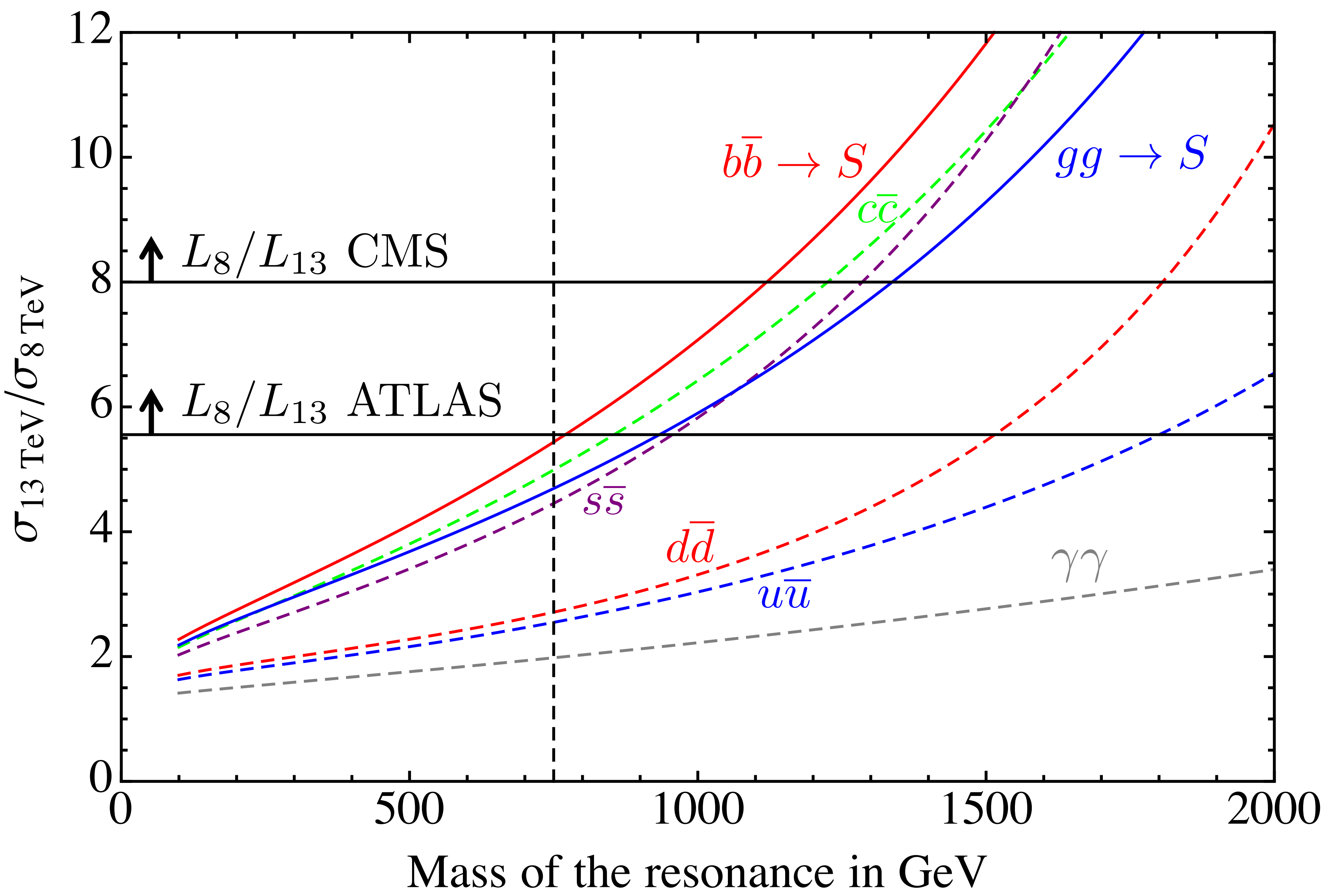
Di-photon returns…

Mihoko Nojiri
(KEK & IPMU)

based on a work with
Chengcheng Han, Koji Ichikawa ,
Shigeki Matsumoto Michihisa Takeuchi
(1602.08100. will be published in JHEP soon)

