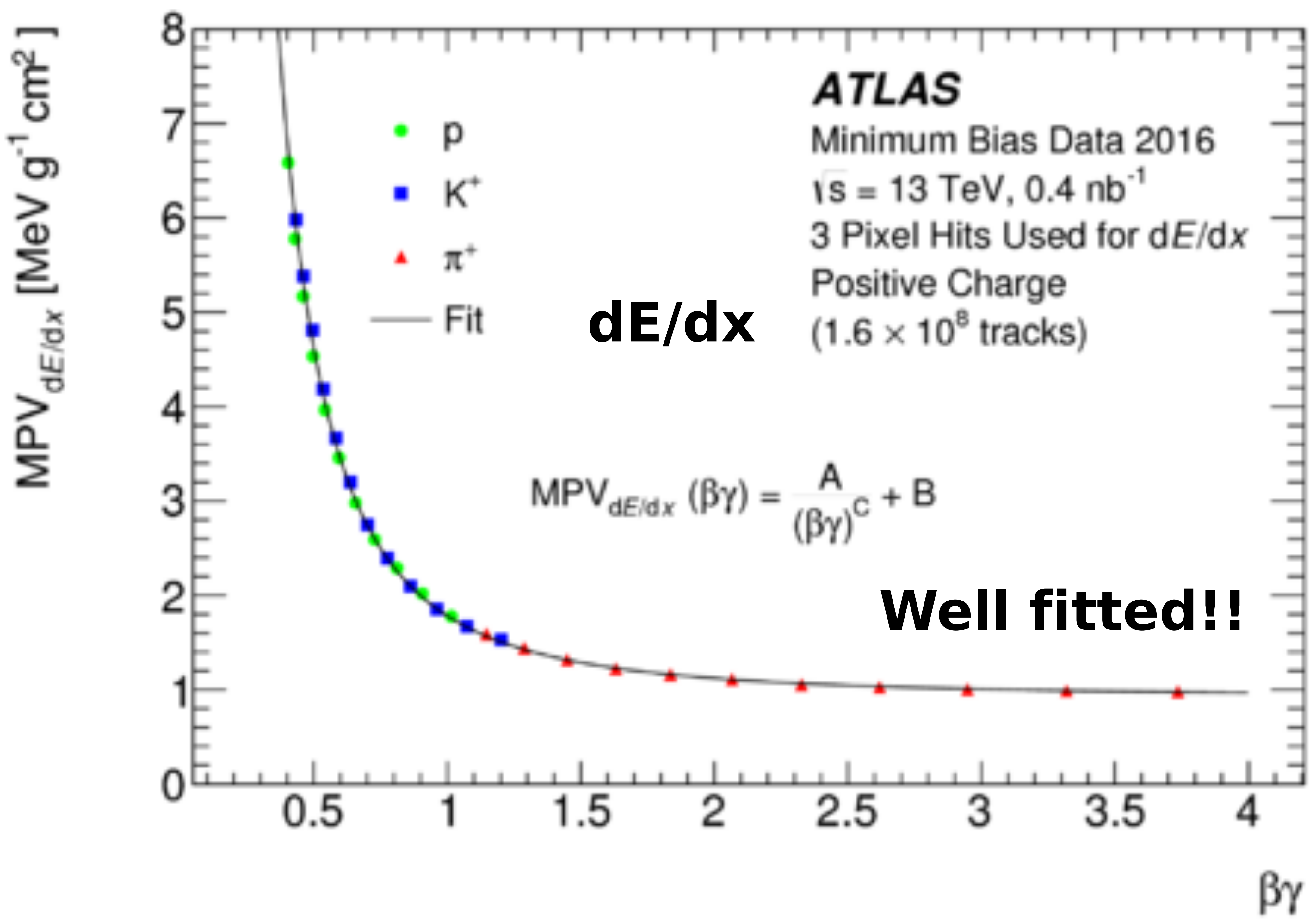


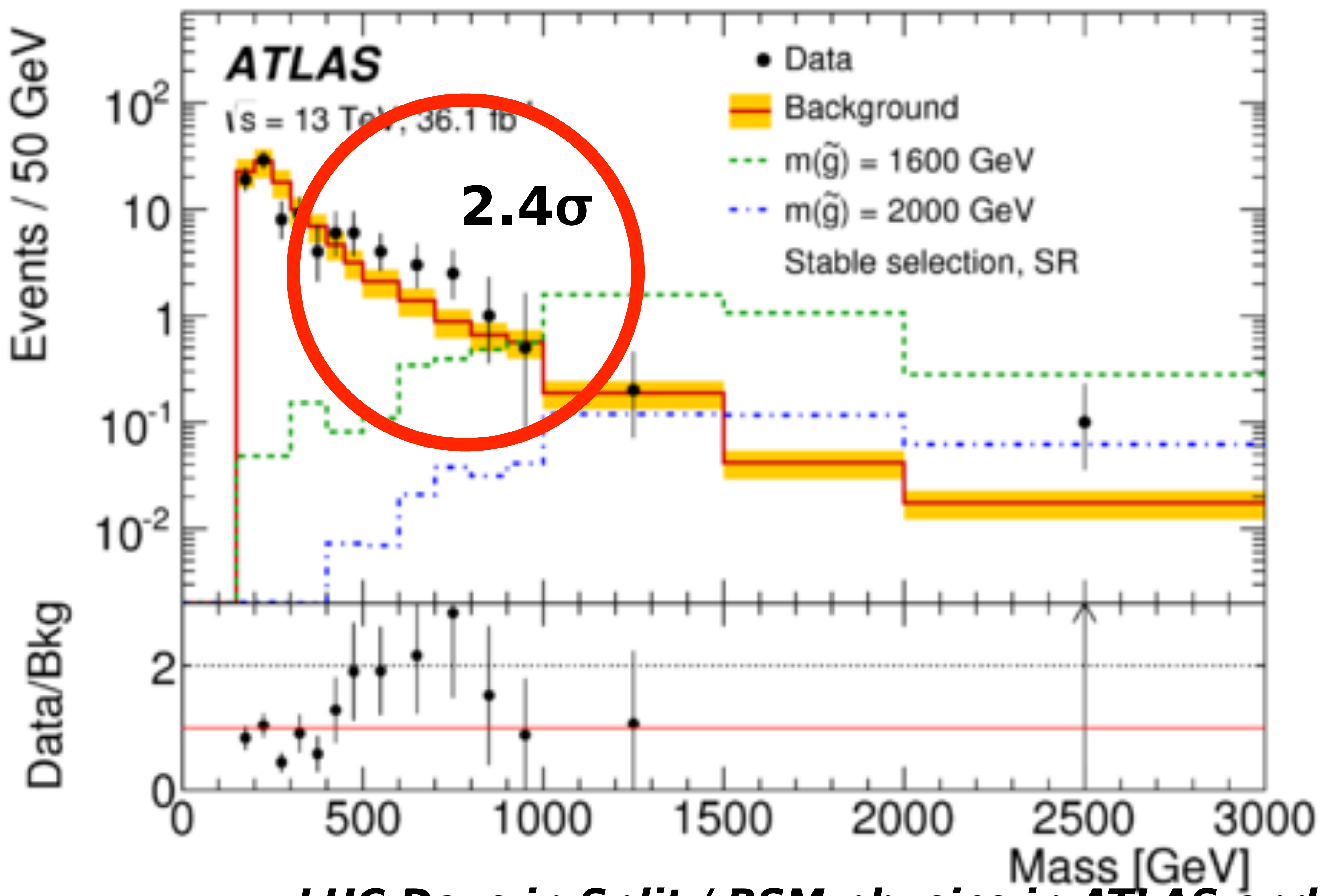


Pixel dE/dx Search in ATLAS @36/fb

<u>**CONF-SUSY-2016-31**</u>

- **Stable charged particle w/ τ > 1nsec :** measure track dE/dx on Pix detector
  - Calibrate proton/Kaon/pion using minimum bias sample
  - Estimate βγ from dE/dx
- **Background** : Estimated by template from low E_T^{miss} and low dE/dx region.
- 2.4σ local excess around long lifetime SR!!(Of course, might be small w/ global p-value.)





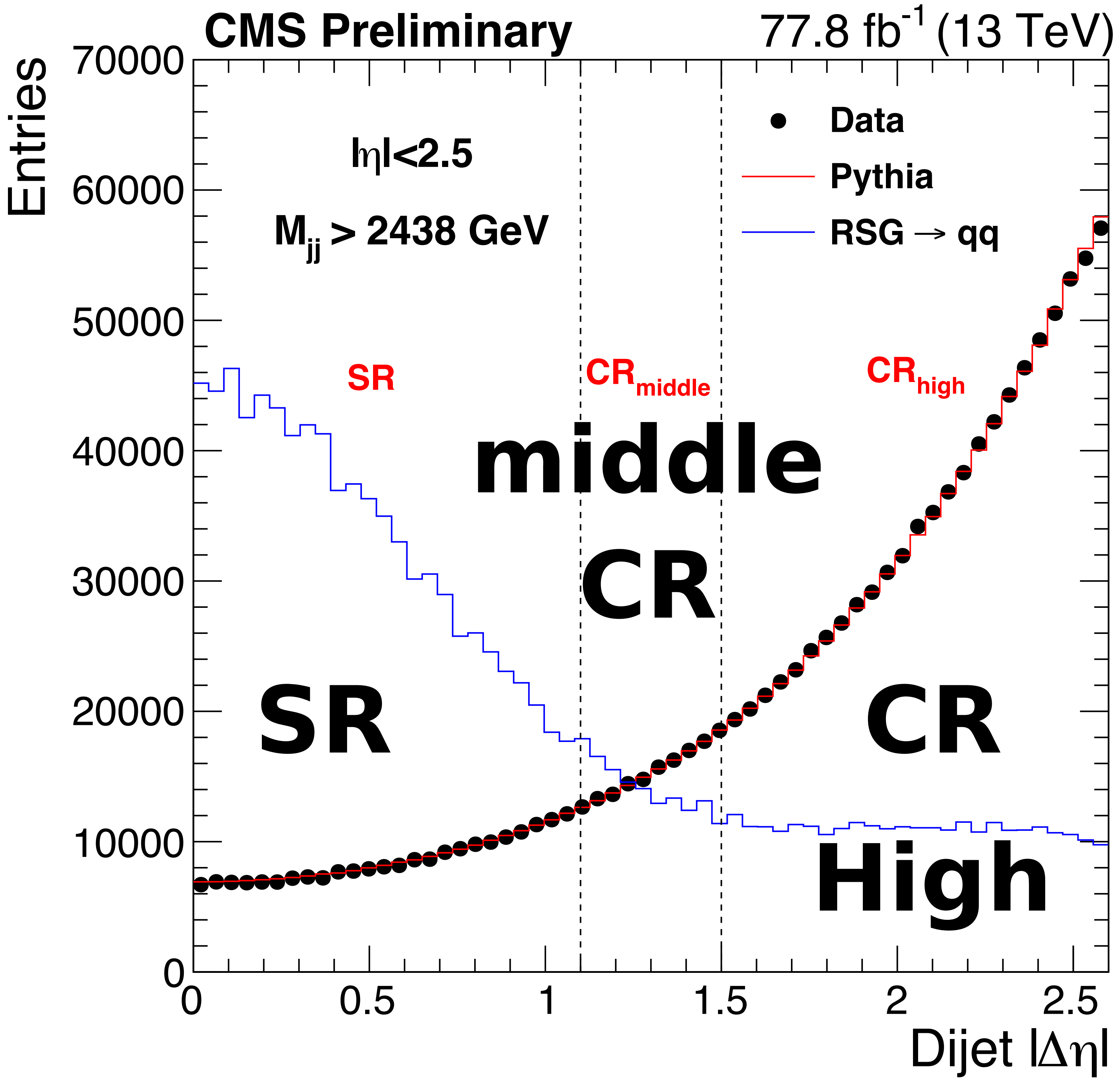
Exotic Analysis

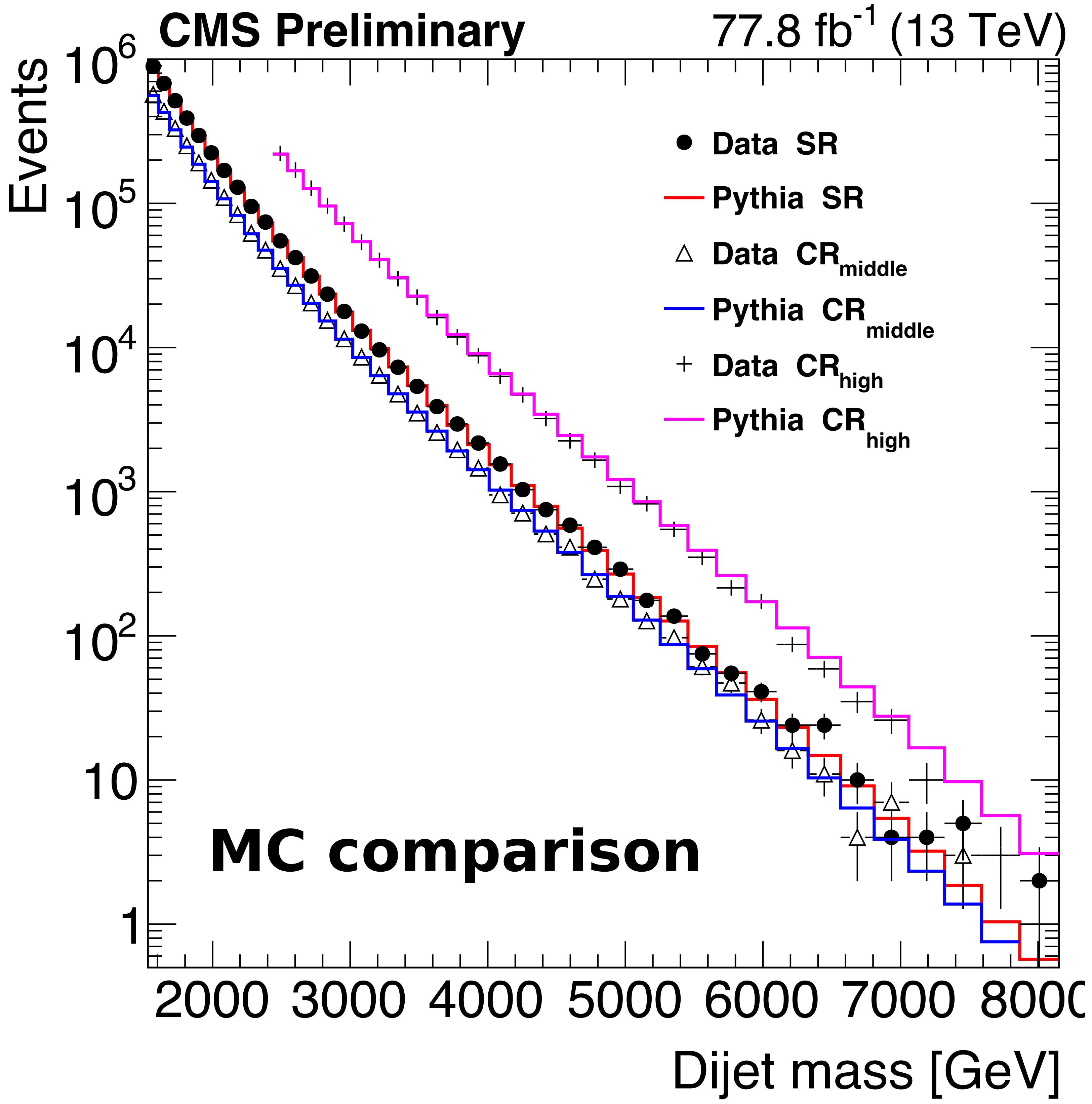
Dijet Signature in CMS @78/fb

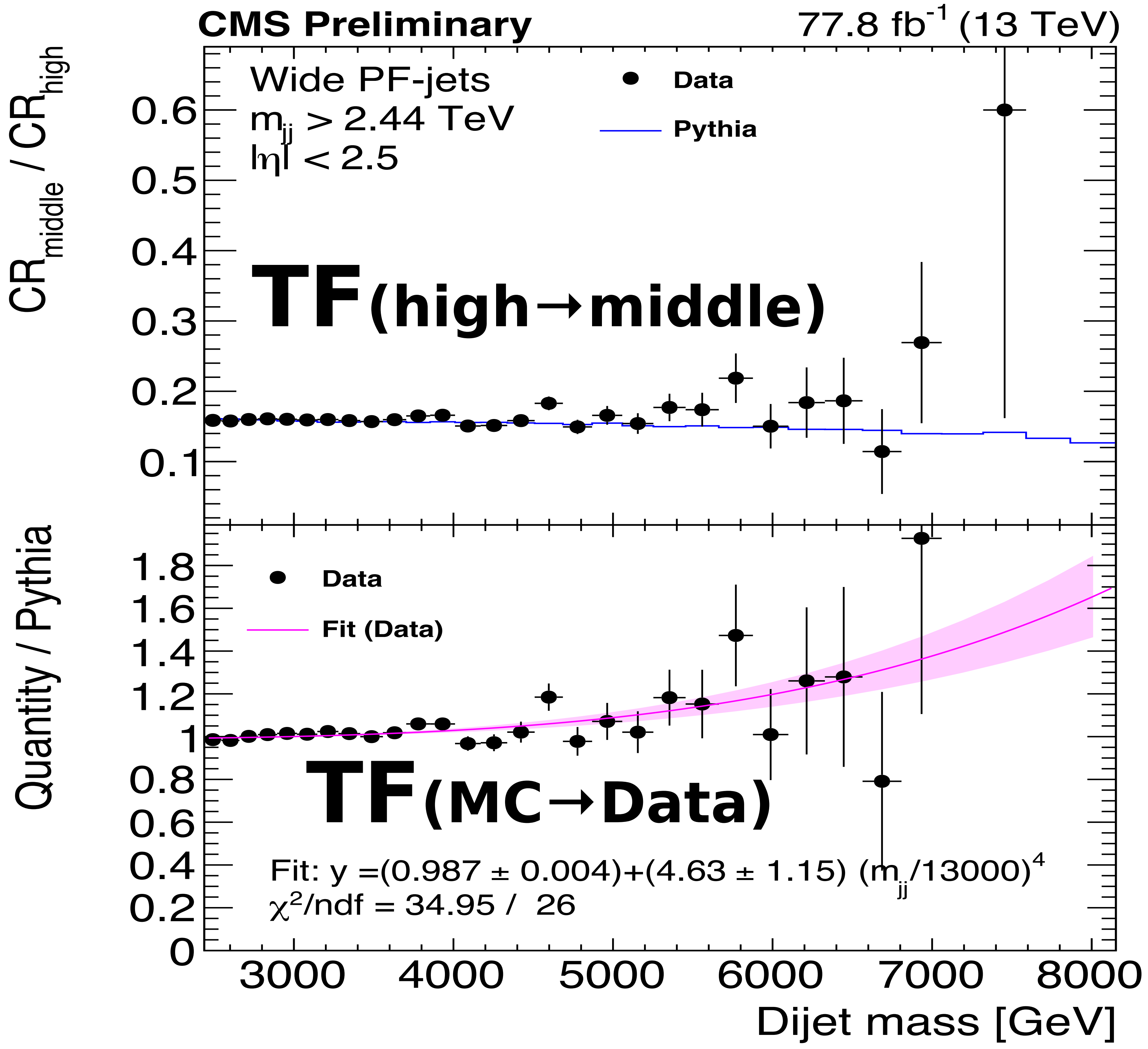
EXO-17-026

New!! 11/Sep

- **W’,Z’, DM mediator, RSgraviton…** : Many signal can be considered.
  - **Background** : Estimated two method for low/high mass region separately.
    - *Fit method* : Using $\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$ extracted mass shape.
    - *Ratio method* : Apply several transfer factor using Δη CR.