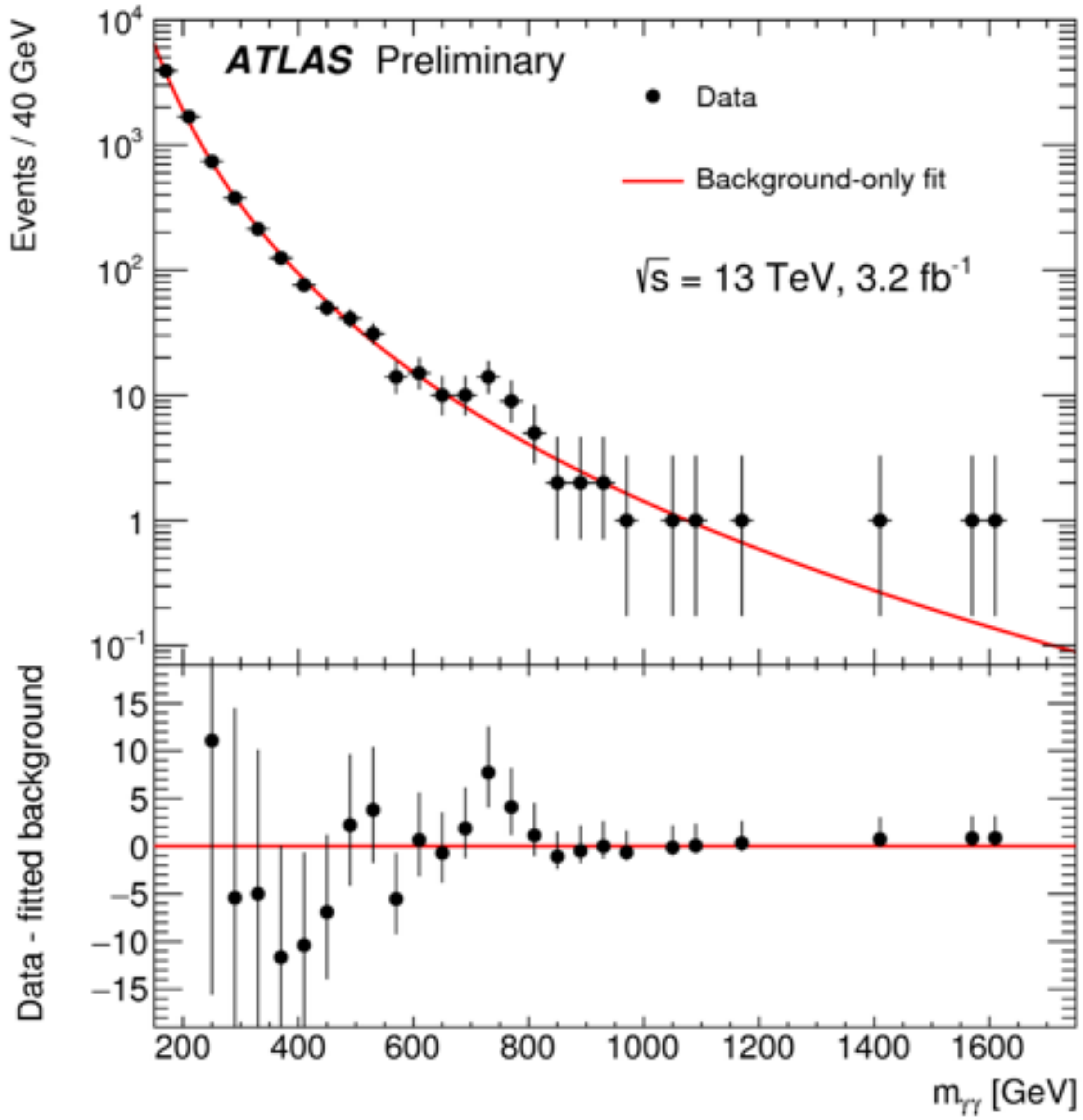
LHC 13TeV last year is still low in luminosity but powerful enough so that we may still learn someghing.