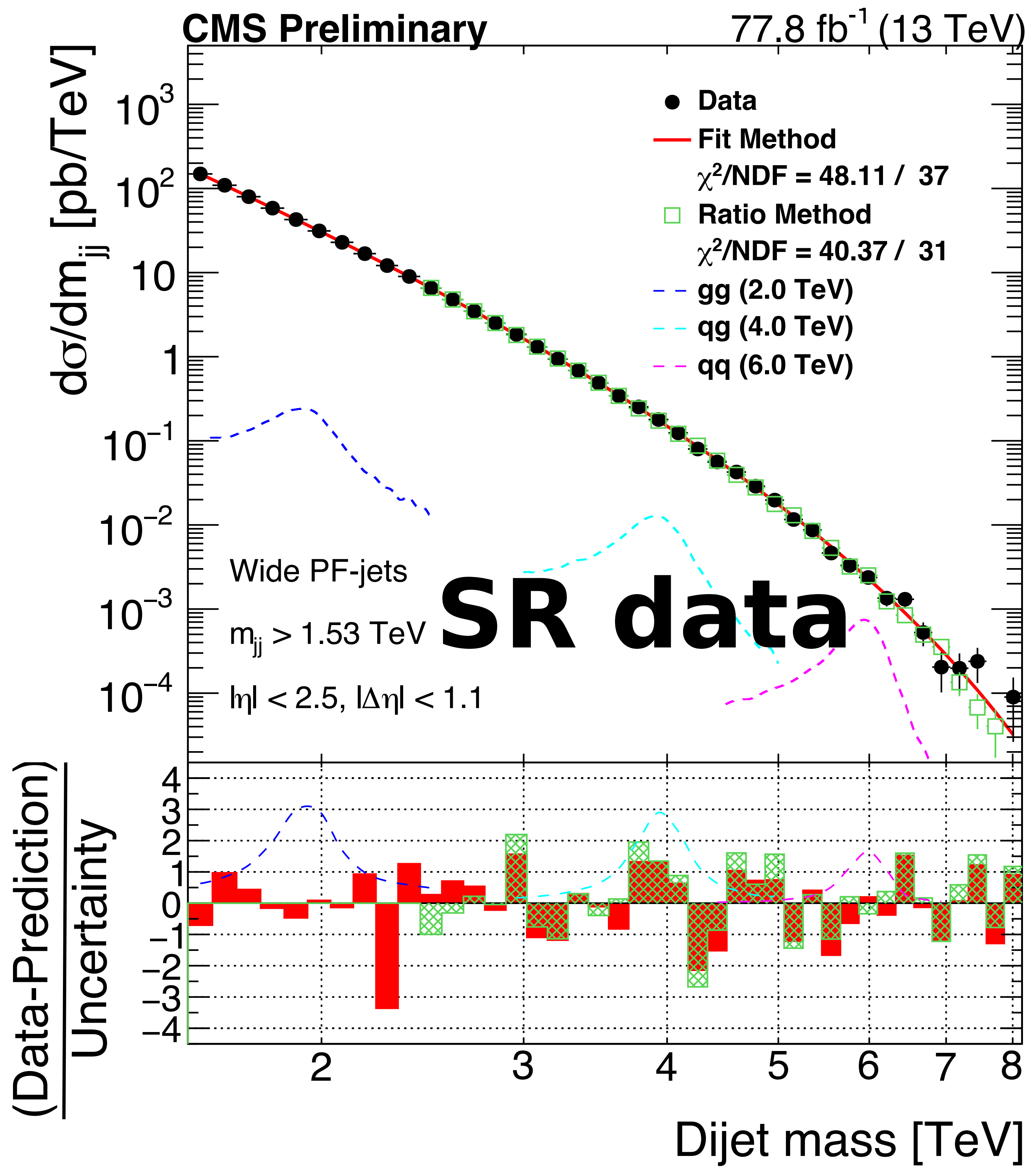


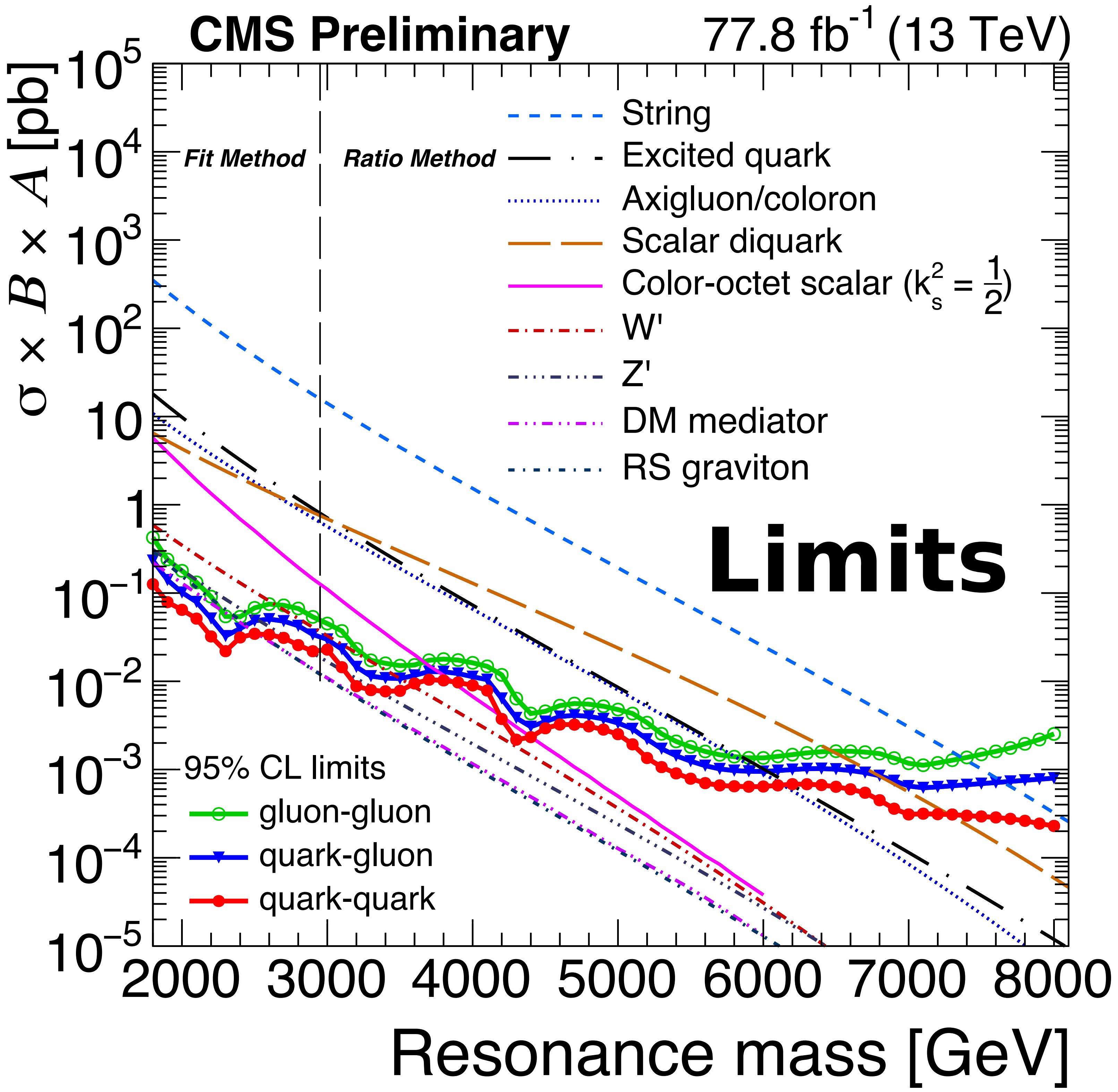
Dijet Signature in CMS @78/fb

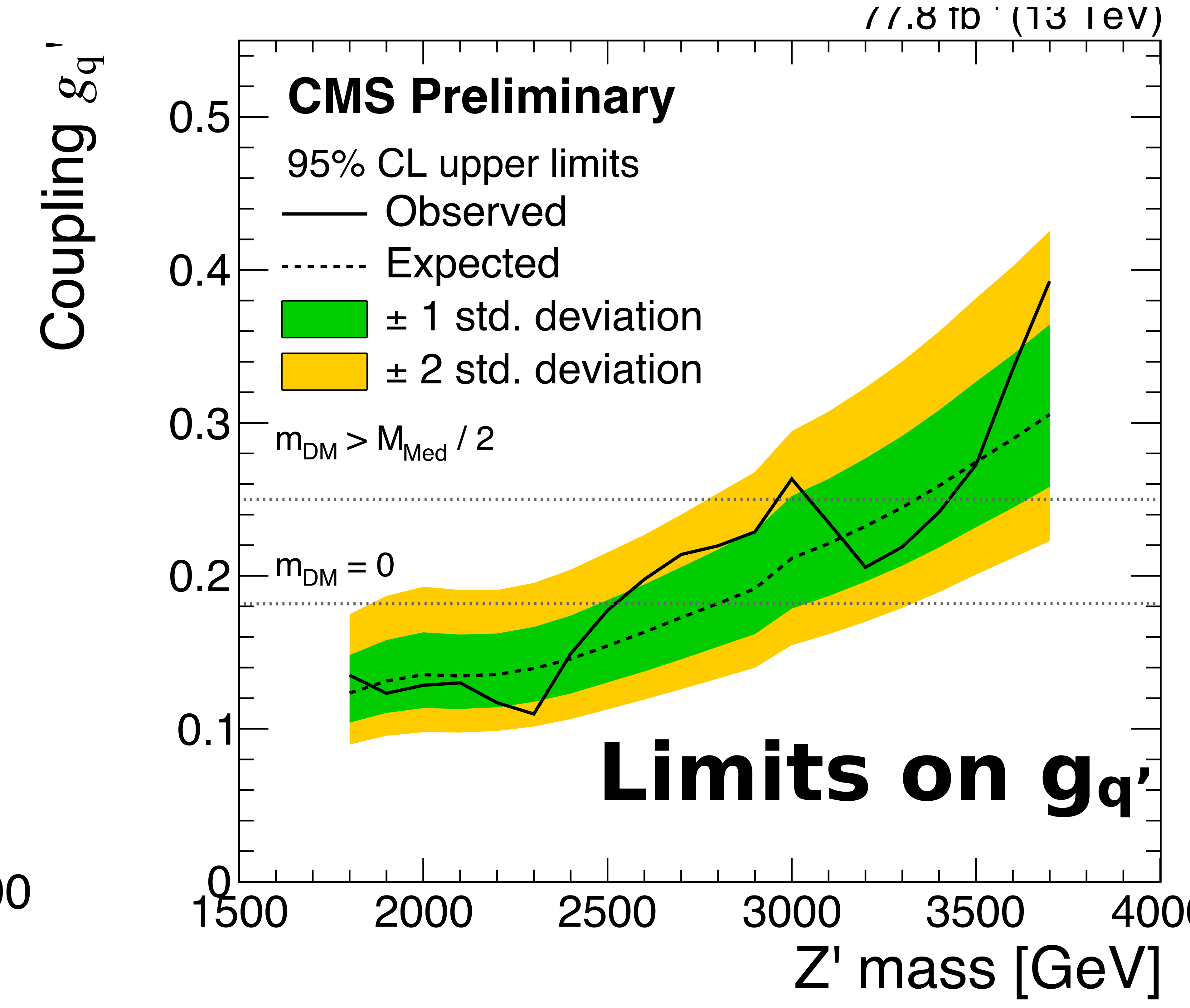
EXO-17-026

New!! 11/Sep

- No significant excess…
  - Set 4 limits for qq,qg,gg production and RS graviton signal.
  - Also set limit on universal quark coupling $g_{q'}$ as a function of Z' mass.
  - (Highest dijet mass is 8TeV!!)





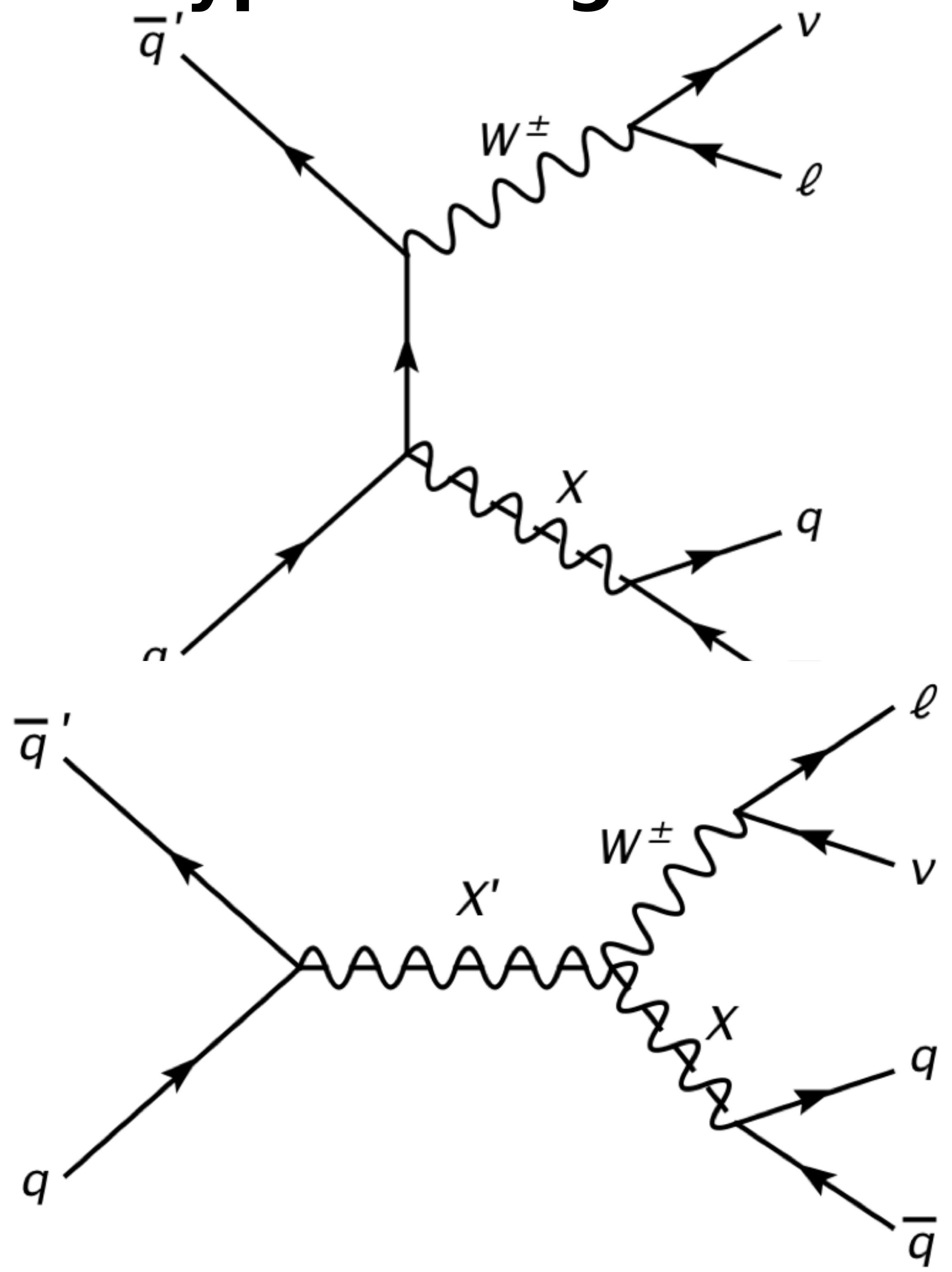


Dijet Signature w/ lepton in ATLAS @80/fb

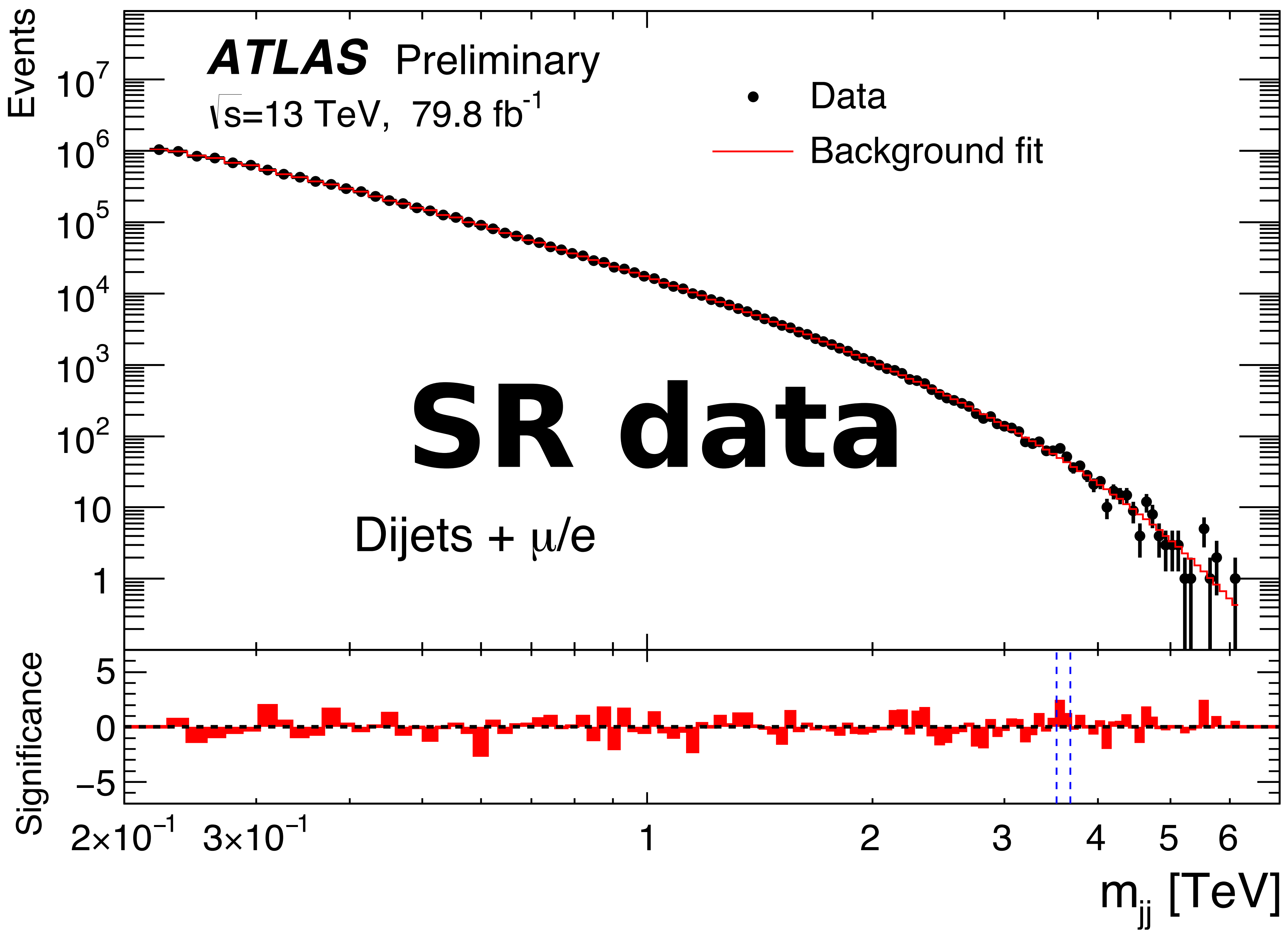
CONF-2018-015

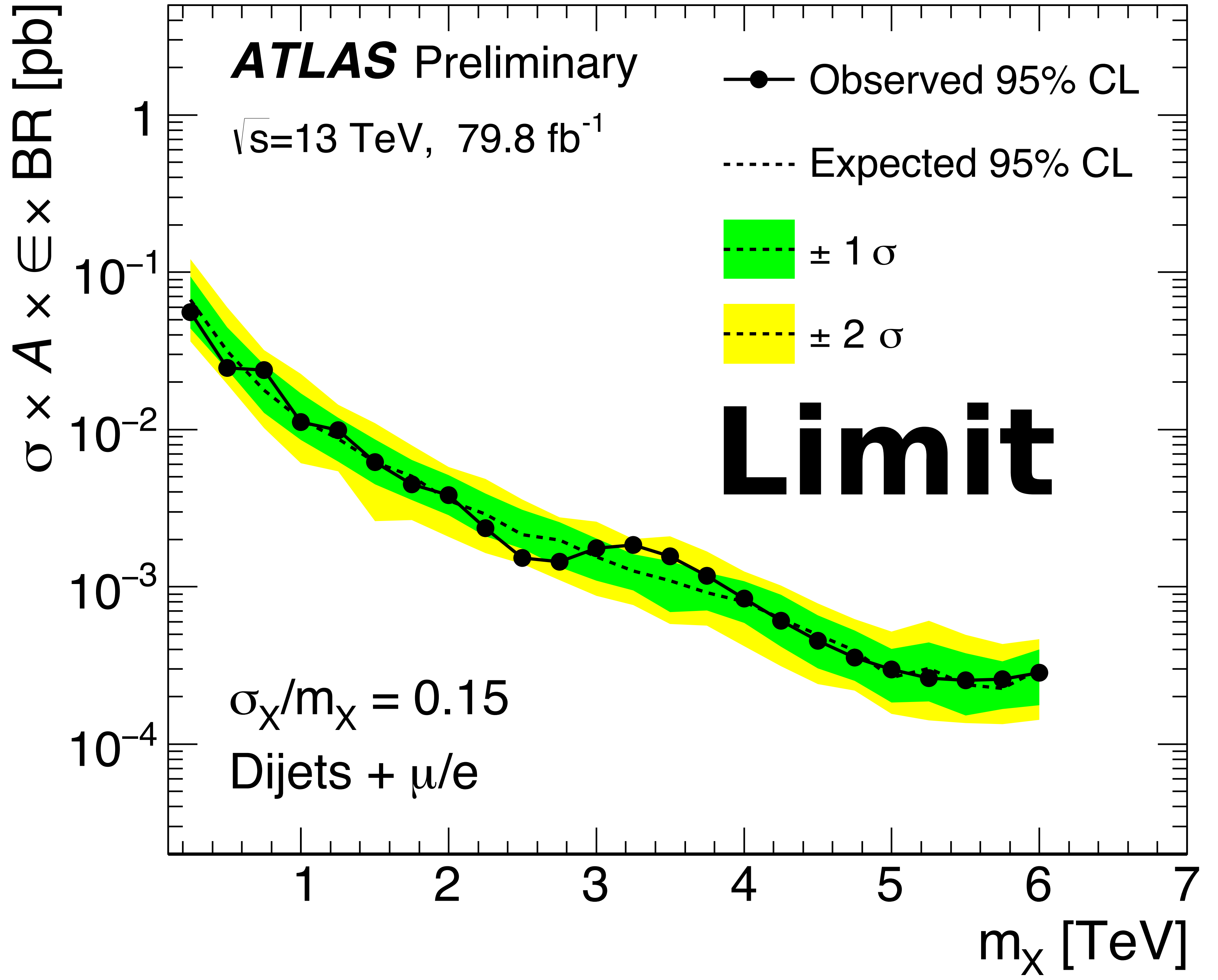
- **Allow one additional lepton** : Less model-dependent search, trigger free analysis
  - **Signal** : W', Z', H±(→qq) expected → e/μ + 2jets + ν, (no cut on E_T^{miss}).
  - **Background** : Validated at CR → 2jets + one additional jet.
  - Fitting with below function w/ x = mjj/√s
- No significant excess...