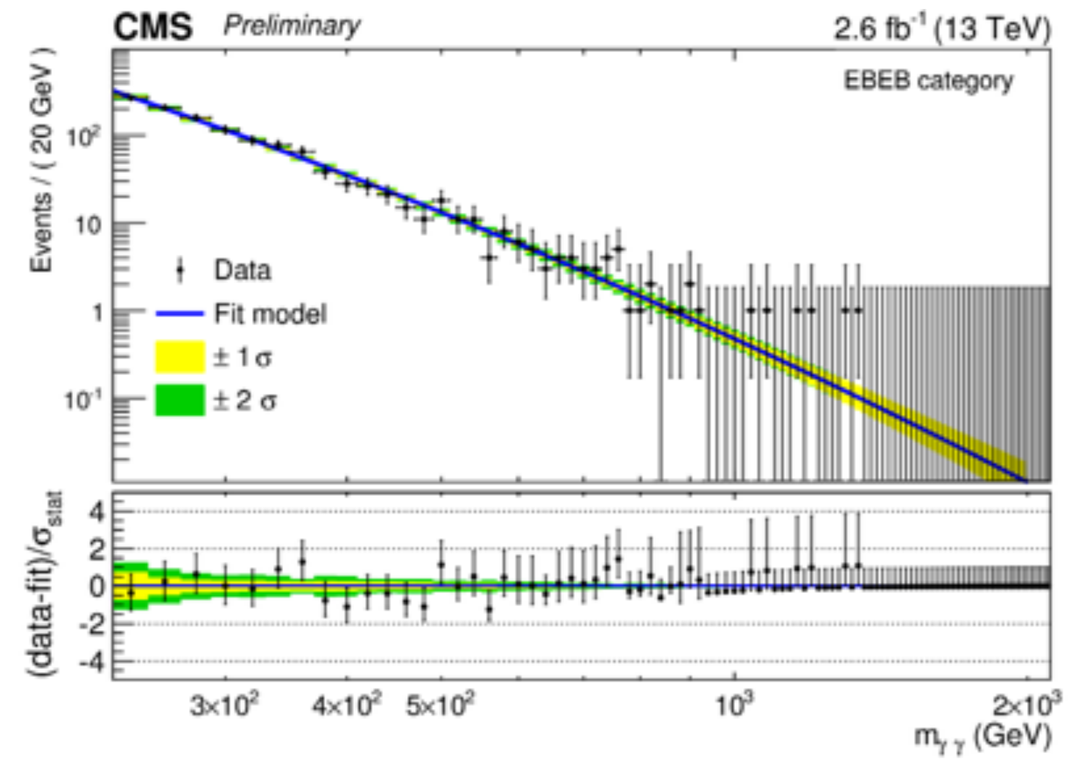
from 1512.04933 Franceschini et al

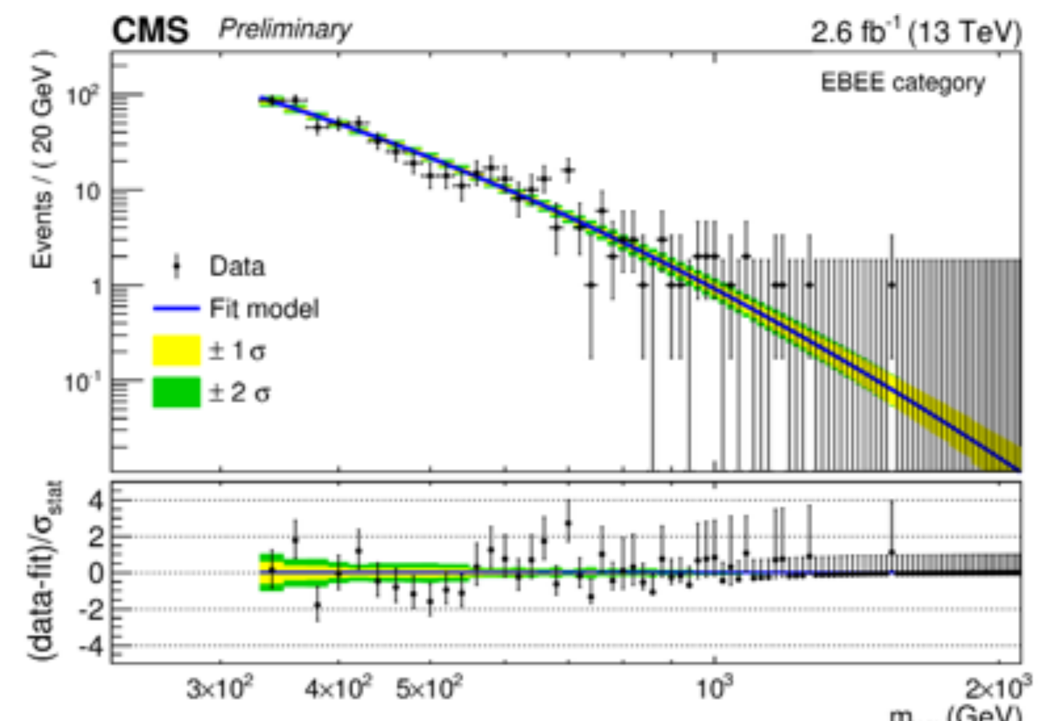
of course there are nothing to worry about this…

ATLAS and CMS



m=750 GeV 3.6σ local (2.0σ global)





m=760 GeV 2.6σ local (<1.2σ global)

$\sigma_{\gamma\gamma} = 4.4 \pm 1.1\mathrm{fb}$ [arxiv:1512.04929]

effective theory approach vs UV completion (if any)

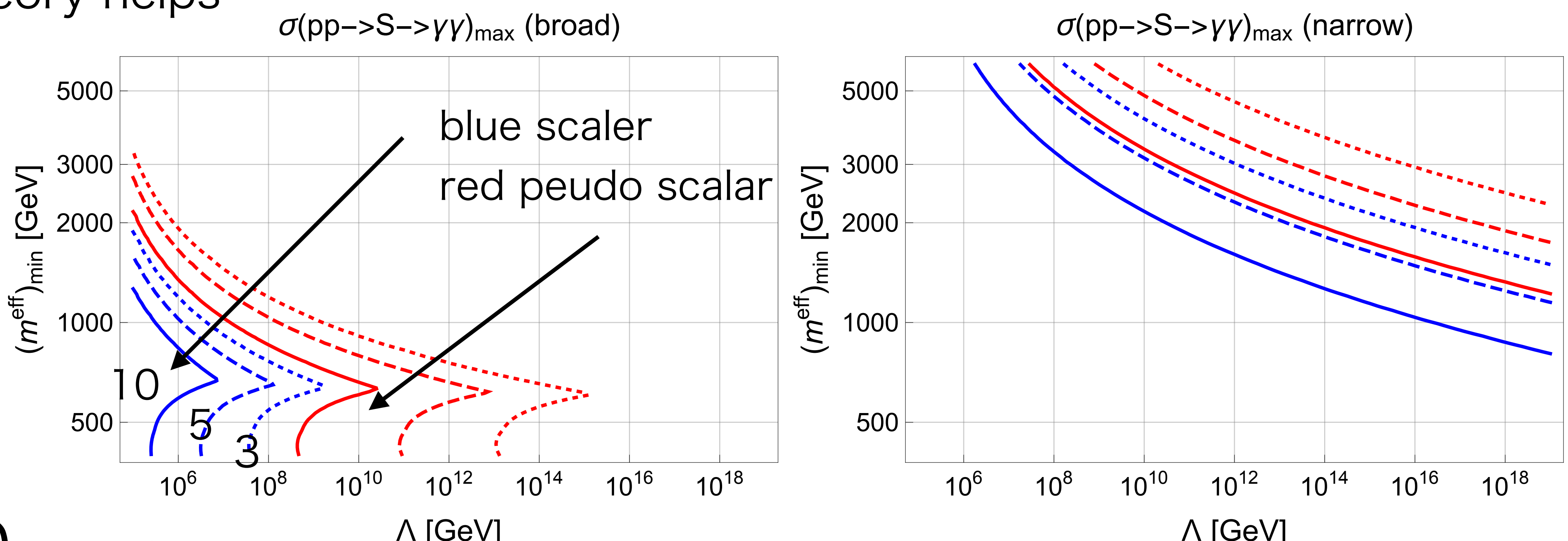
- Need New scalars couples to gg and $\gamma\gamma$ (fermion loops)

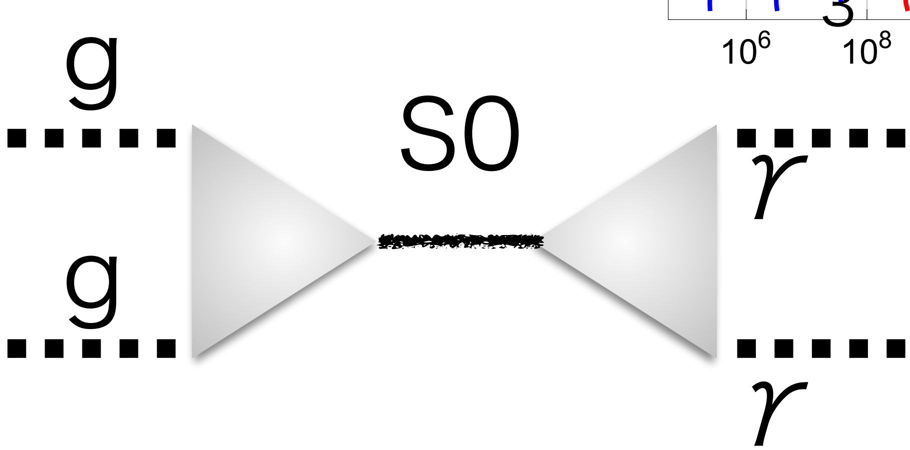
$$\mathscr{L}_{\text{eff}} \supset \frac{C_{BB}}{m_{S_0}} S_0 B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{C_{gg}}{m_{S_0}} S_0 G^{a\mu\nu} \tilde{G}^{a}_{\mu\nu},$$

- To achieve the desired cross section, we need to many intermediate particles if it comes from fermion loop

(coupling is essentially β fun)