Typical diagrams



$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x + p_5 \ln^2 x},$$





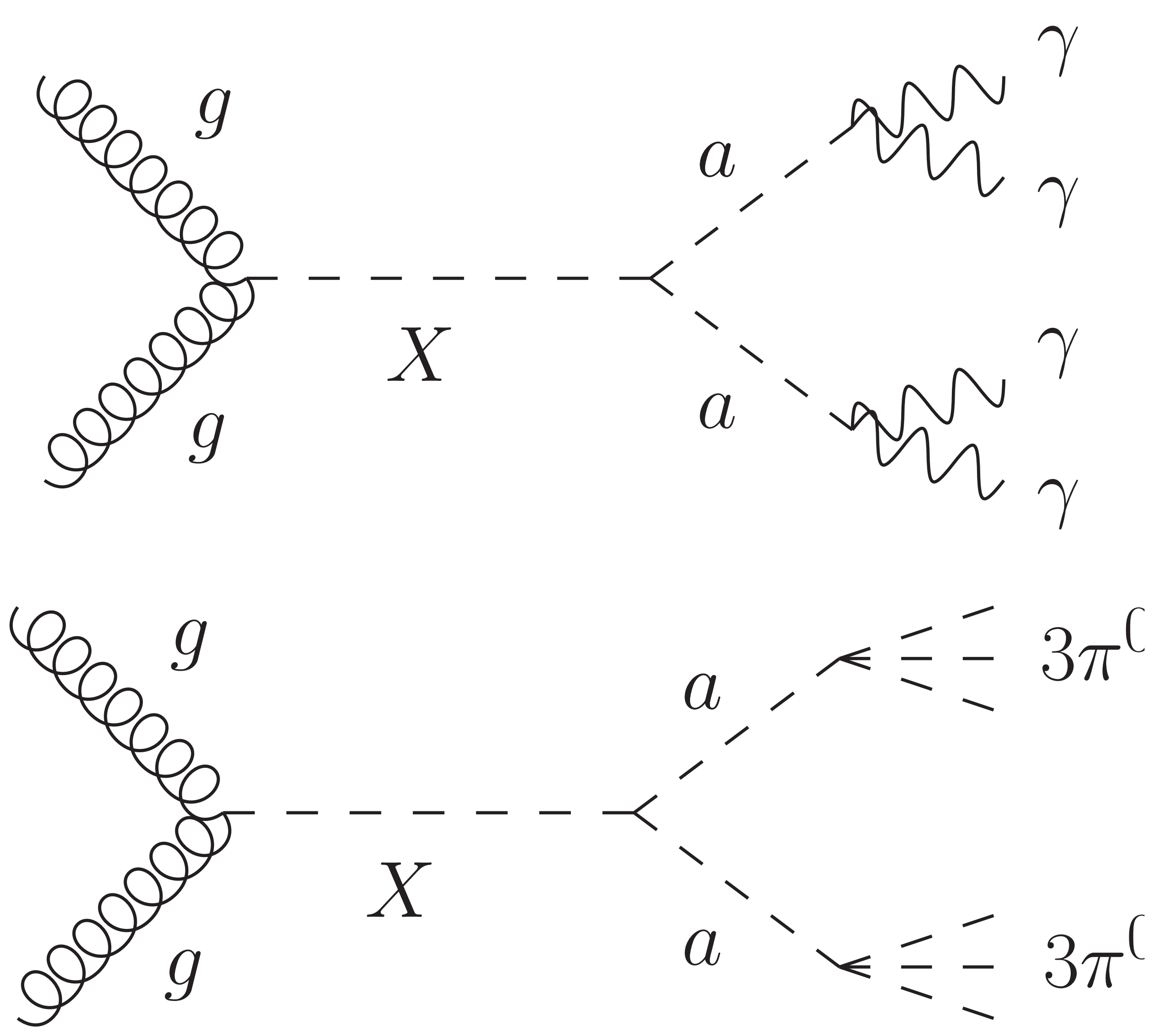
Photon-jets resonance pair in ATLAS @36/fb

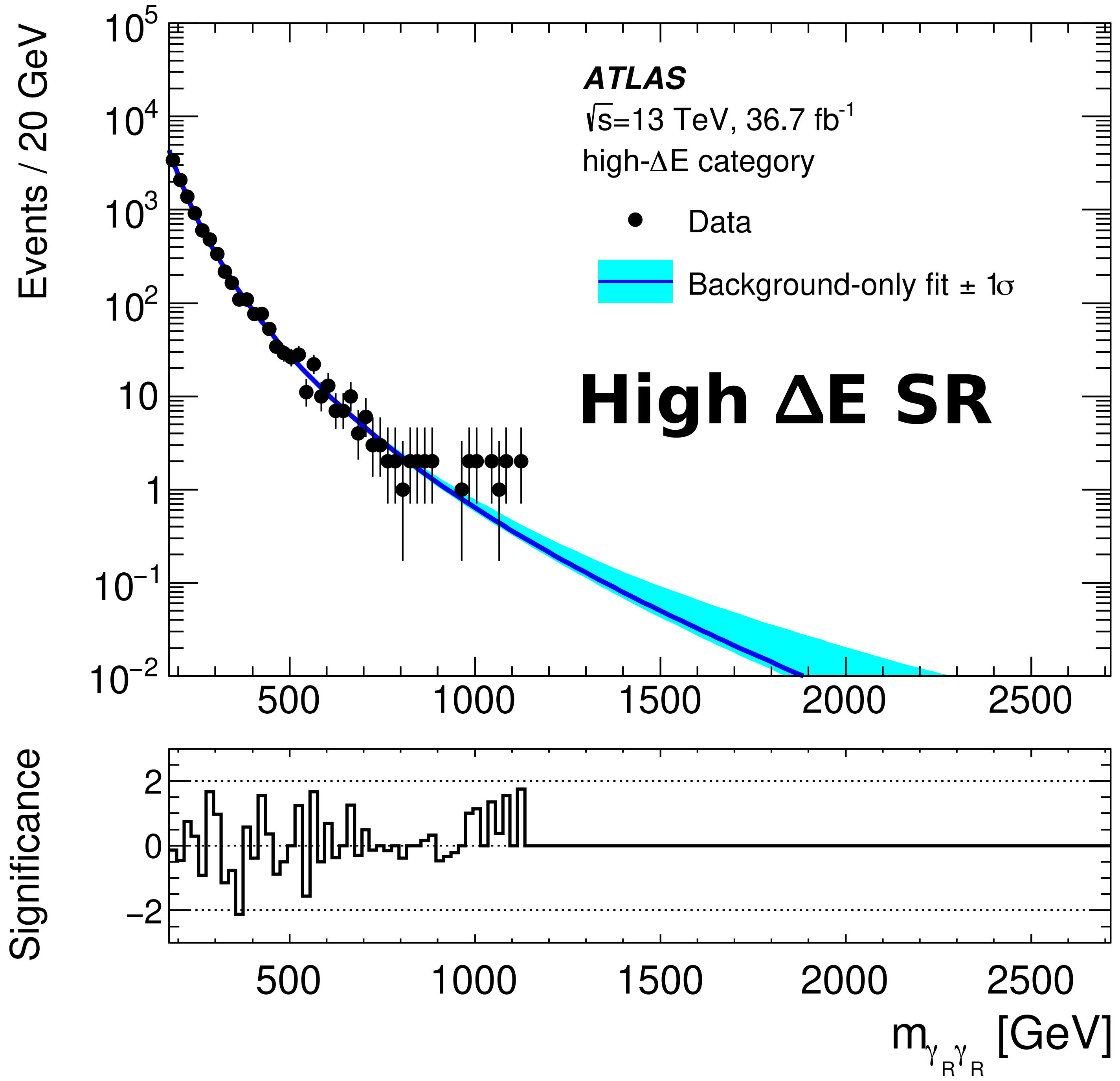
EXOT-2017-08

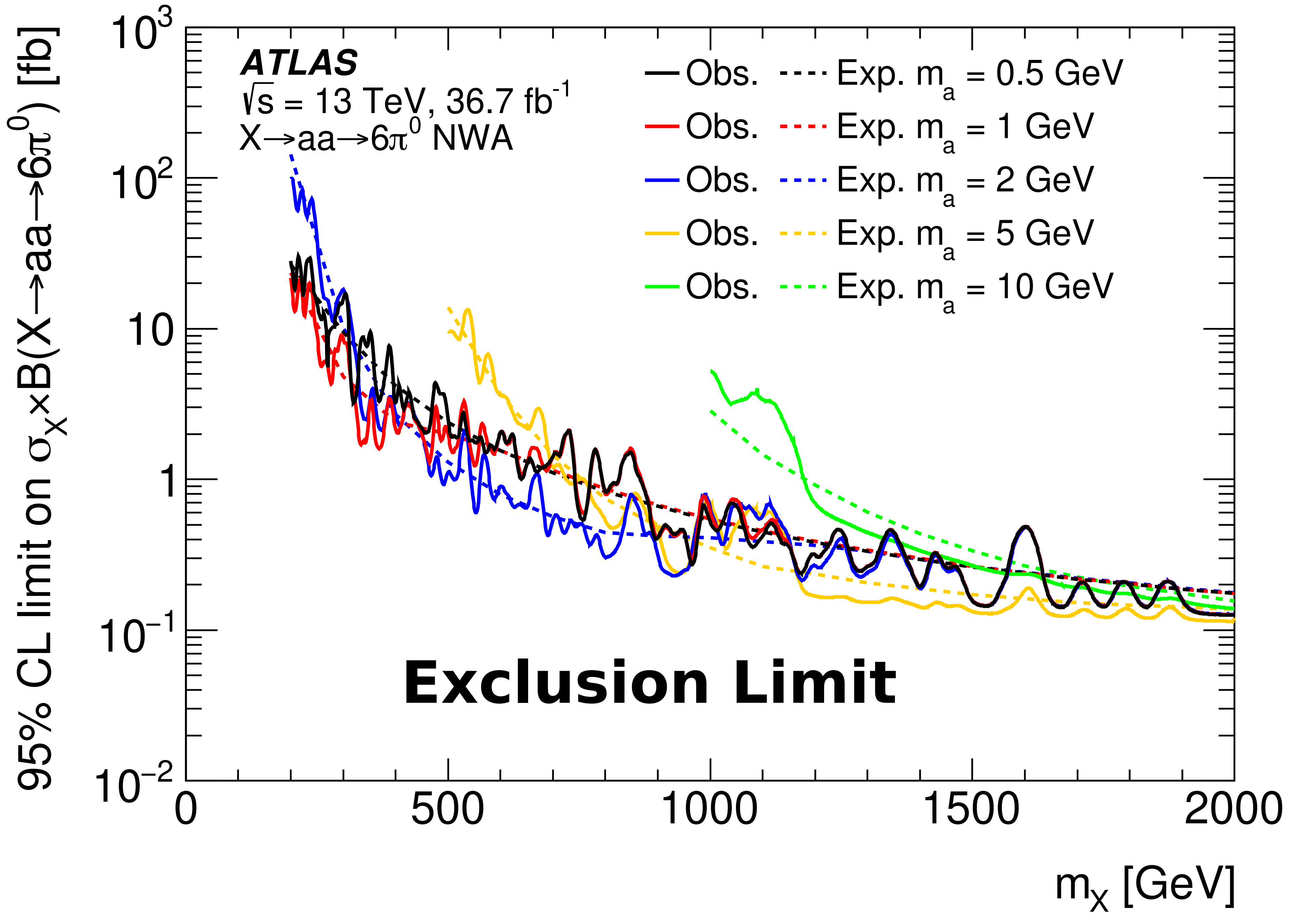
New!! 30/Aug

- **Spin0 itermidate a**: decays into 2 photon or $3\pi^0$ → two collimated photon-jets
  - **Photon-jets** : Using EM cluster shape information → calibrated with $\pi^0 \to \gamma\gamma$ data.
  - **Signal Regions** : Define two Sos with ΔE(photon-jets) is low or high.
  - Background : Unbinned fit with $g_{(k)}\left(x; a, \{b_j\}_{j=0,k}\right) = N\left(1 - x^{\frac{1}{2}}\right)^a x^{\sum_{j=0}^{k} b_j (\log x)^j}$ (similar w/ dijet)
- No significant excess…
  - Limit on cross-section w/ several intermediate a mass as a function of m_X.

Typical diagrams



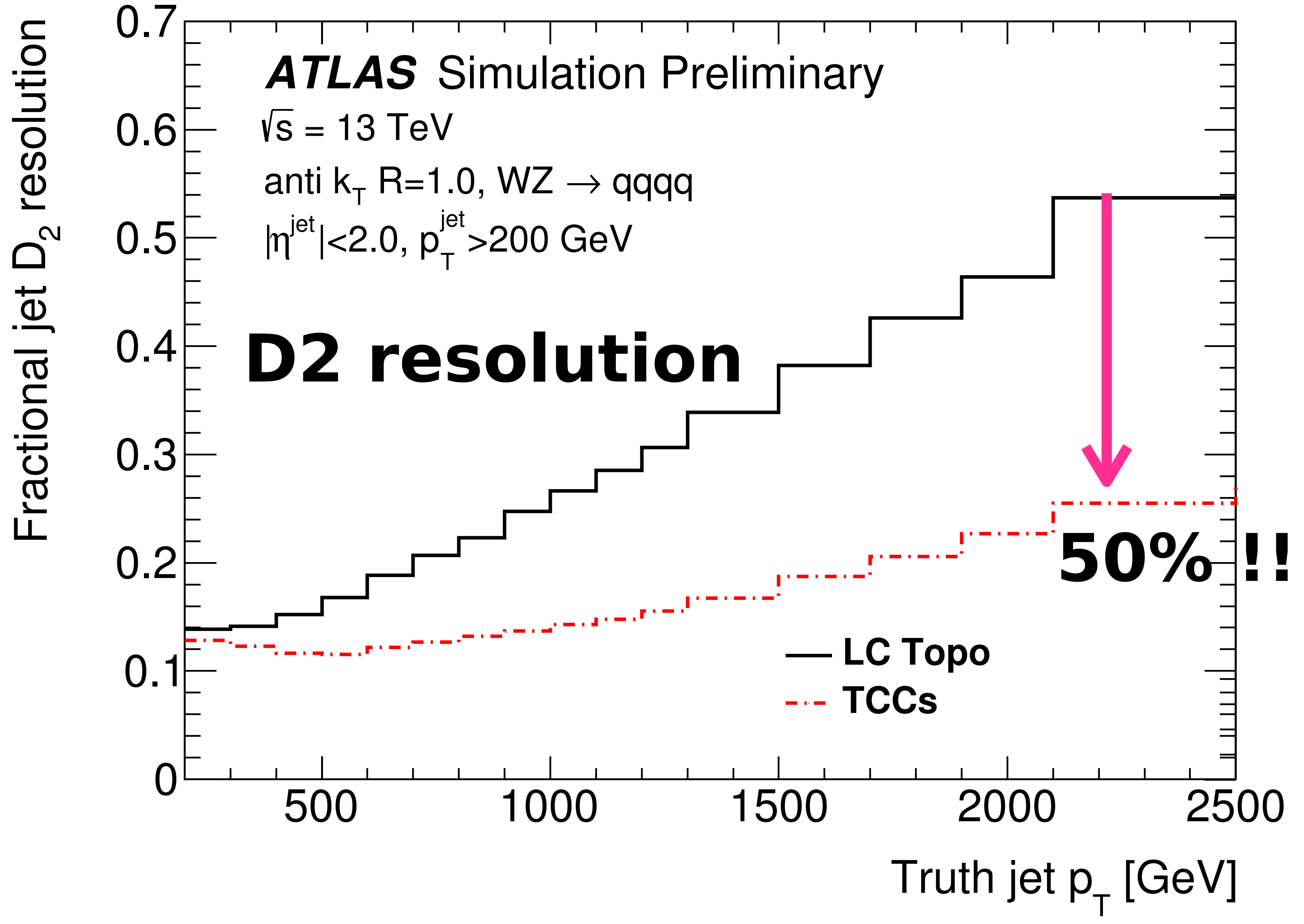


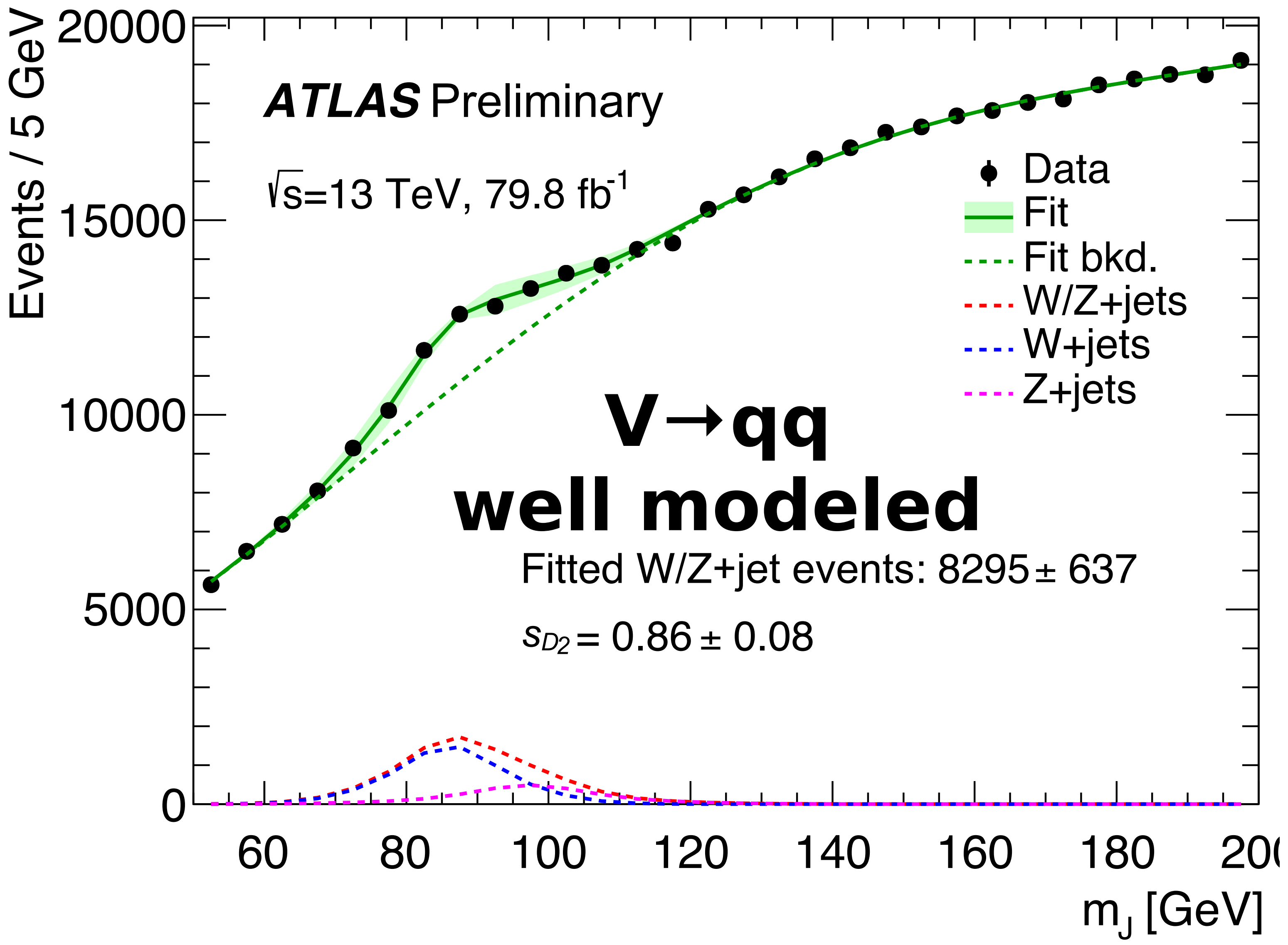


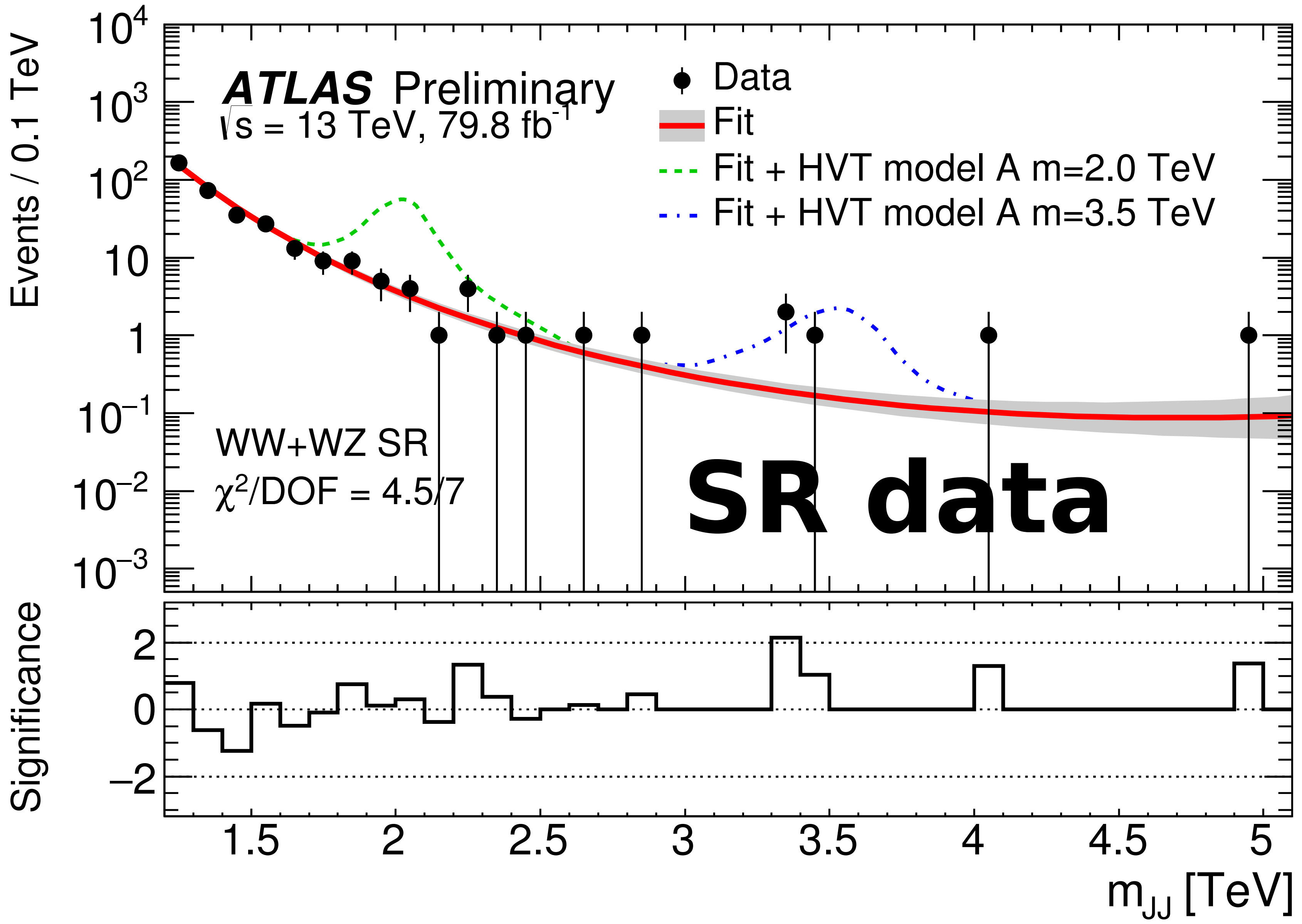
Diboson in ATLAS @80/fb

<u>**CONF-2018-016**</u>

- **New boosted boson tagging technique** : Using **<u>Track CaloClusters</u>**(TTC)
  - **TTC** : improve large-R jet mass and D2 response → **50% gain!!**
  - **Signal** : Heavy Vector Triplet(HVT), KK RS graviton or other scalar signals → WW/ZZ or WZ
  - **Background** : Validated at CR → ABCD-like method,
- Signal accumption : several mass width/production are tested with
- No significant excess...







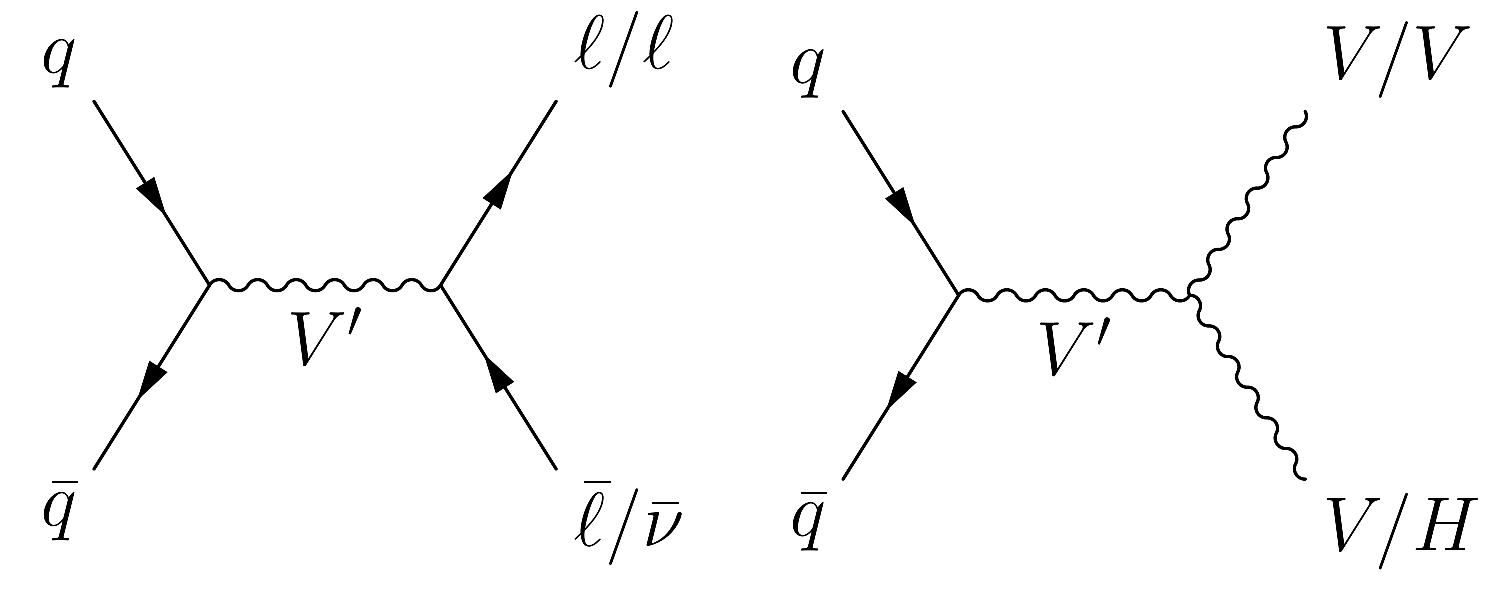
Diboson Combination in ATLAS @36/fb

1808.02380

New!! 8/Aug

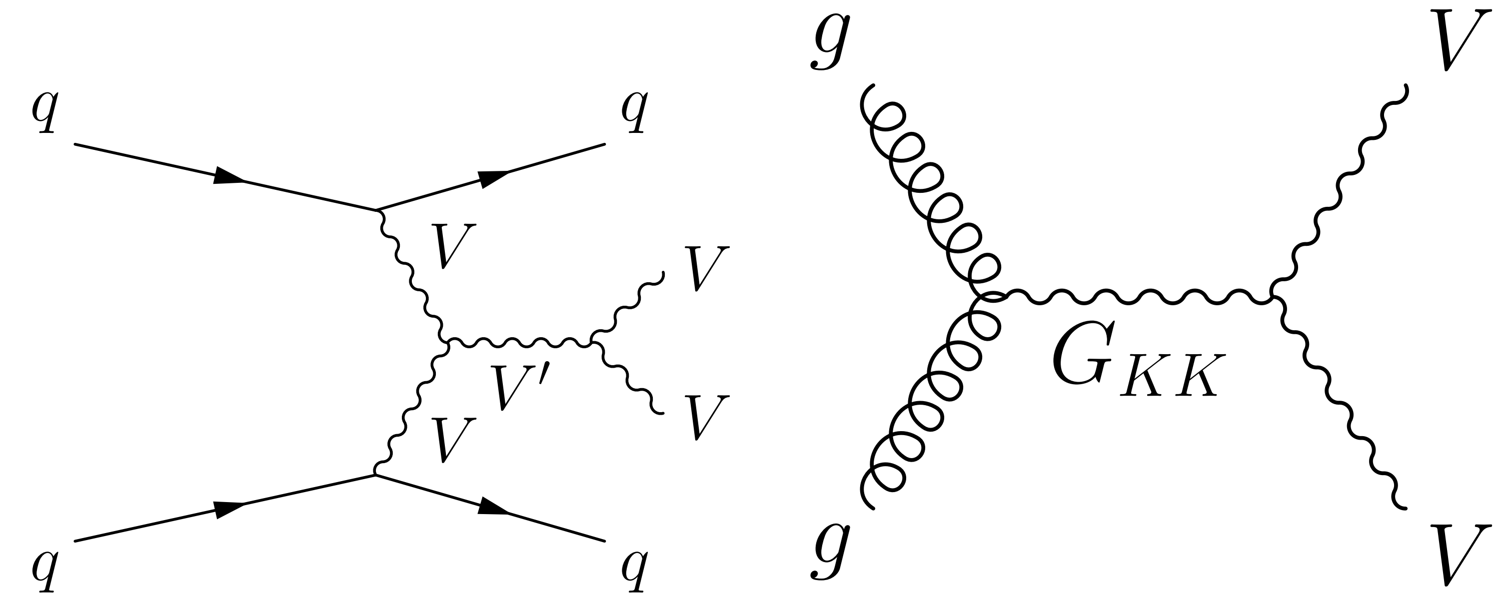
- **Full combination of heavy resnances into bosonic/leptonic :**
  - VV: WZ→qqqq, lvqq, lvll, WW→qqqq, lvqq, lvlv, ZZ→qqqq, vvqq, llqq, llvv, llll
  - VH : WH → qqbb, lvbb, ZH→qqbb, vvbb, llbb
- **Signal** : production w/ ggF, VBF, DY
  - bulk RSKK graviton(spin-2), Scalar, HVT
- Exclusion limit on 1D and 2D plane(couplings) are achieved.

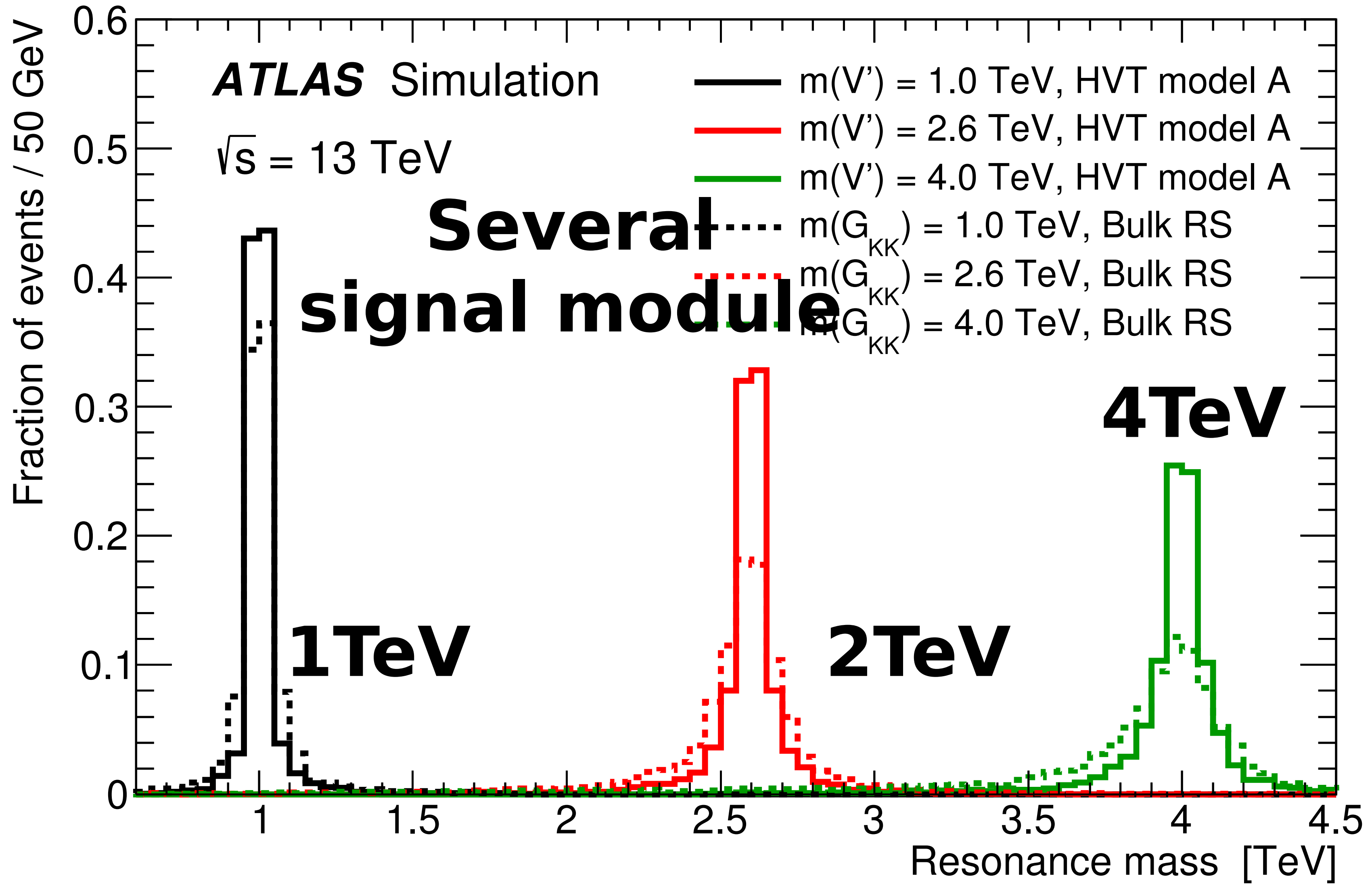
Model \ Decay mode	WW	WZ	ZZ	WH	ZH	$\ell\nu$	$\ell\ell$
HVT	Z'	W'		W'	Z'	W'	Z'
Bulk RS	G_{KK}		G_{KK}				
Scalar	Scalar		Scalar				

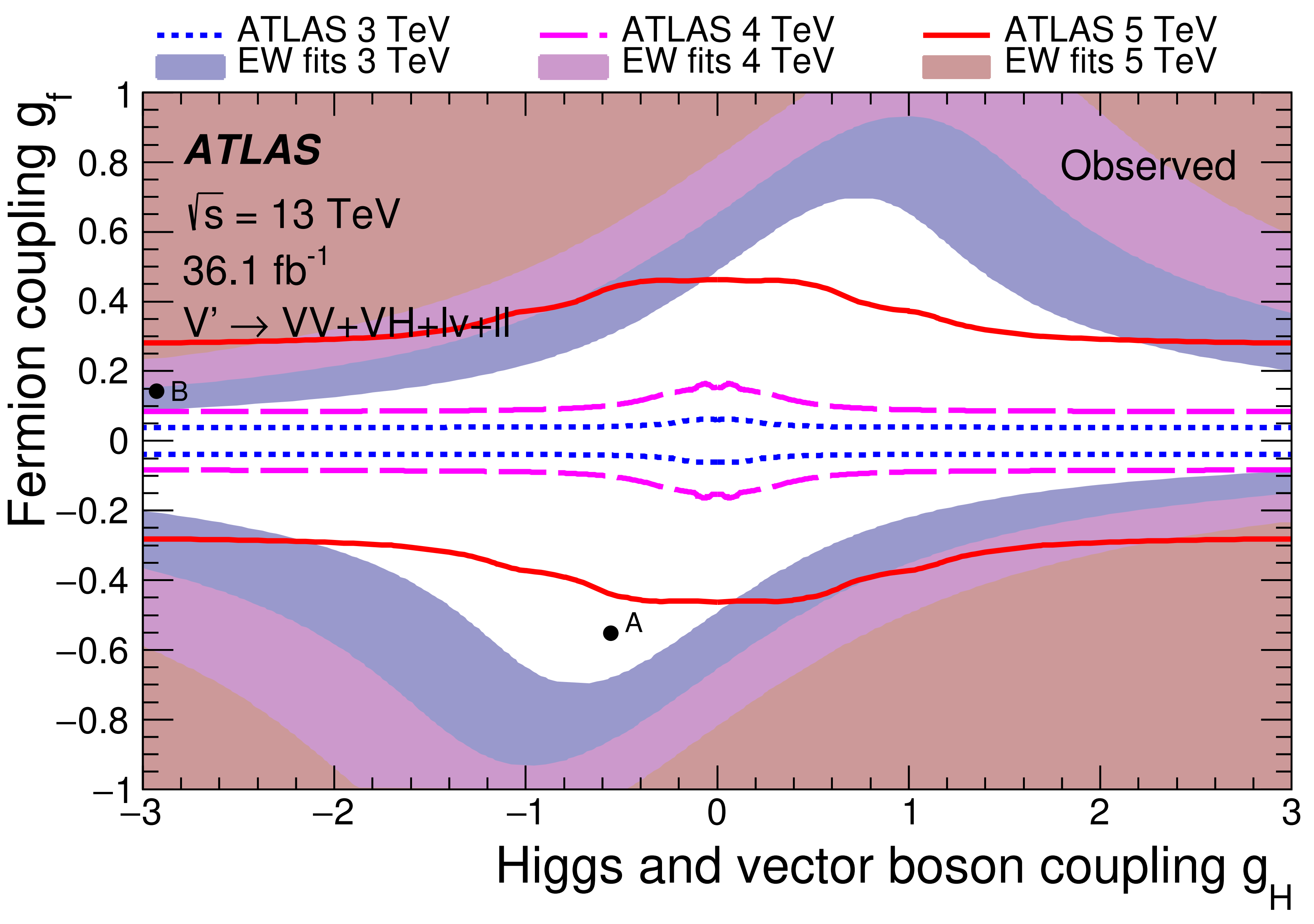


(a) (b)