- Field theory helps





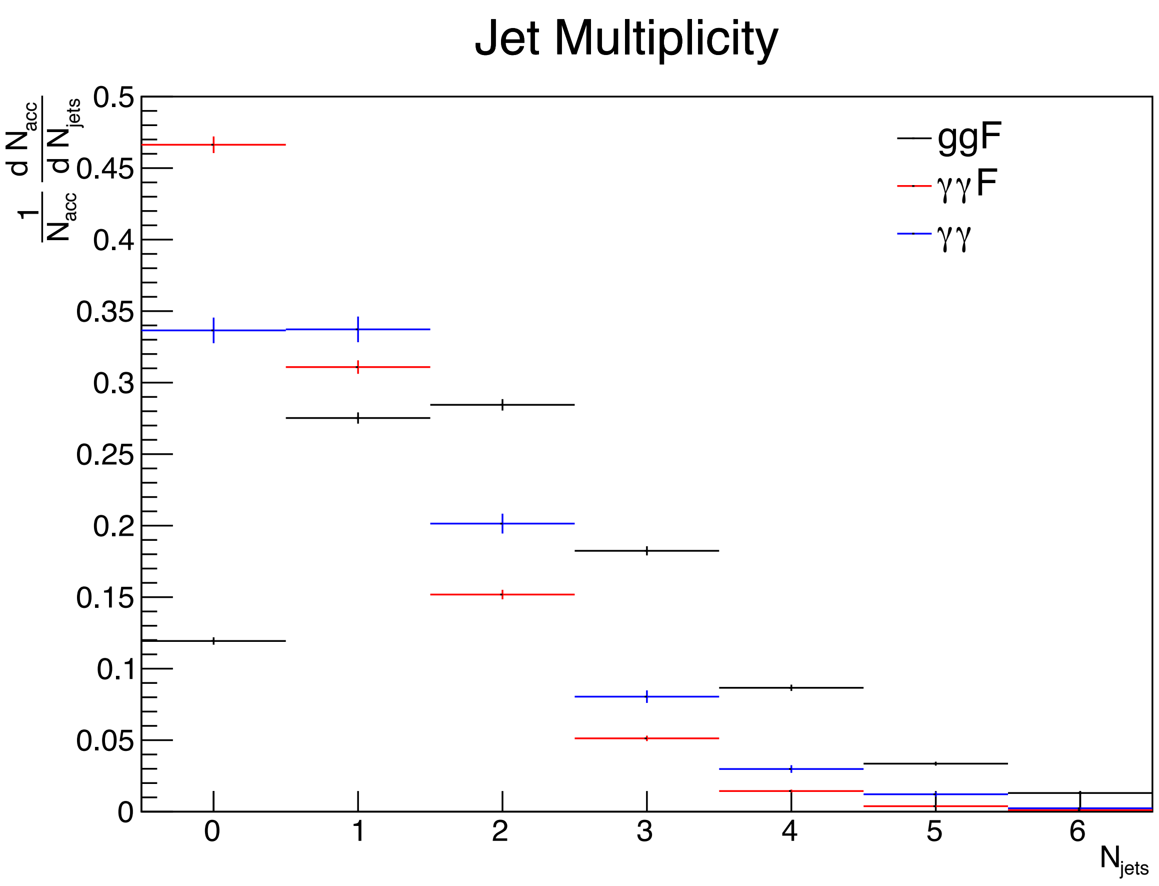
scale where coupling brow up

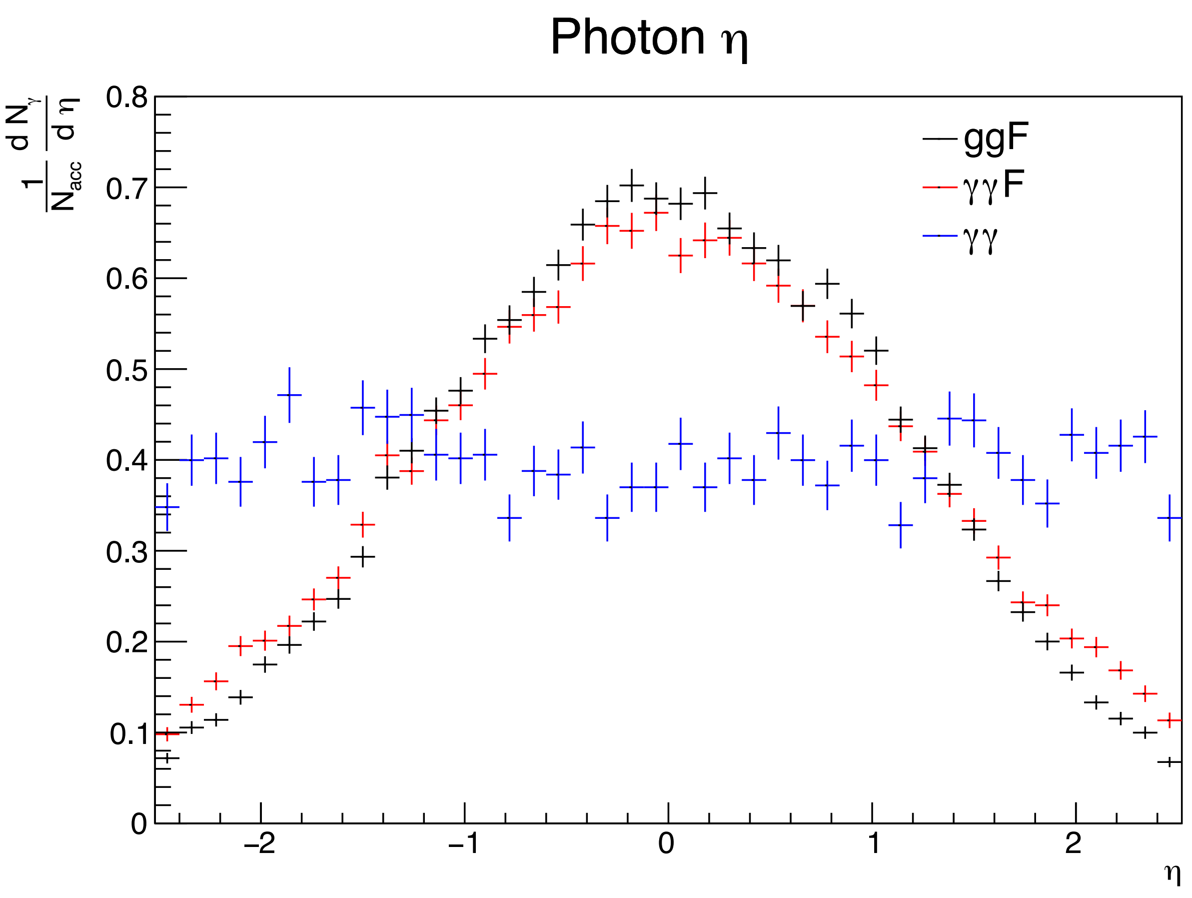
1602.03653 Bae, Endo, Hamaguchi, Moroi

with higher luminosity

- number of additional jets , photon eta distribution

1601.00638 Csaki, Hubisz, Lombardo, Terning





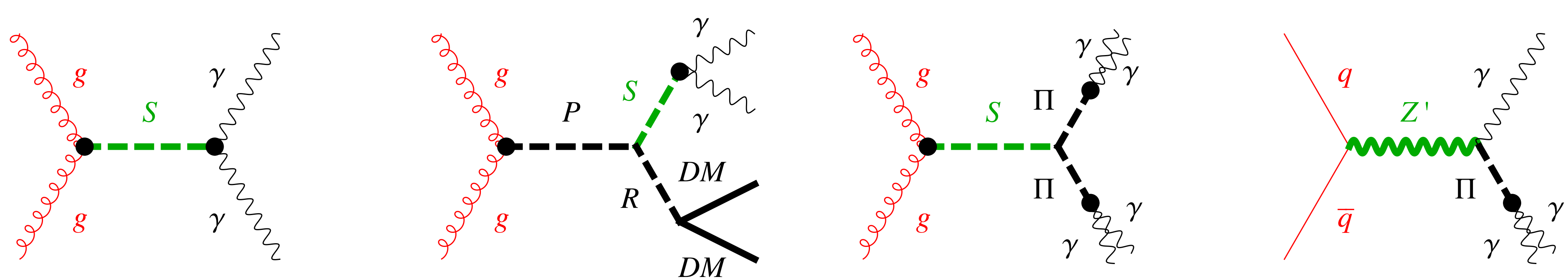
spin correlation of ISR is in principle sensitive to the CP of scalar

eta distribution and $\cos\theta^*$ of photon is sensitive to spin 0 or 2