Typical diagrams





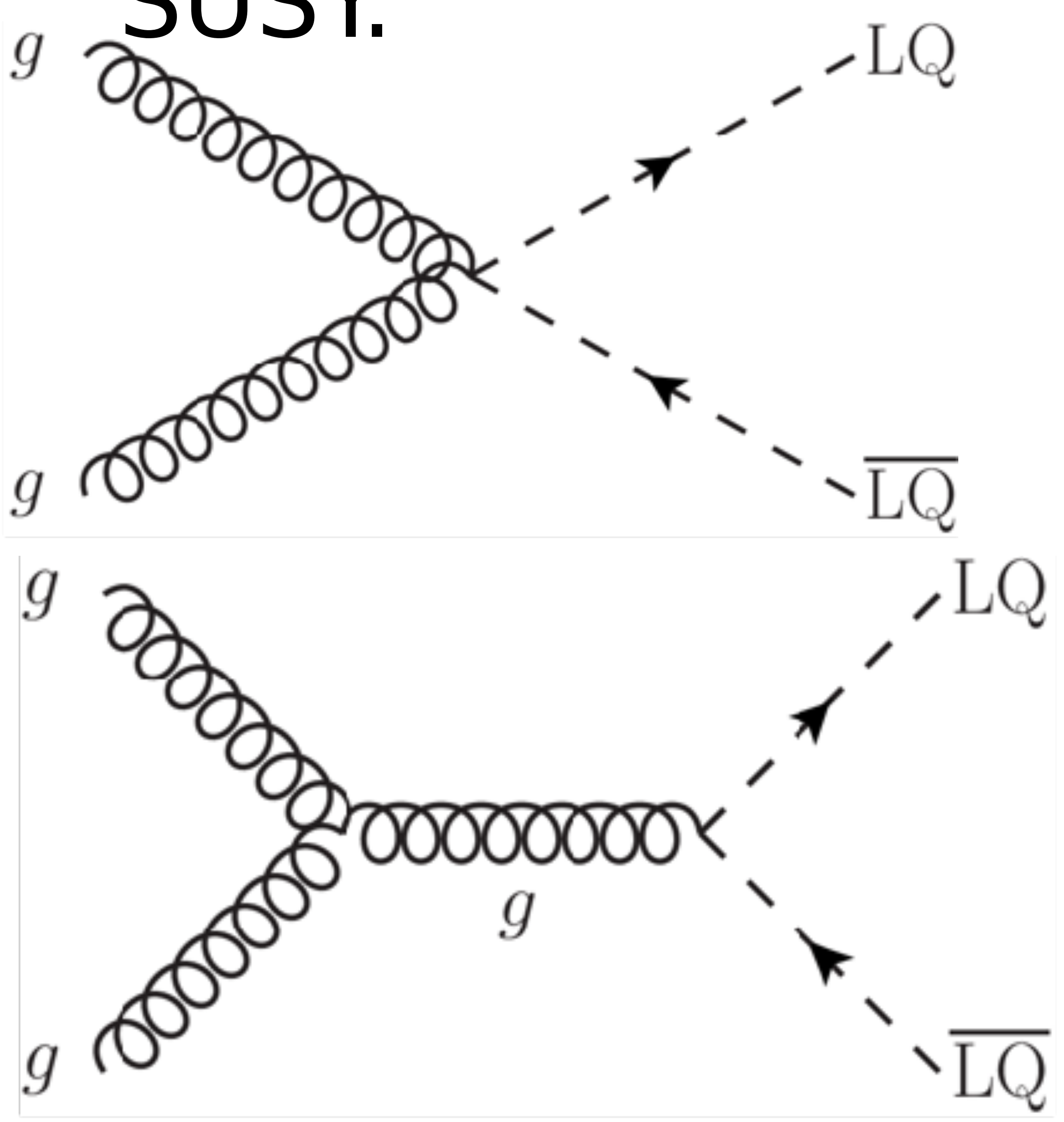


Leptoquarks in CMS @36/fb

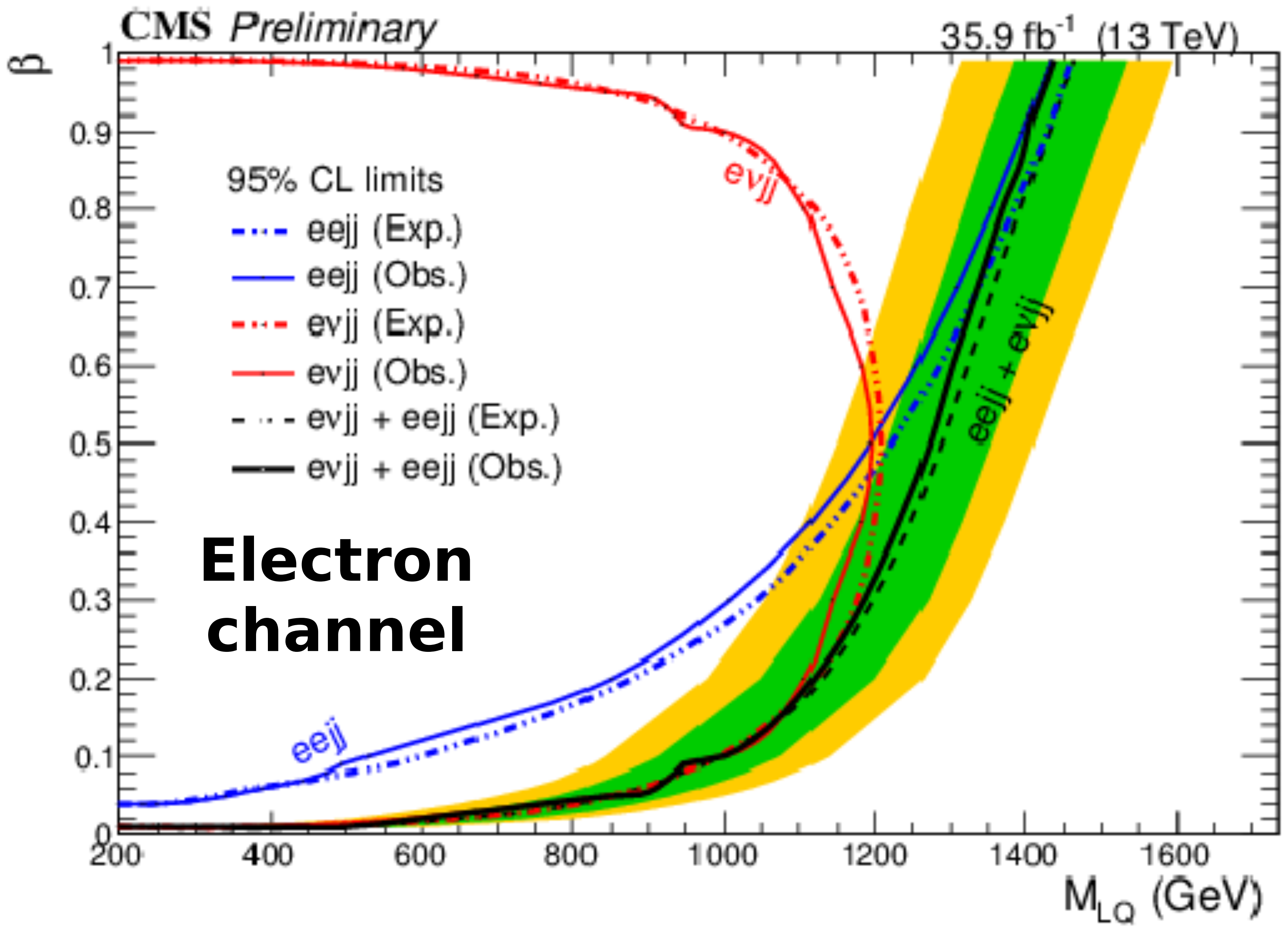
EXO-17-003

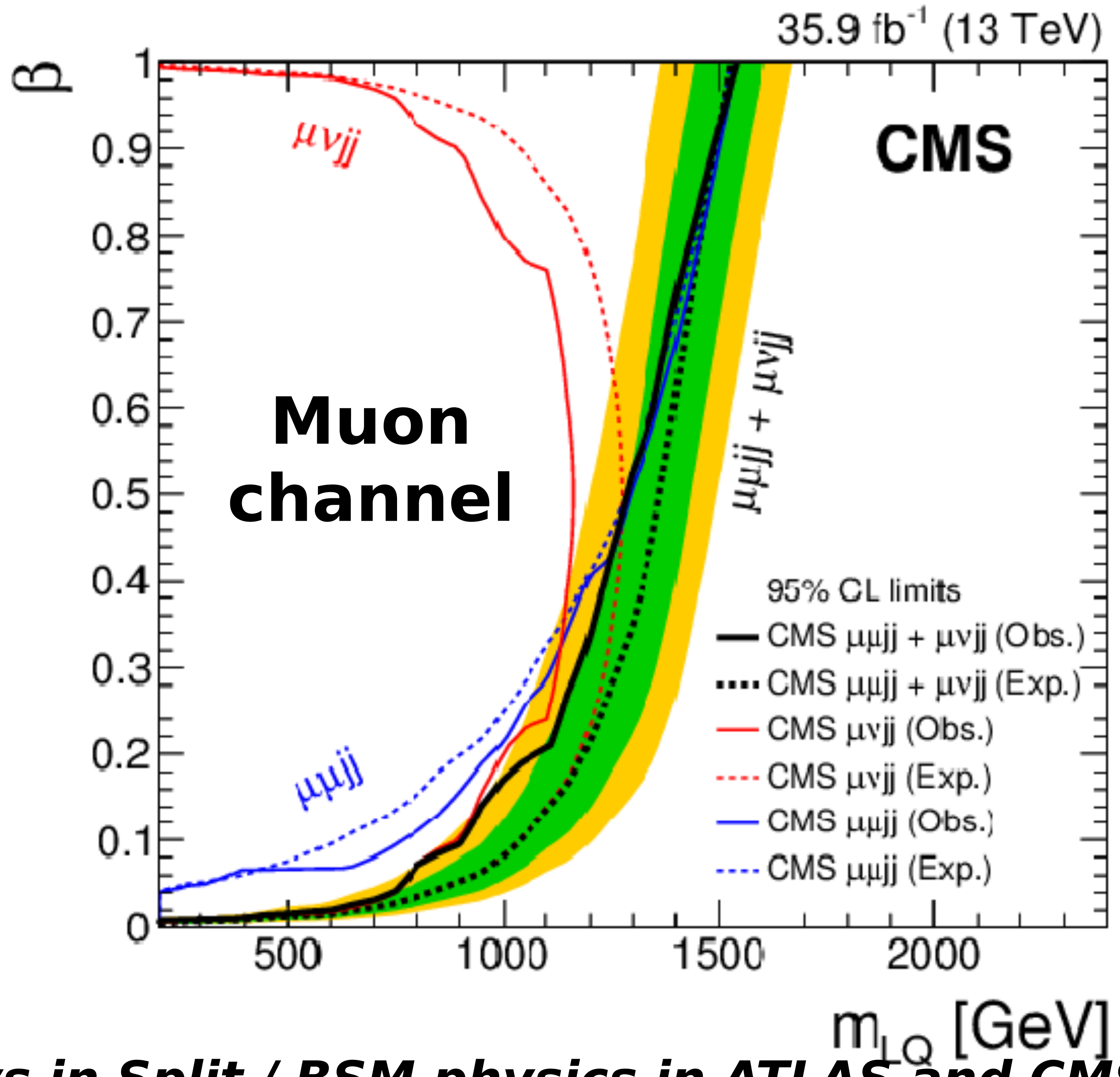
EXO-17-009

- **Favored from R_K/R_D anomaly on b-physics.**
- **1st/2nd generation leptoquarks** : ee/μμ+jets or e/μ + jets + E_T^{miss} final state
  - Simple analysis : LQ → e/μ + quark
  - Using selection of $m_{e(\mu)J}$, $m_{e(\mu)\nu/\mu\mu}$, $S_T^{e(\mu)\nu jj/ee(\mu\mu)jj}$ as a function of reconstructed m_{LQ}
- No significant excess…
  - Limit on 2D plane of the bracing ratio β and m_{LQ} are set and interpretation for LLP RPV SUSY.



Other two diagrams are considered as LO process

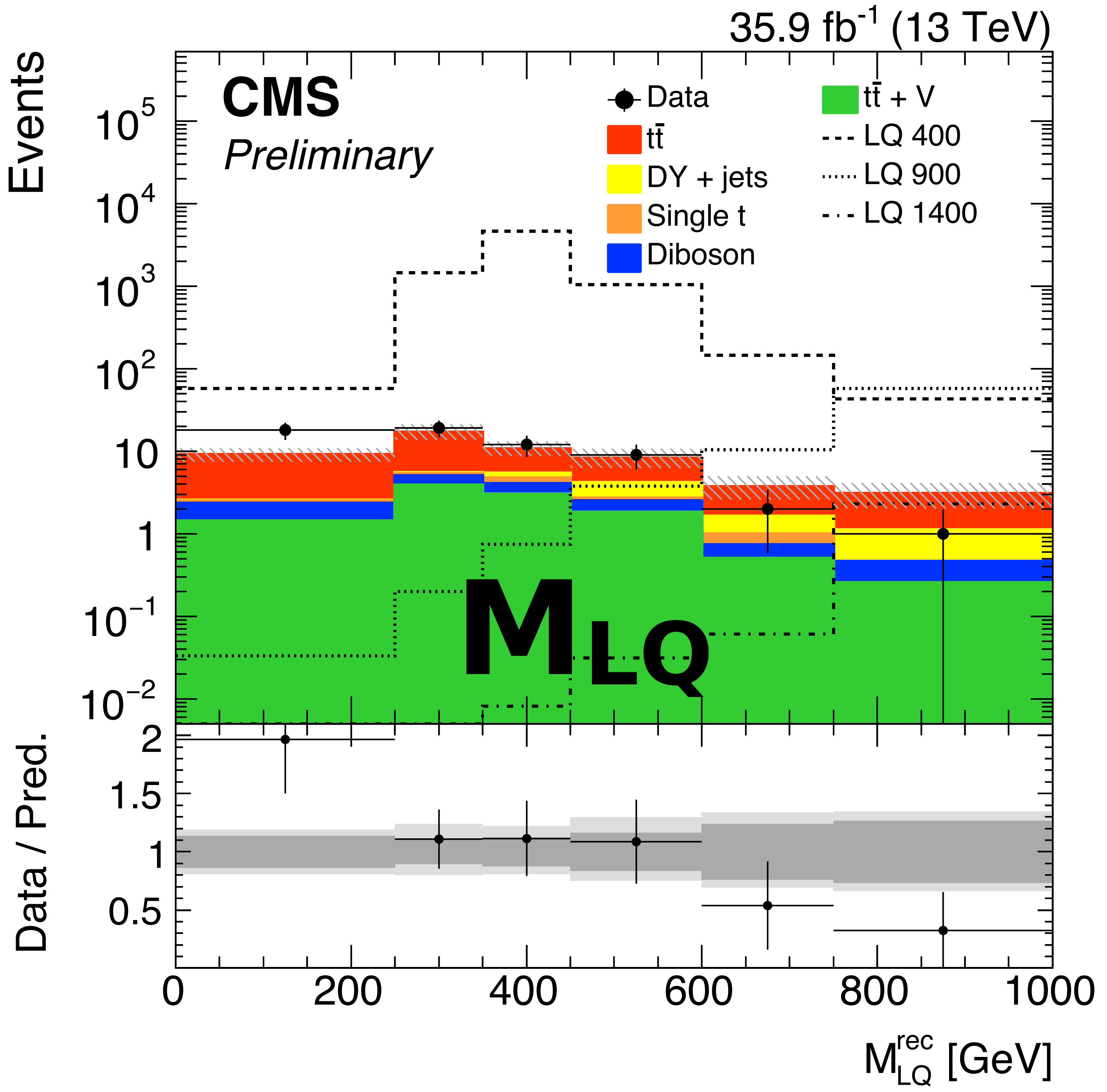


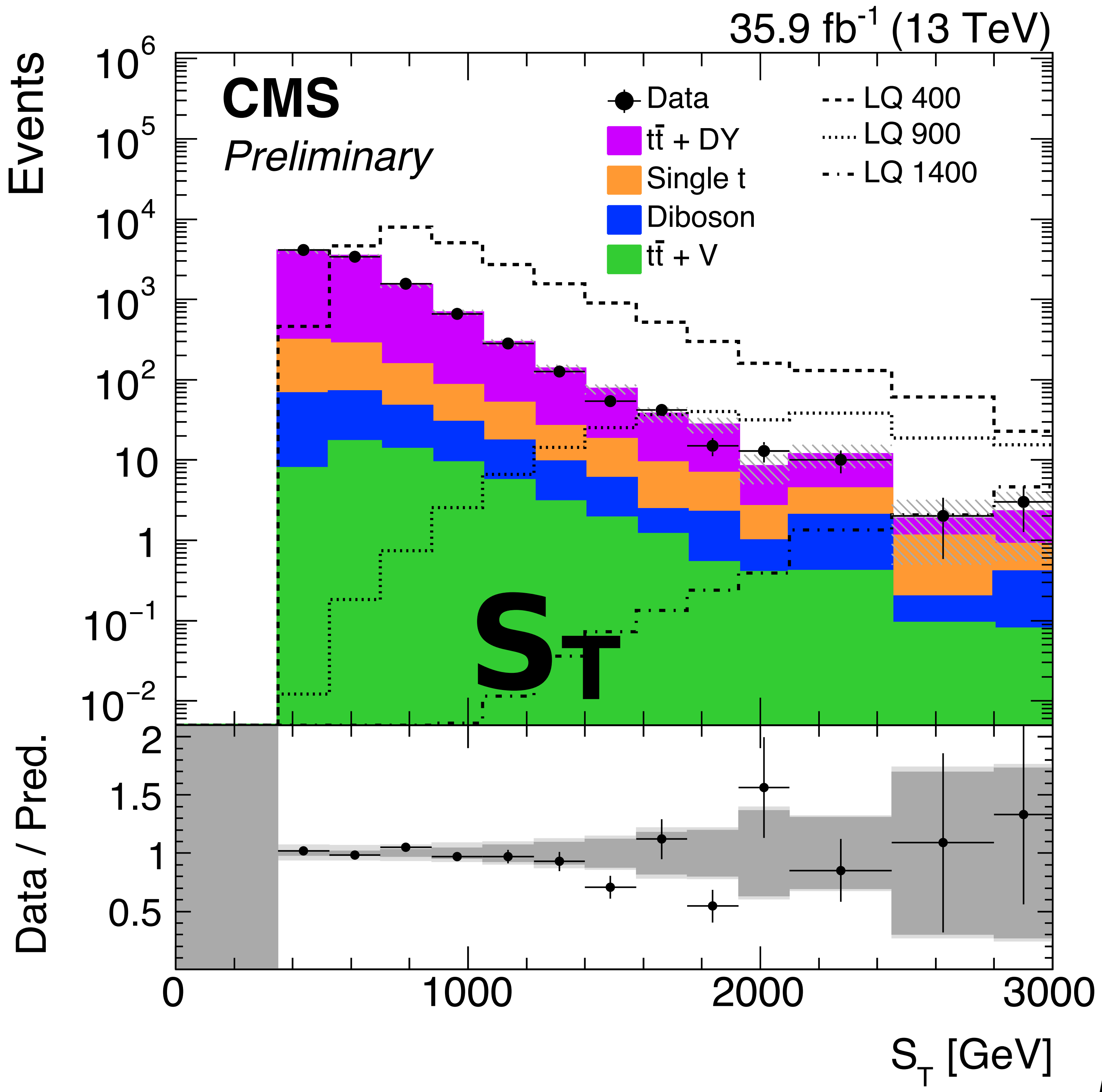


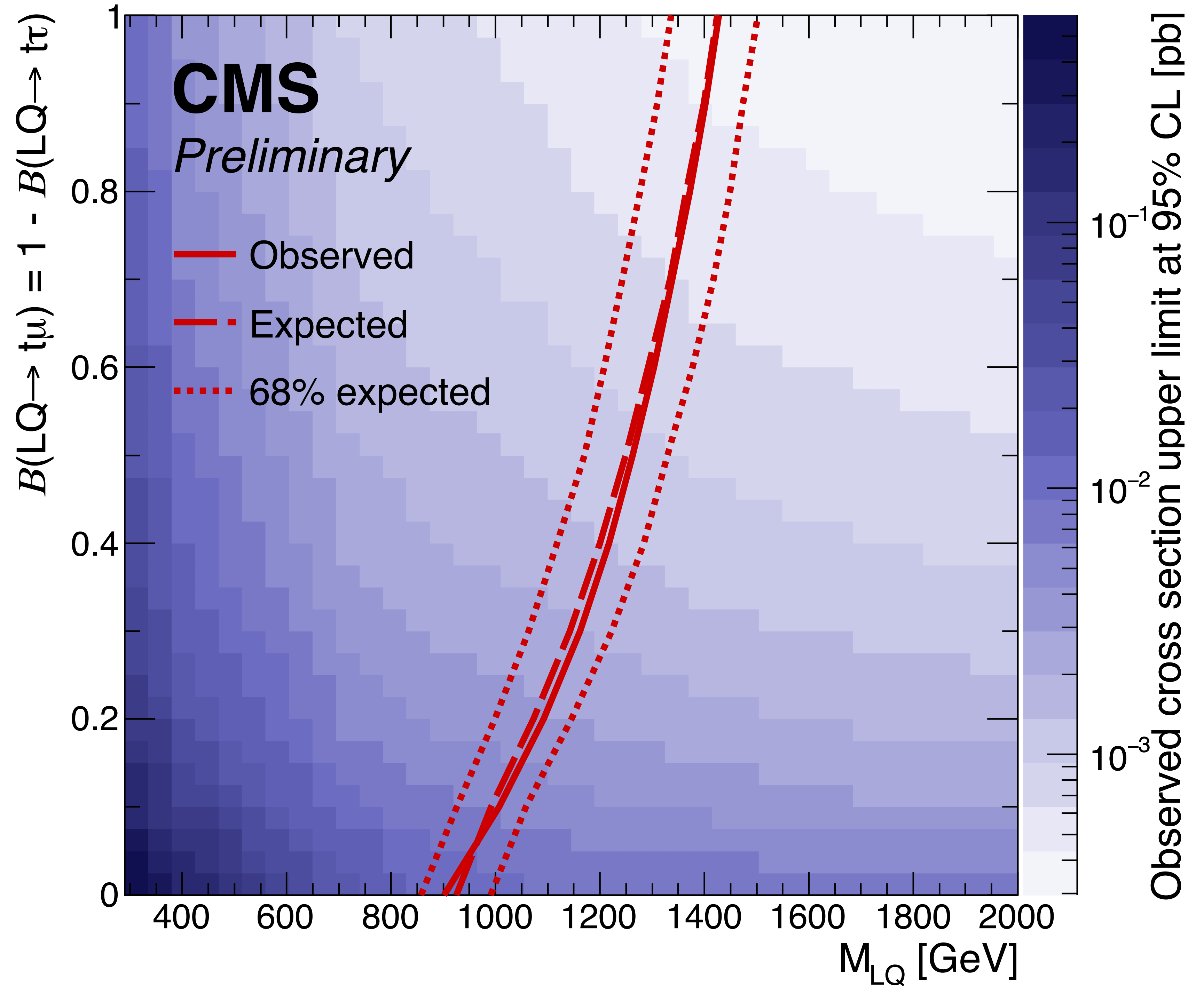
Leptoquarks in CMS @36/fb

B2G-16-027

- **Favored from R_K/R_D anomaly on b-physics.**
- **3rd generation leptoquarks** : μμ + b-jet + jets + E_T^{miss} + e/μ.
  - tμ, bμ, bν, tμ are considered as decay mode.
  - Using reco m_{top} for leptonic/hadronic : $m_{\ell\ell}$ > 111GeV, S_T > 200GeV.
- No significant excess
  - Limit on 2D plane of the bracing ratio β and m_{LQ} are set.



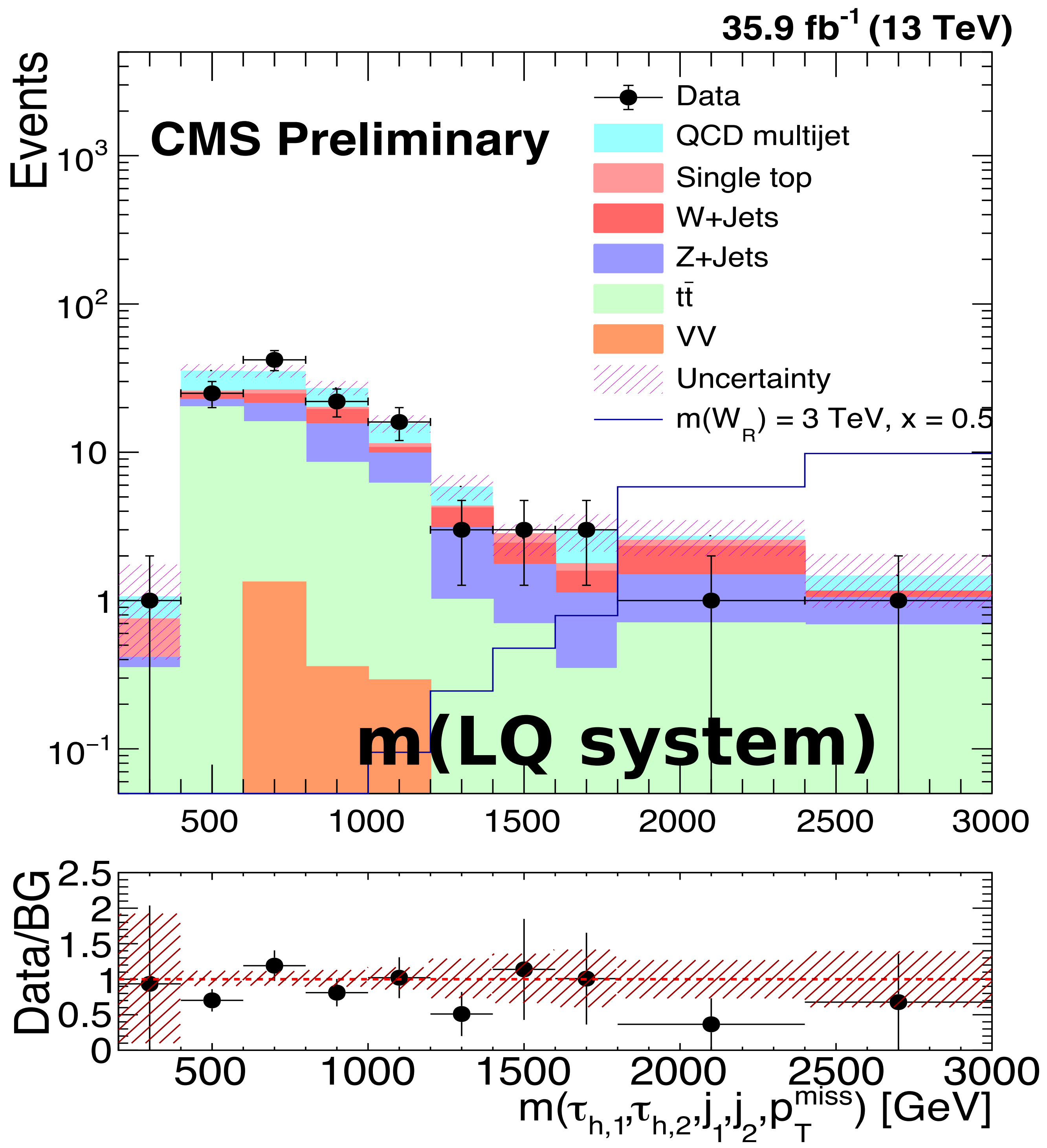


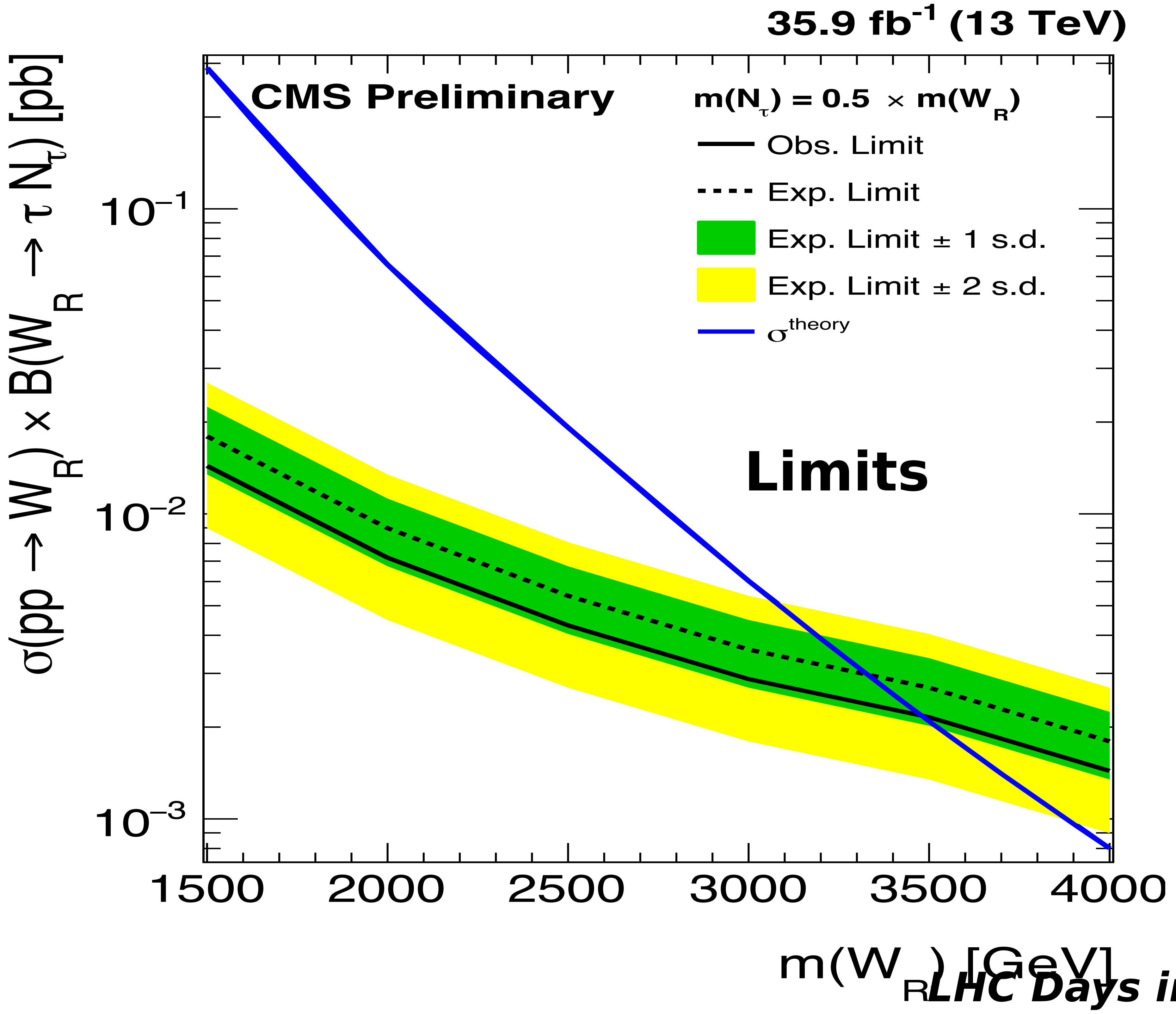


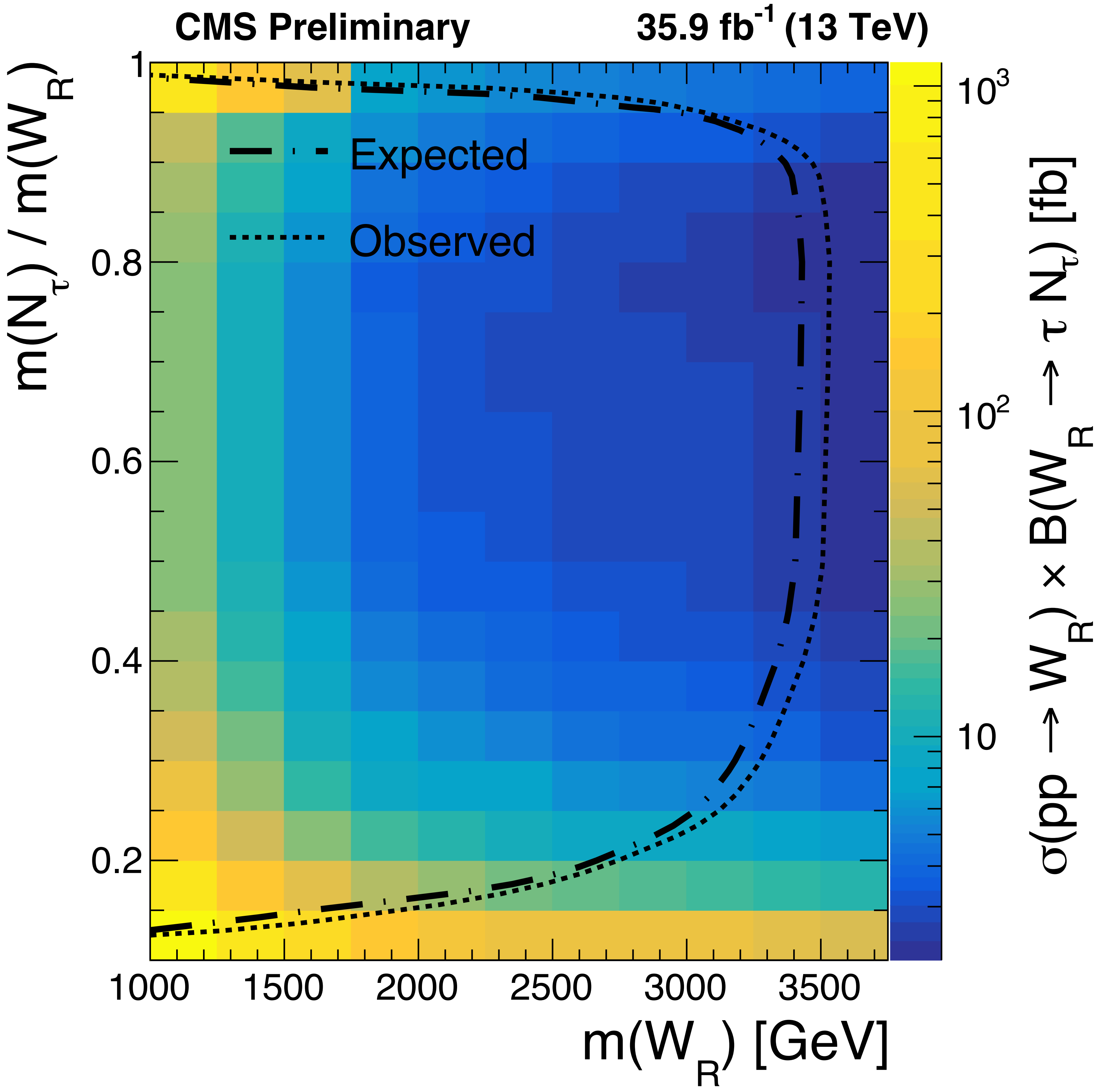
Leptoquarks in CMS @36/fb

EXO-17-016

- **Favored from R_K/R_D anomaly on b-physics.**
- **3rd generation leptoquarks** : two hadronic tau + jets
  - Right-handed boson/neutrino : e/μ + e/μ + $\tau_{had}\tau_{had}$ is considered.
  - Background : ABCD method for fake-τ background(E_T^{miss},iso).
- No significant excess : 1D limit and 2D limit(m_{WR} and $m_{N\tau}$)







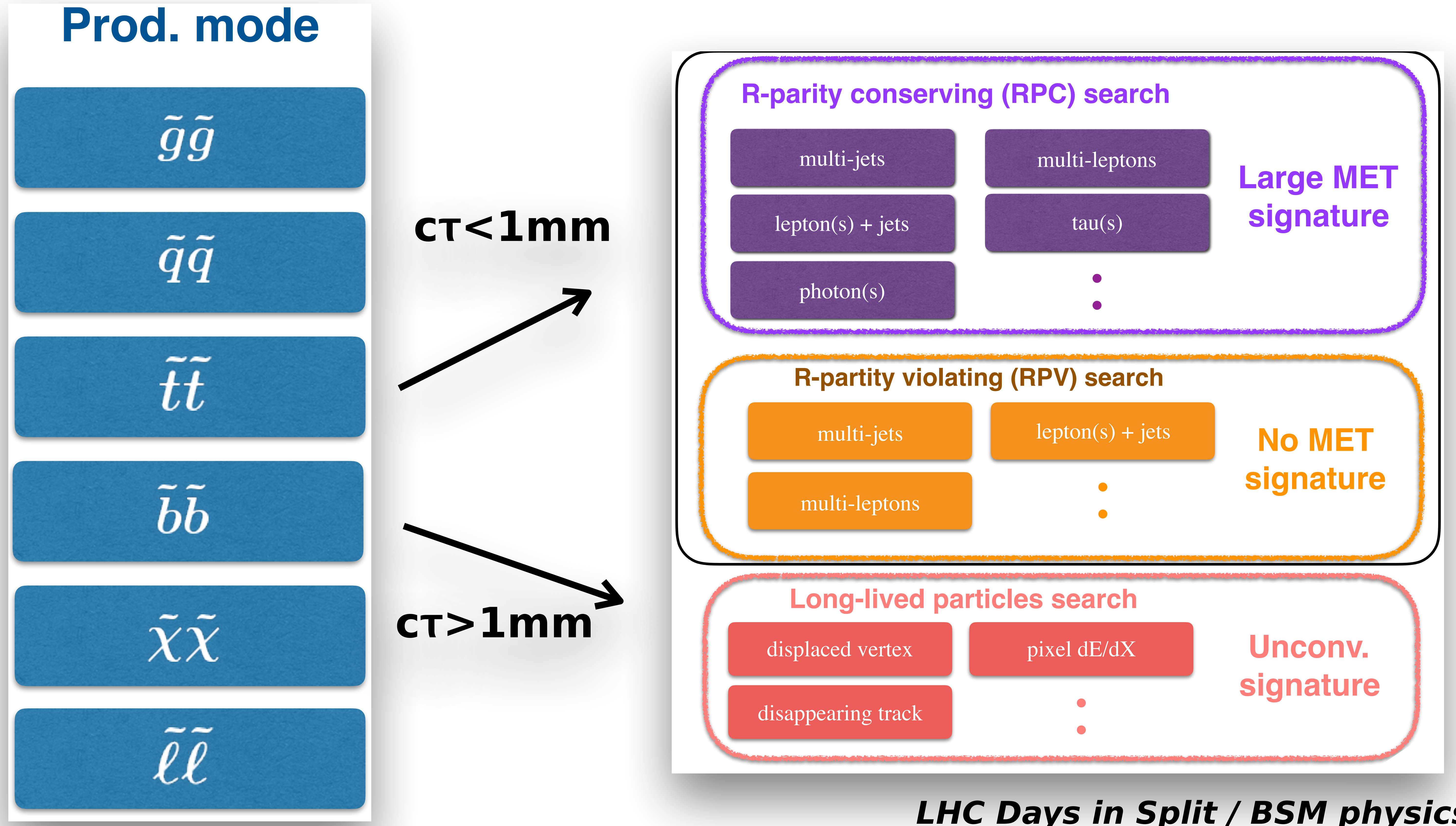
Summary and Outlook

- There are no significant sign of new BSM physics.
  - But there are many BSM physics not searched/considered yet at the LHC.
- Recently new technique have been introduced,
  - e.g. Machine Learning : Boost sensitivity **Jet-imaging**, **TrackML**,
  - e.g. Complicated FPGA based trigger : Boost data-taking, **hls4ml**, **FTK**.
- Also we have more data right now!! Will reach ~ 100/fb order,
  - This will help us to find more complicated/low cross section signal.
  - Our quest for BSM physics has been just started!!

“backup”

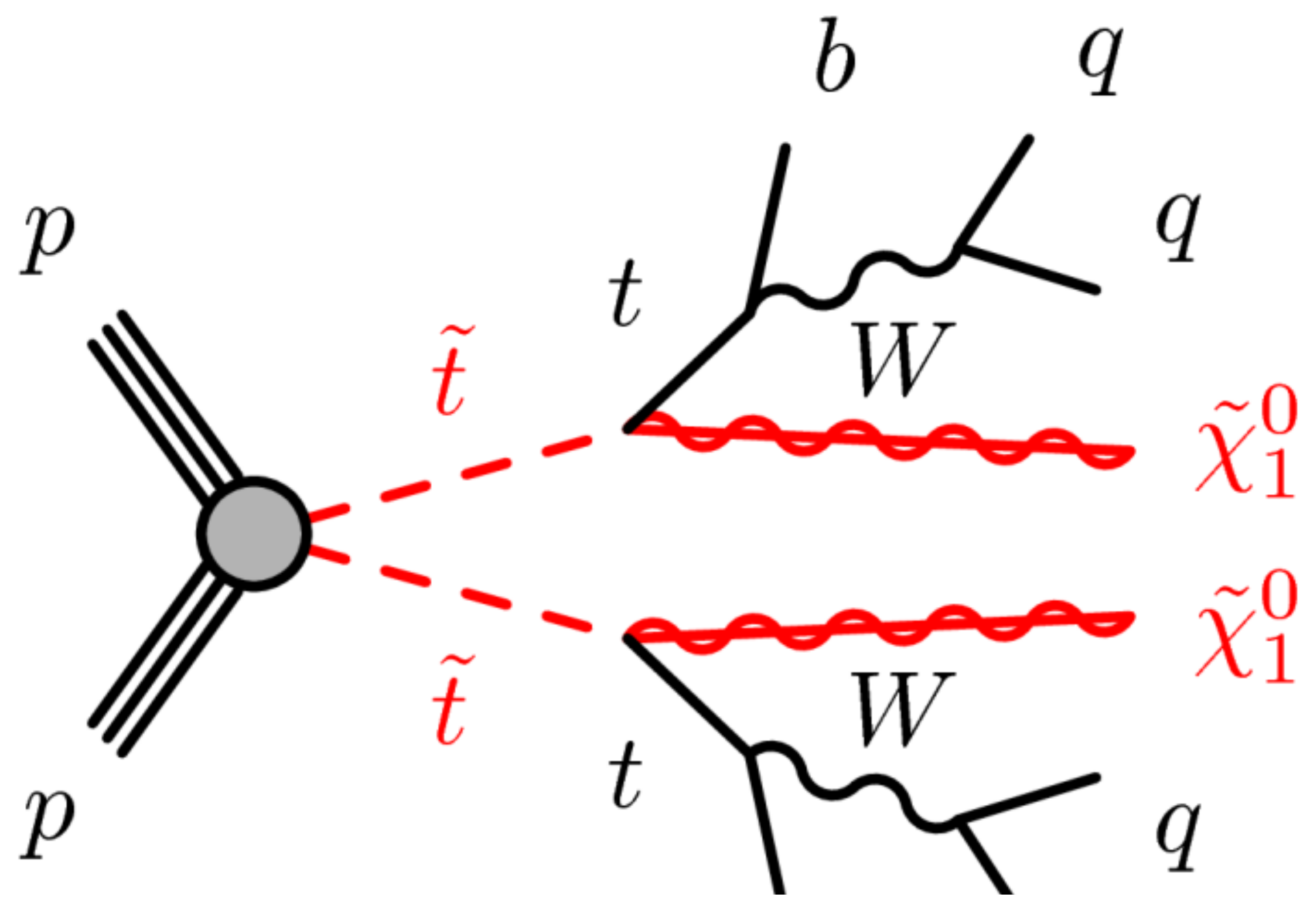
SUSY Search Strategy

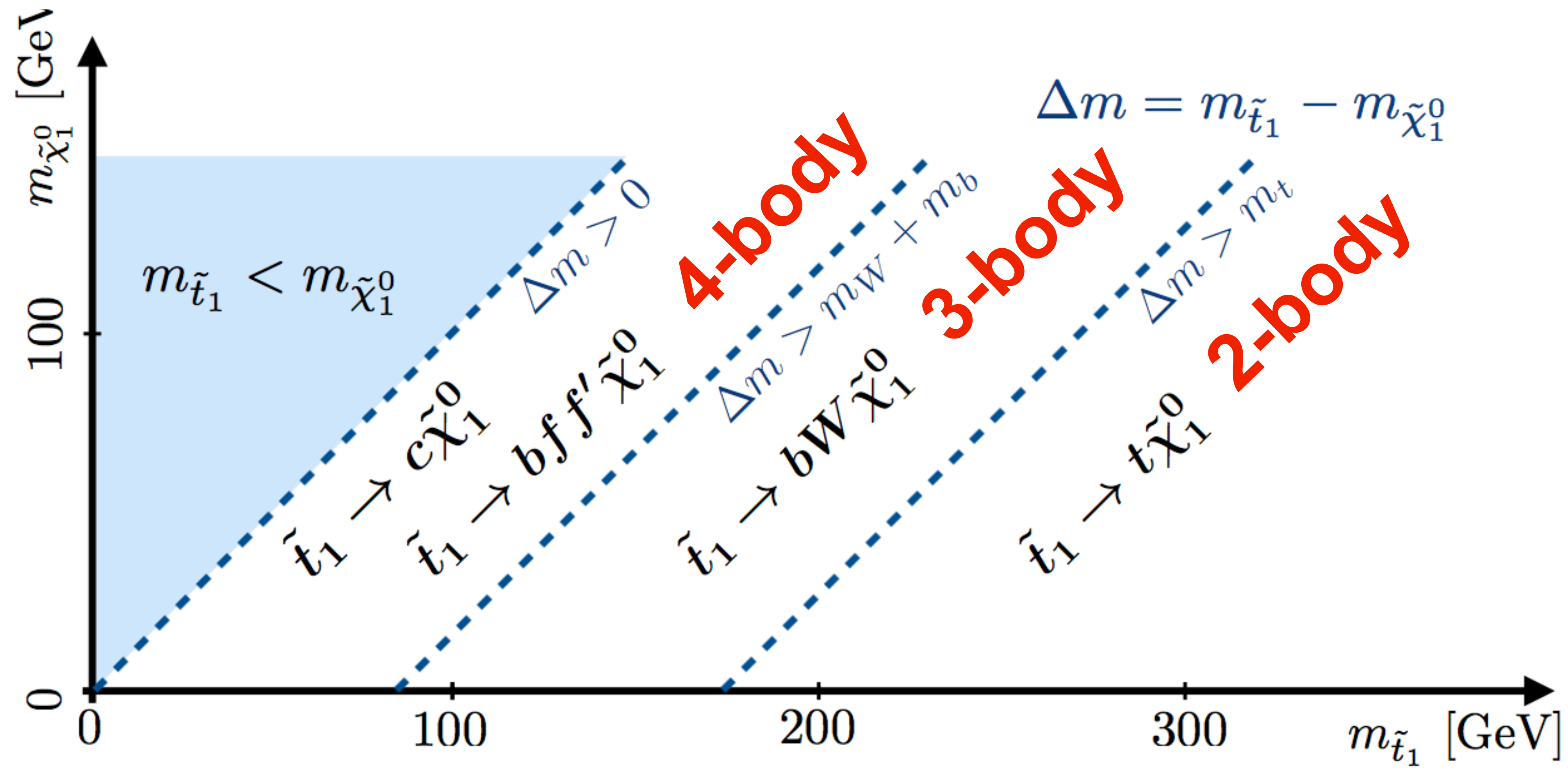
- In general, consider three scenarios :
  - **Standard scenario** : Neutralino LSP, R-parity conserving(RPC)
  - **GSM-like spectra** : G LSP, (Possibly Axino LSP or Singlino LSP) …
  - **R-parity Violation(RPV)** : LSP decay into SM particles.
- Consider a model as inclusive as possible : Search all possible final state and mass spectra.

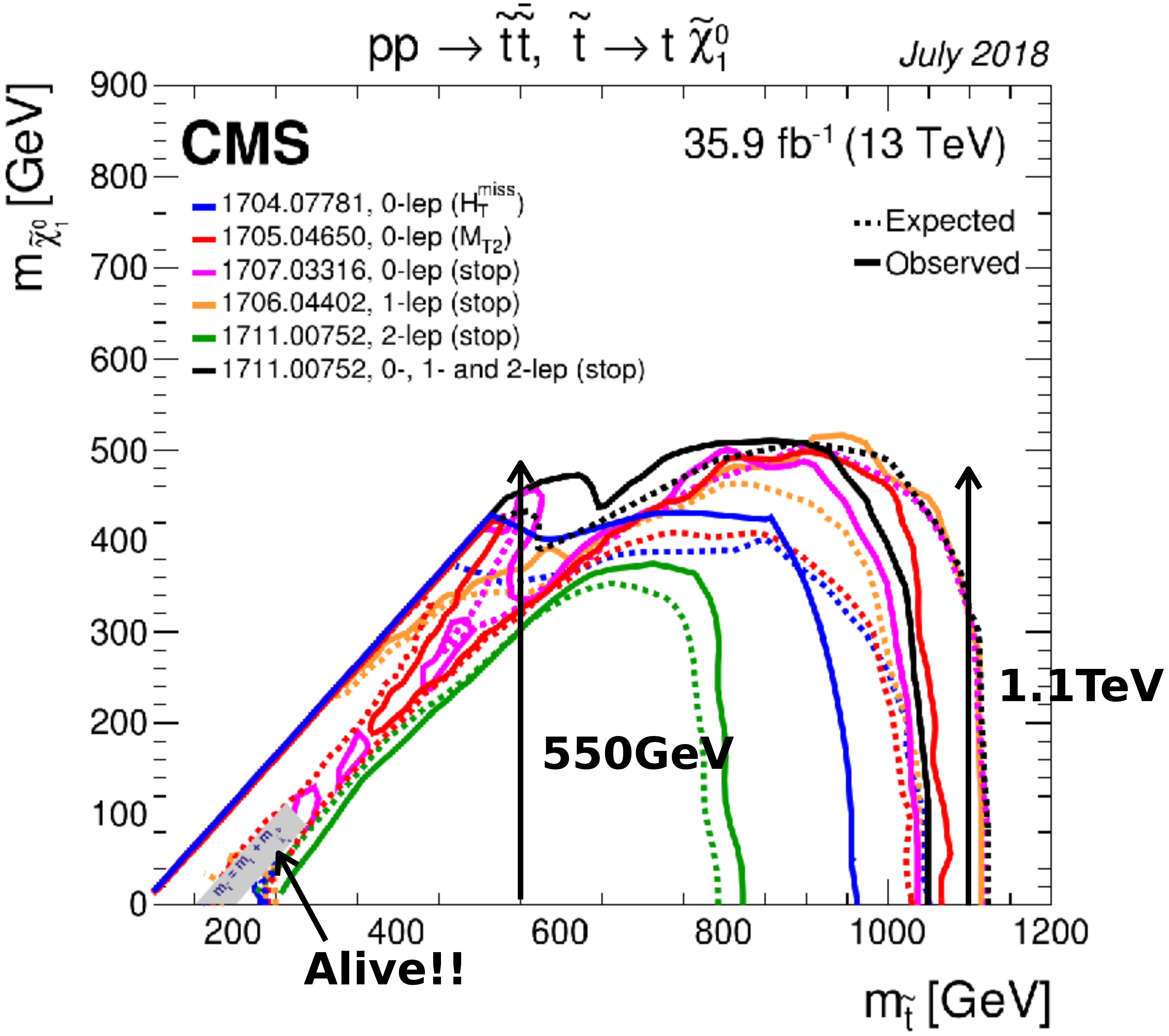


Stop/Sbottom :

- Naturalness → Light stop
- Stop decay (tN, bC) or LSP components(bino/wino/higgsino) → several signature!!