Photon jet

A more complicated kinematics?

Compatibility between runs 1, 2 improved if S decays from a heavier particle.



*LY theorem

Tuning $M_P \approx M_S + M_R$ needed to avoid $\not{p}_T$. S virtuality can fake S width.

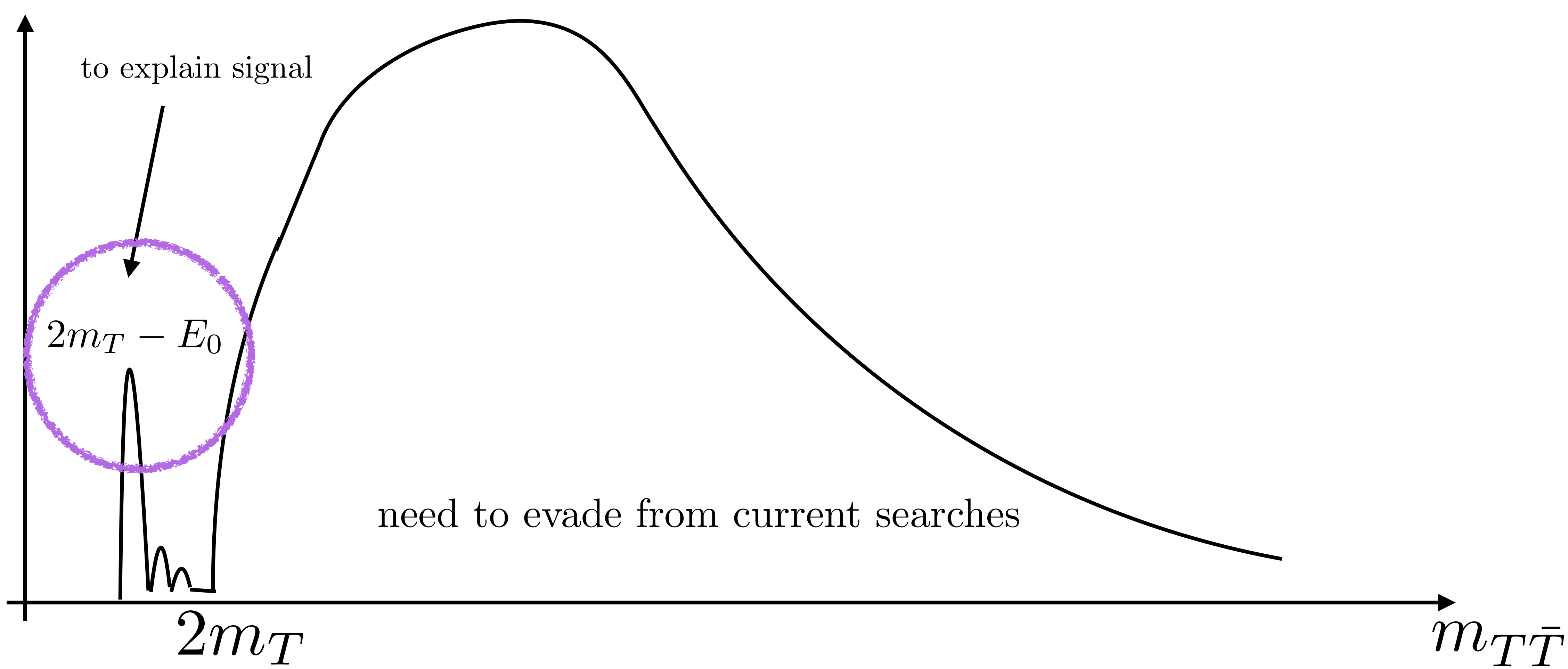
Or large $S \to \Pi\Pi$ with $\Pi \to \gamma\gamma$, collimated and seen as a single γ if $M_\Pi \ll M_S$. Traveling in the detector material, ‘photon jets’ give more $\gamma \to e^+e^-$.