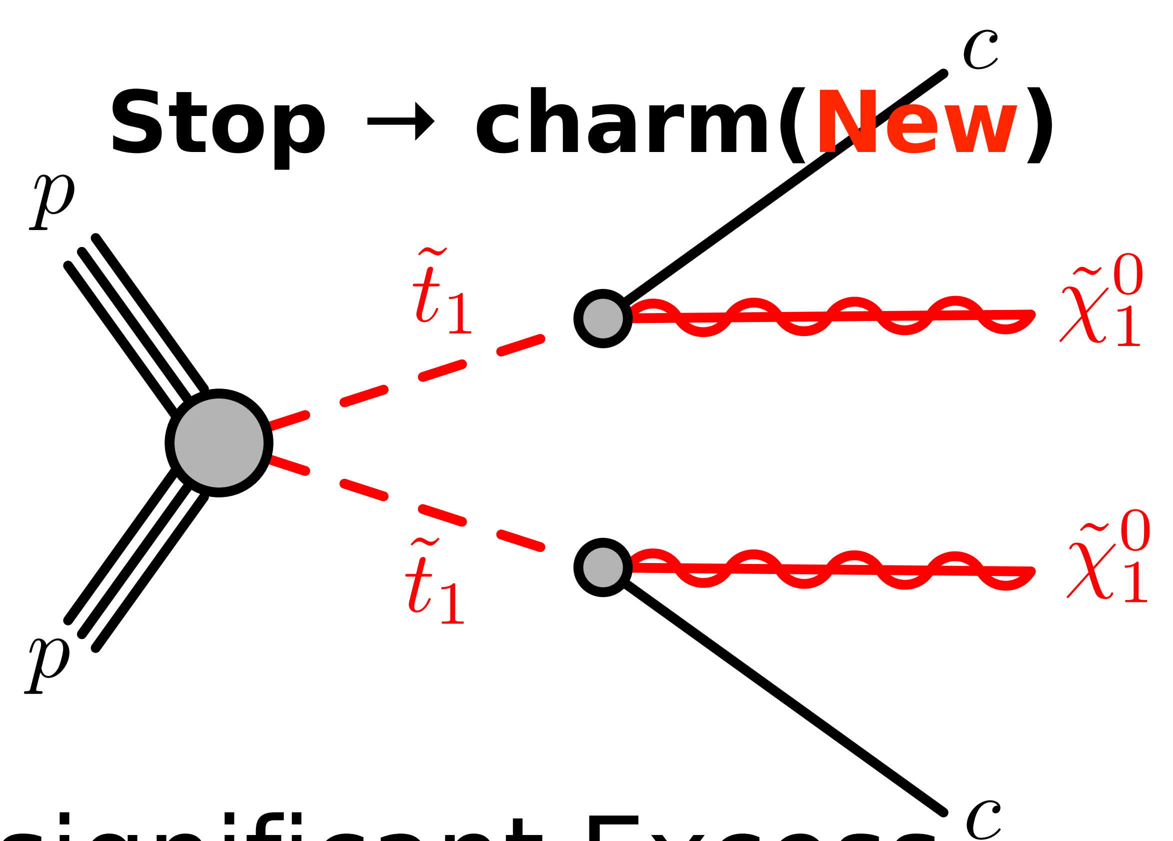




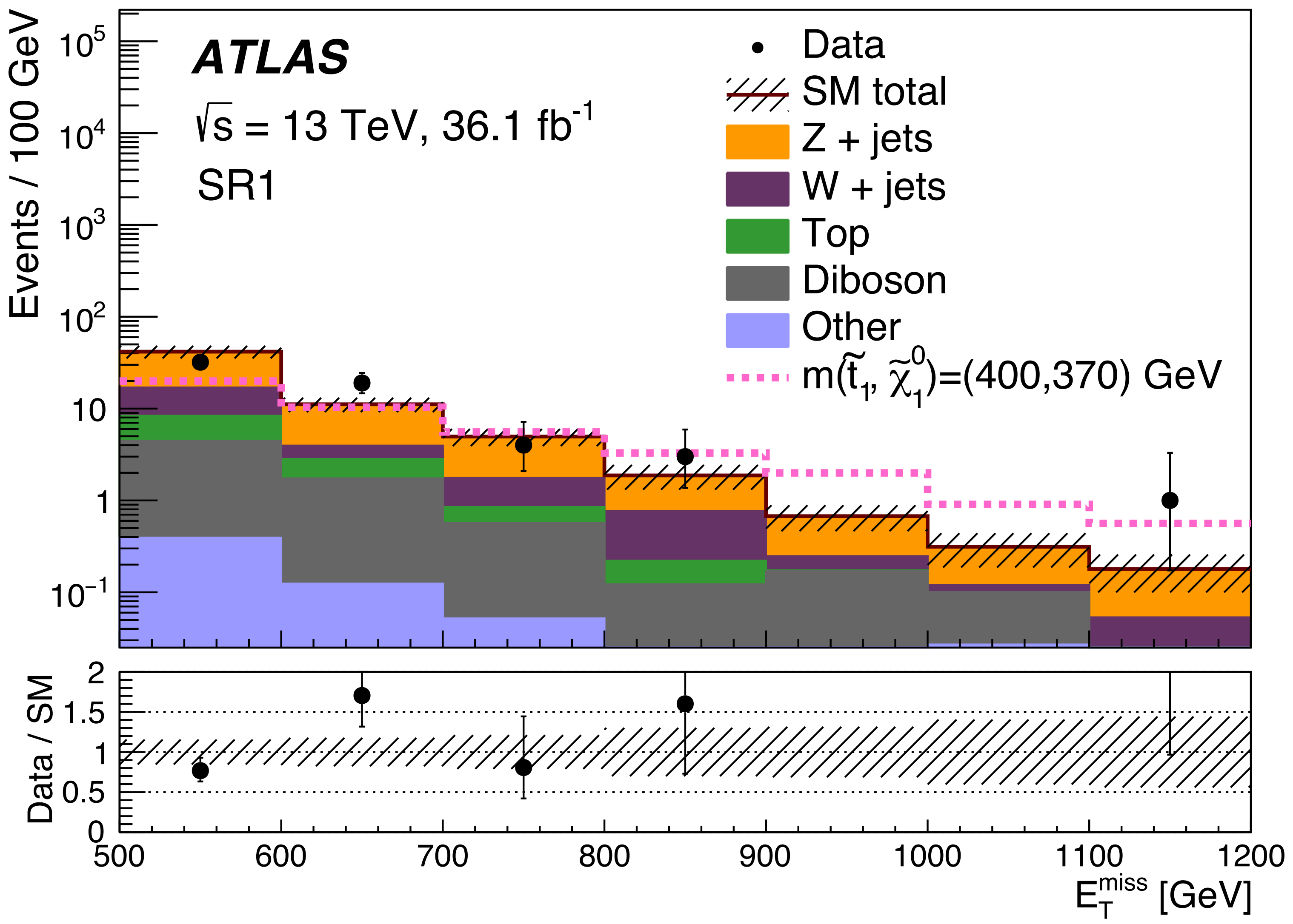
Other 3rd generation squark signature

- Charm tagging technique, ISR tagging → No significant excess
  - 5 SRs and validate w/ CR
    - (Z+jets, W+jets, Top)
  - c-tagging syst. ~ 8%

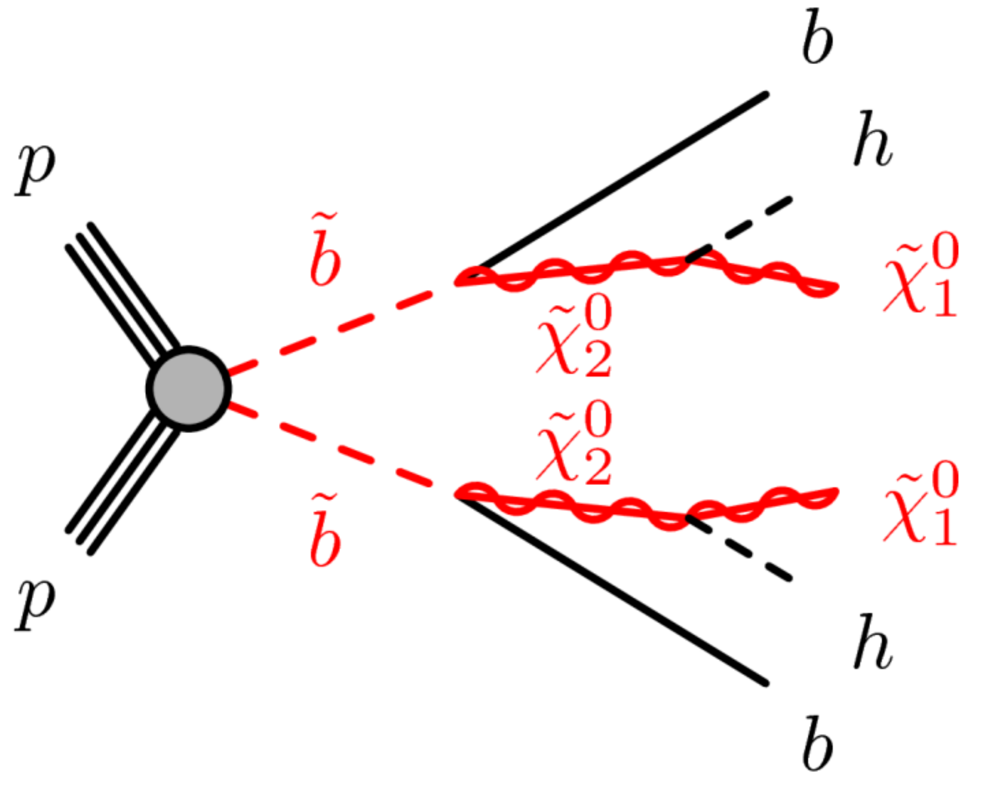
Stop → charm(New)



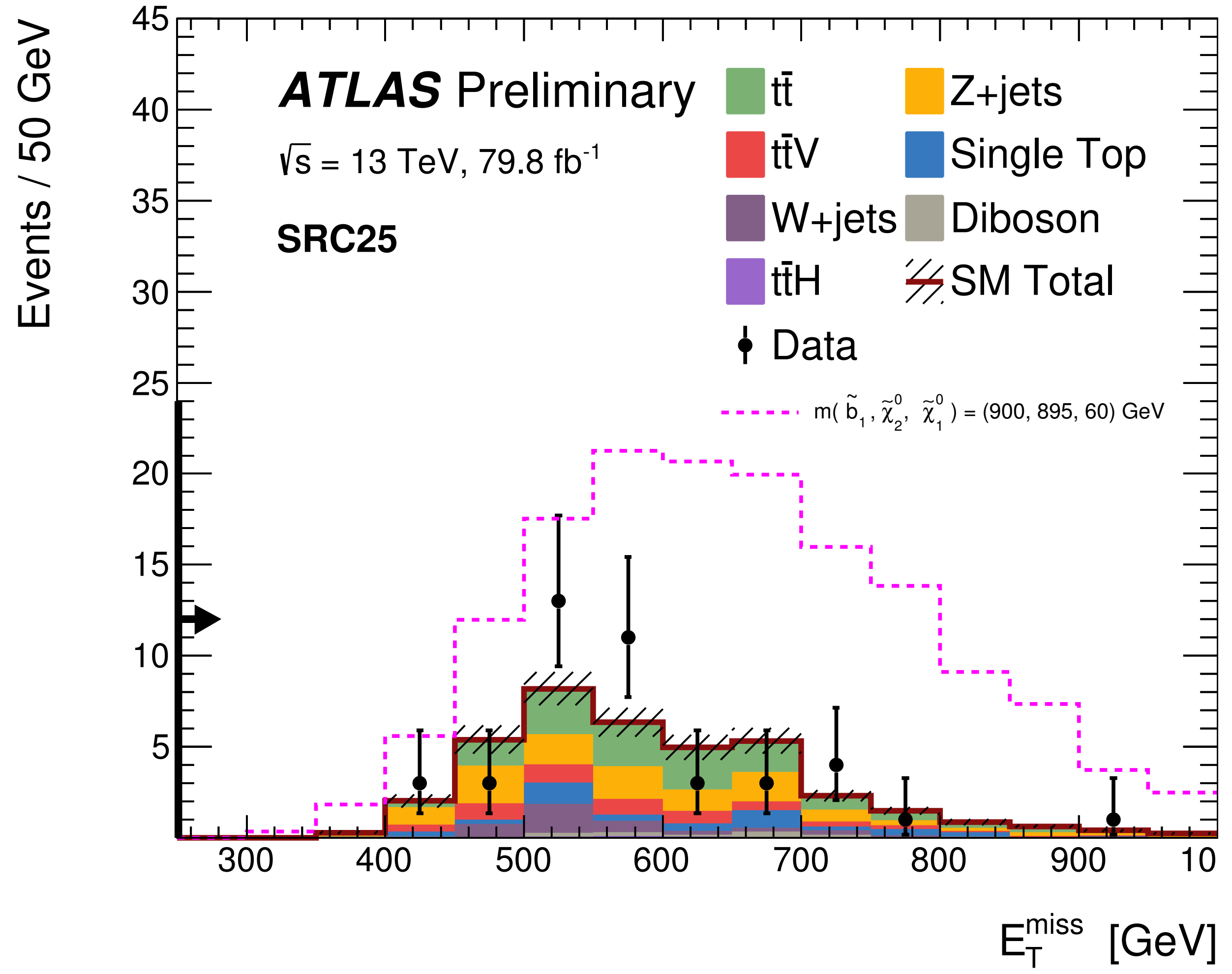
1805.01649

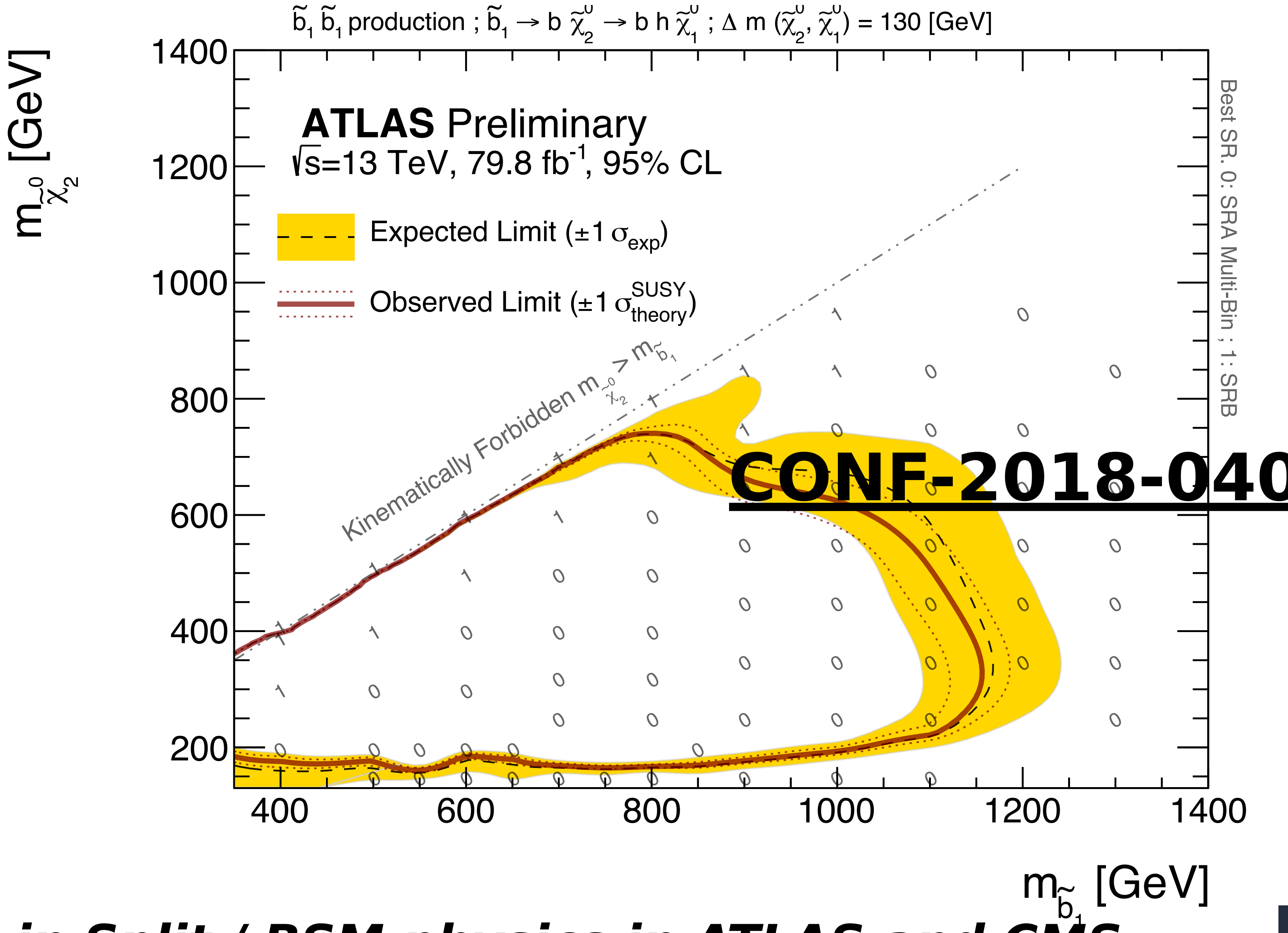


- 0L + E_T^{miss} > 250GeV, 3 or 4 b-jet → No significant Excess
  - 3 SRs w/ different event kinematics
  -



Sbottom → hNeutralino(New)