Or many collimated γ. Or not a peak. Or two nearby narrow resonances.

Talk by Strumia at ‘Beyond the SM’ at OIST, 3/4, 2016

Another possibility: bound state of heavy fermion

$1S(J^{PC} = 0^{-+})$ $at\ 750GeV$ $m_T:\ 375 \sim 380GeV$



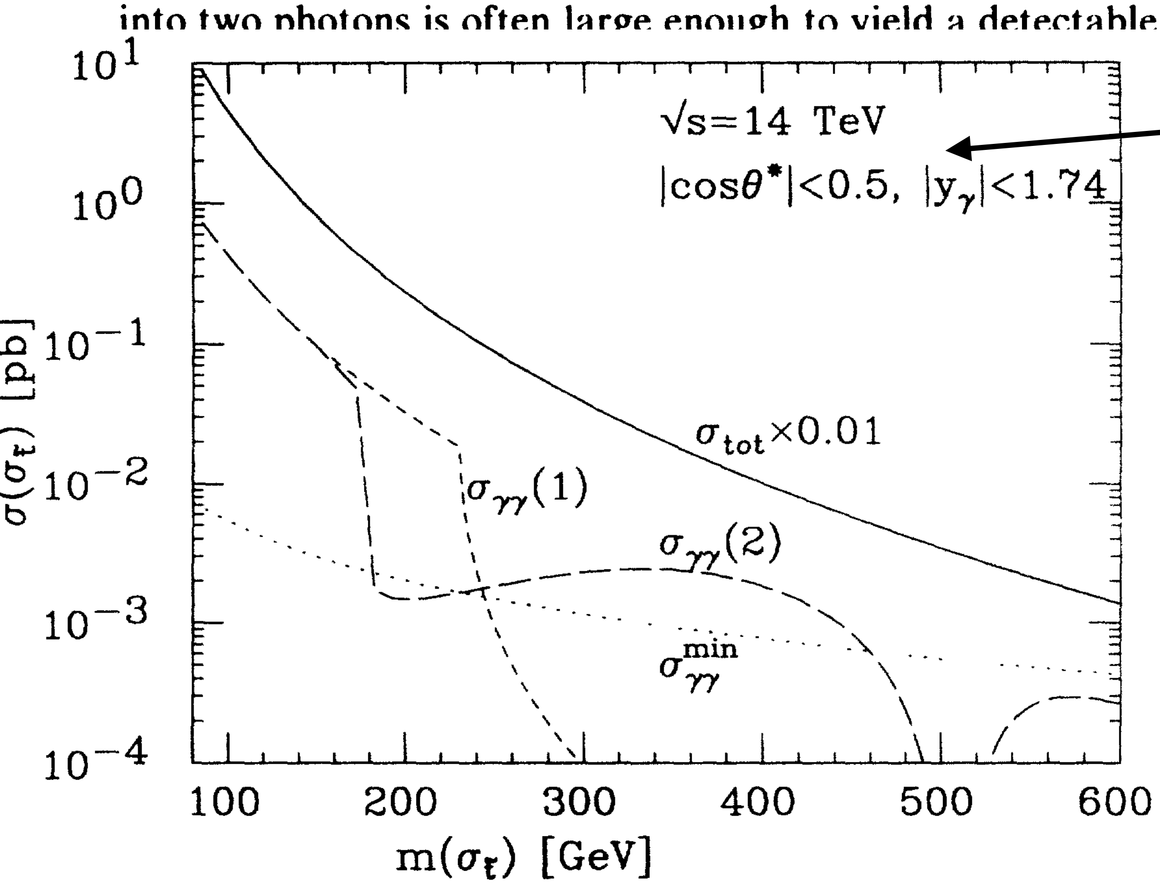
Proposed New Signal for Scalar Top-Squark Bound-State Production