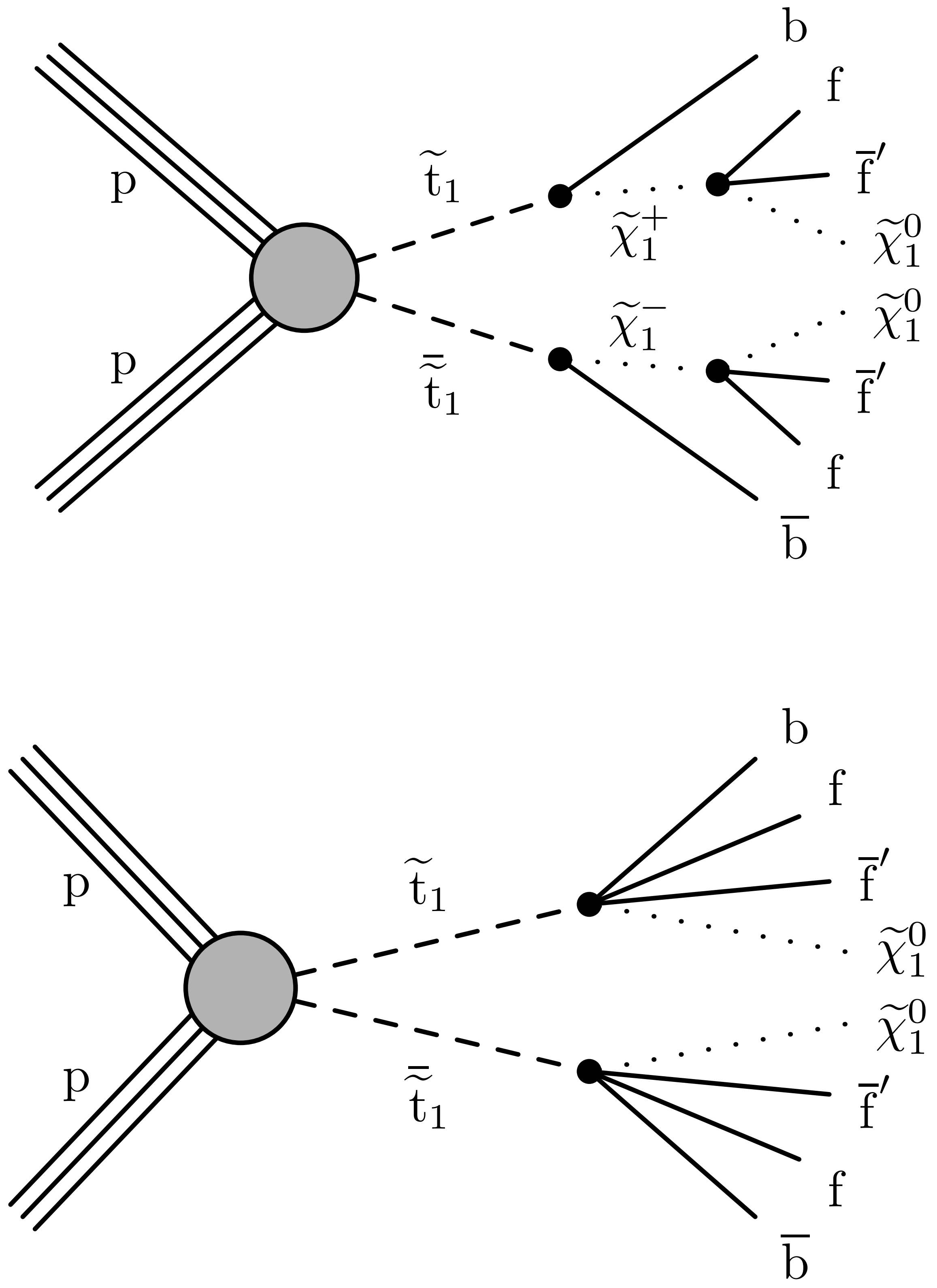


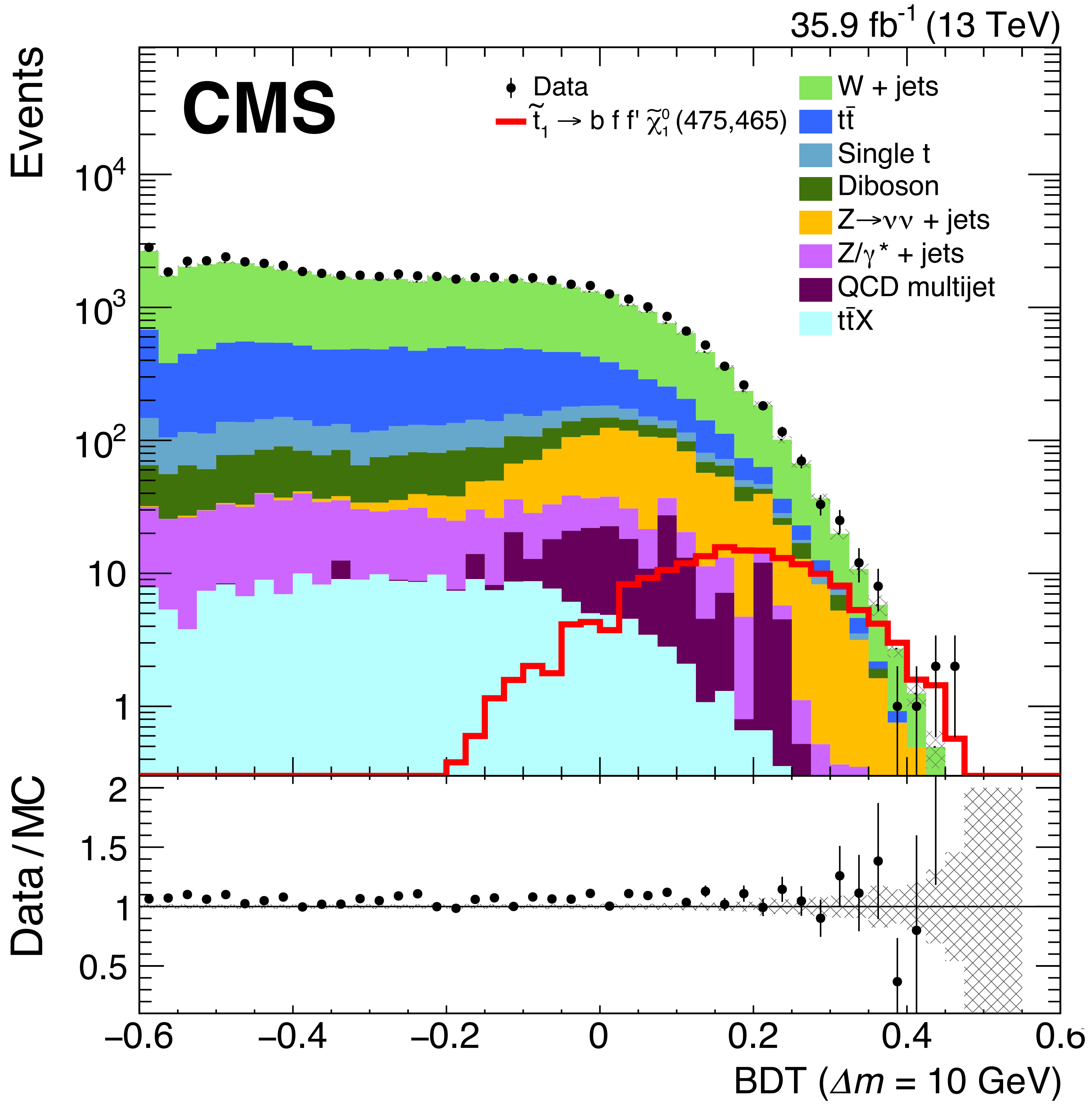
CONF-2018-040

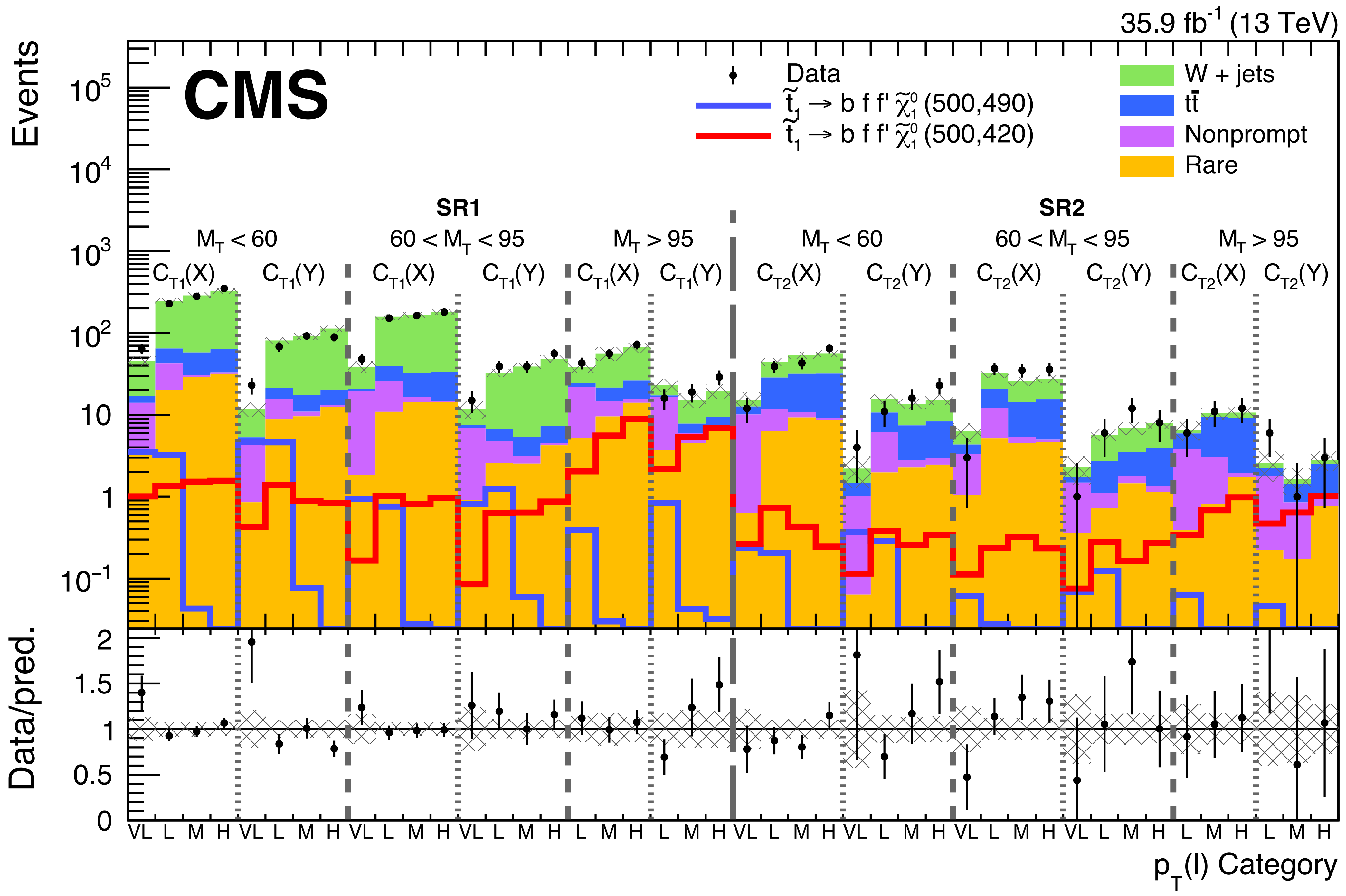
Stop 4-body decay in CMS @36/fb

1805.05784

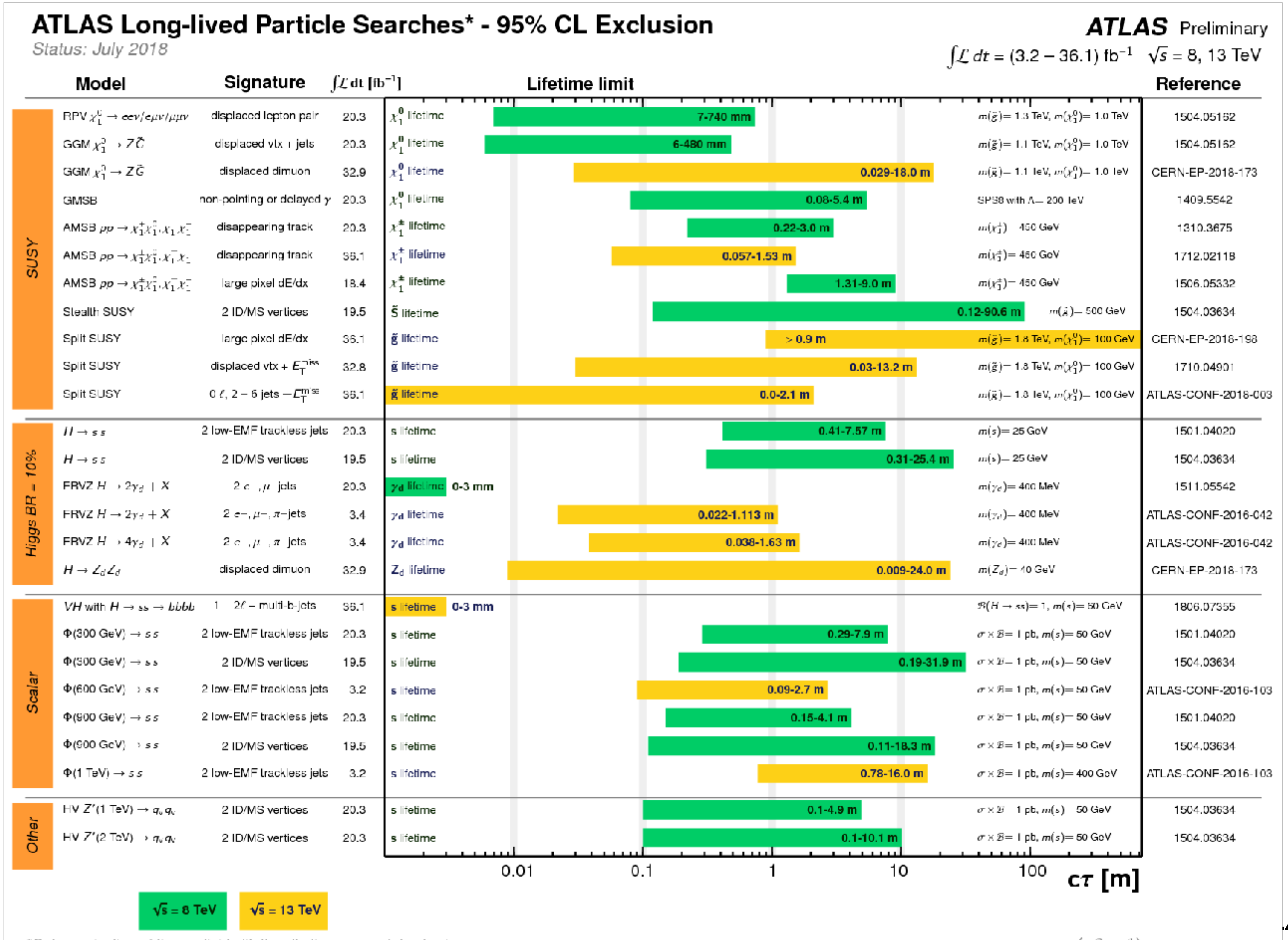
- Soft-lepton + soft b-tagging technique, pT> 5/3.5 GeV for electron/muon.
  - Cut & Count SR(for comb.) + MVA SR
    - MVA : ΔM =10-80 GeV w/ 10GeV step, w/ 12 input variables
- No significant excess in data







ATLAS Exotic Summary



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

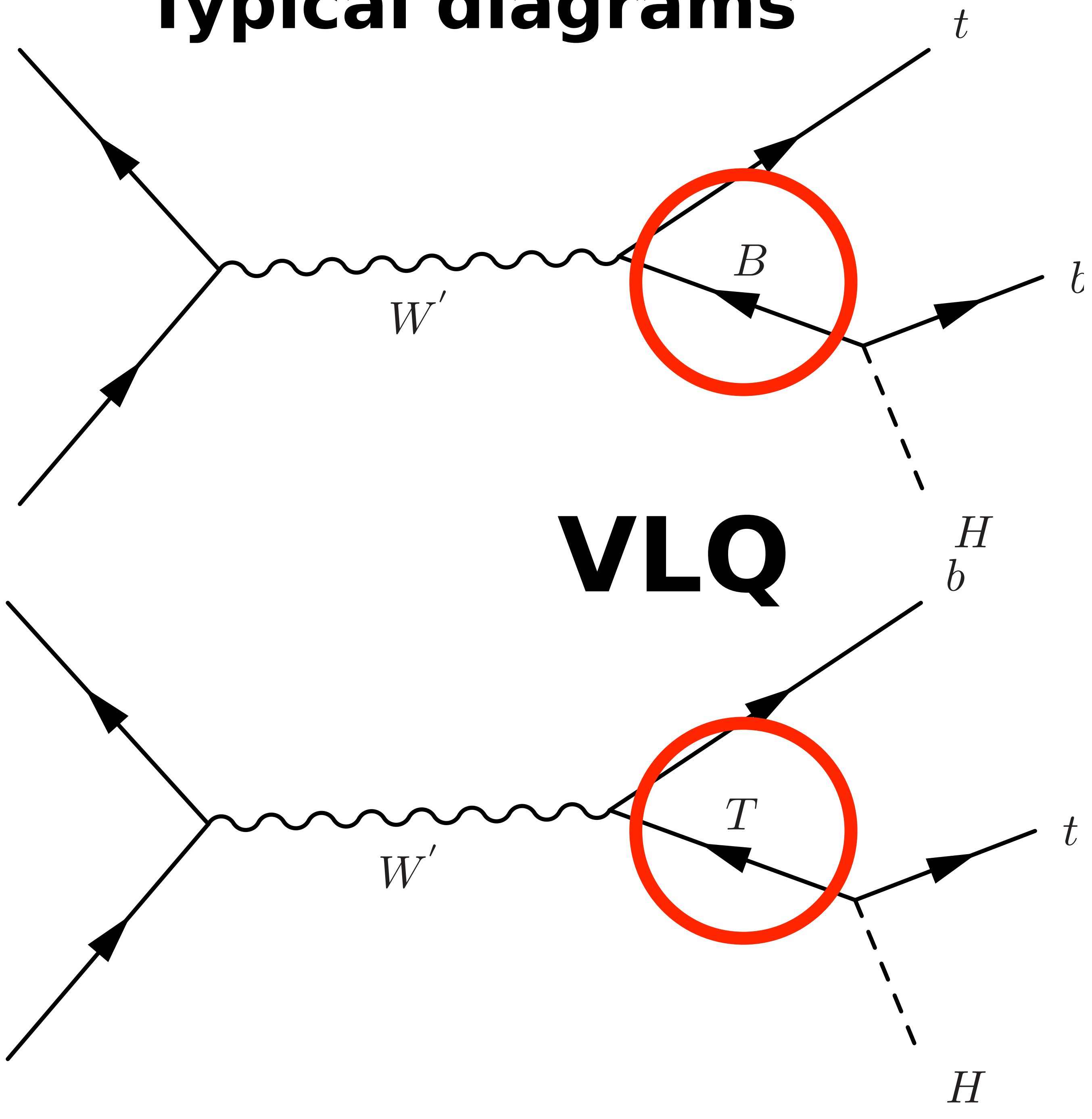
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	1 – 4 j	Yes	36.1	M_D	7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	Z' mass	4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass	3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	79.8	W' mass	5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	W' mass	3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	79.8	V' mass	4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass	2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass	3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	Λ	40.0 TeV	η_{LL}^{-}	1707.02424
	CI $tttt$	$\geq 1\ e, \mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	1 – 4 j	Yes	36.1	m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	1 – 4 j	Yes	36.1	m_{med}	1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	LQ mass	1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	LQ mass	1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass	640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass	1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3} T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e, μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3} Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	3.2	Y mass	1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	$0\ e, \mu$, $2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass	6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	N^0 mass	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	spin-1 invisible particle mass	657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass	785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188

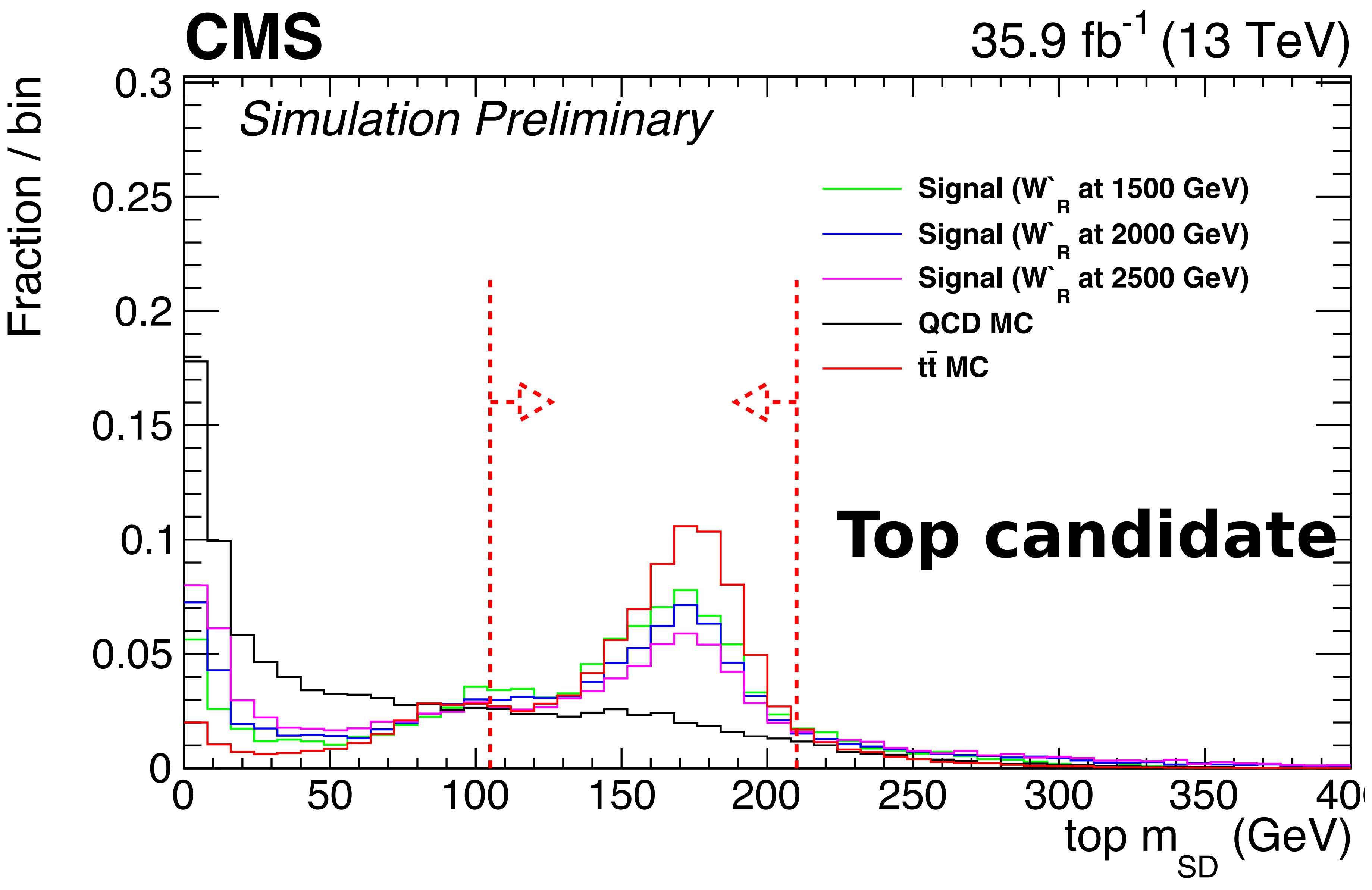
W' into VLQ + top/bottom hull hadronic in CMS @36/fb

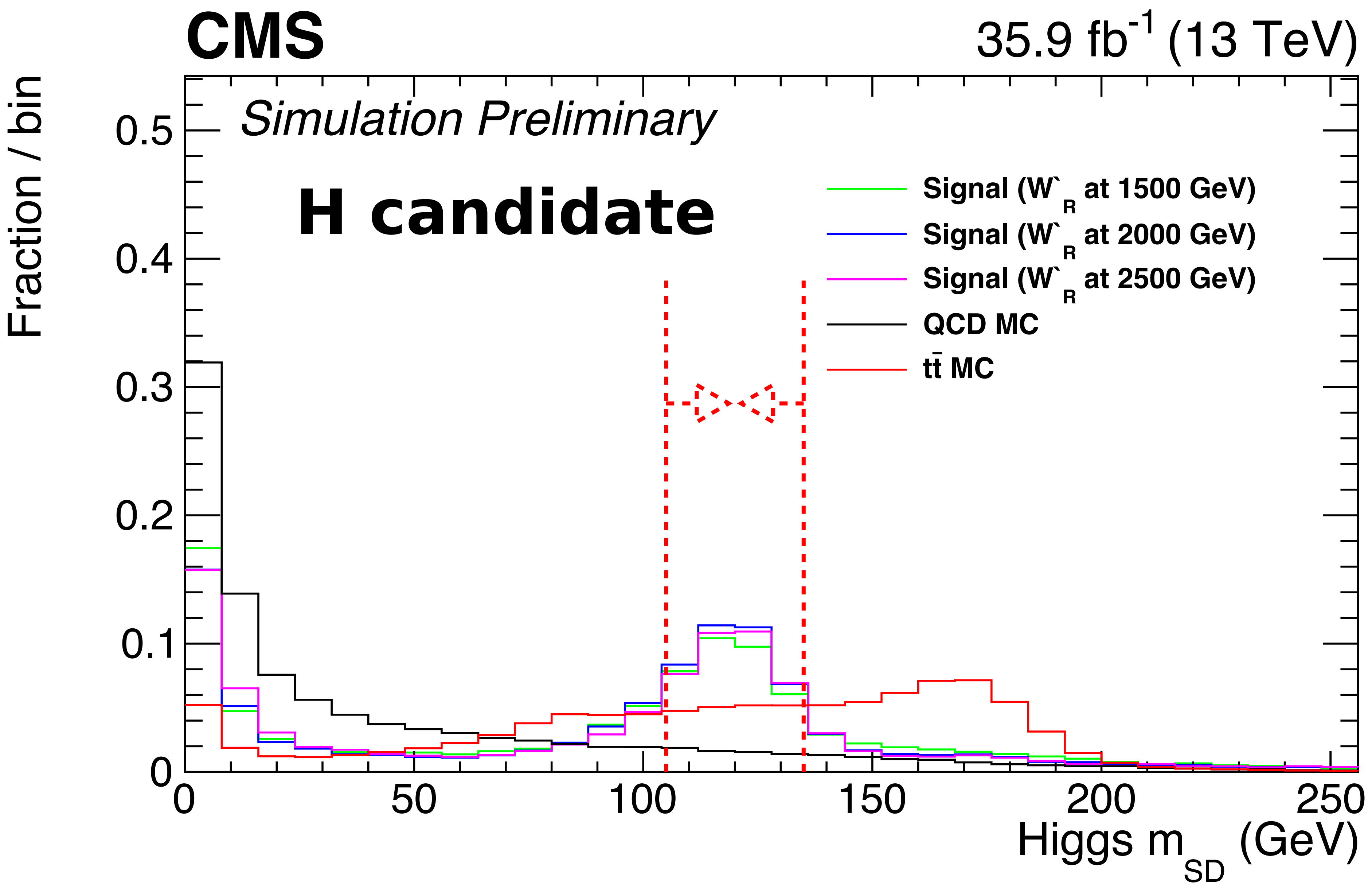
B2G-18-001

- **W'→B/T VTQ**: VLQ decay into top/bottom + Higgs
  - HT trigger is used w/ 1TeV threshold → eff. Is measured by single-muon-trigger
  - Higgs/top-jet tagging : soft drop/subjetness variable is used !!
  - **Selection** : m_{top} and m_H, sub-b-tag(top), double b-tag(Higgs)
  - **Background** : QCD is main bkg estimated using CR data.

Typical diagrams







W’ into VLQ + top/bottom hull hadronic in CMS @36/fb

<u>B2G-18-001</u>

- **W’→B/T VTQ**: VLQ decay into top/bottom + Higgs
  - Background : QCD is main bkg estimated using CR data.
- No significant excess…
  - Limit on $m_{W'}$: w/ Low/Central/High VLQ mass hyop(1/2, 2/3, 3/4 m_{VLQ}).
  - Need more sensitivity → Run2 full data will help!!