Manuel Drees
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

Mihoko M. Nojiri*
Theory Group, KEK, Oho 1-1, Tsukuba, Ibaraki 305, Japan
(Received 4 October 1993)

SSC canceled Oct 31 of the year

We study the production and decay of a scalar $(\tilde{t}_1\tilde{t}_1^*)$ bound state $\sigma_{\tilde{t}_1}$ at hadron supercolliders, where $\tilde{t}_1$ is the lighter scalar top eigenstate. If $\tilde{t}_1$ has no tree-level 2-body decays, the dominant decay modes of $\sigma_{\tilde{t}_1}$ are gg or, if $m_h < m_{\tilde{t}_1} \ll m_{\tilde{t}_2}$, a pair of light scalar Higgs bosons h. Nevertheless, the branching ratio into two photons is often large enough to yield a detectable signal.



yes! we replaced the figure

LHC was 14TeV and 1year means 100fb-1 and it was supposed to start 2003 or even 2001 (I forgot) because it was competing with SSC

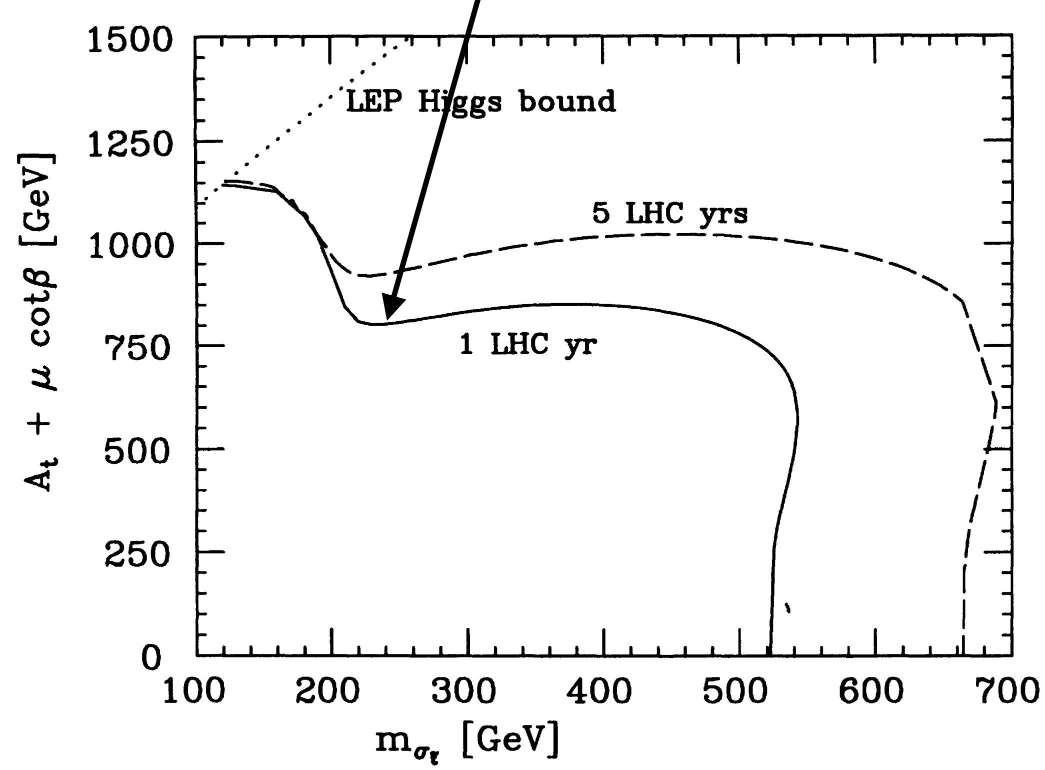


FIG. 10. Region in the pl
$m_{\sigma_{\tilde{t}}}$ and $A_t + \mu\cot\beta$ that can b
1 (solid curve) and 5 (dashed
running the LHC at full lum
fb^{-1} per year). The region
corner is excluded by LEP sea
Higgs bosons. The curves hav
for $m_t = 150$ GeV, $\tan\beta = 3$
$m_{\tilde{t}_L} = m_{\tilde{t}_R}$, $\mu = 750$ GeV, and
depend little on these choices u
as discussed in the text.

worse, I even forgot all about this…
SSC is… really really long time ago

points of this PRL paper (at that time)

- It was the time that we were not at all sure about jet signature at hadron colliders.

- **We did not know how to use ISR jets** for degenerate SUSY search. (CKKW is 2001, Alwall et al for BSM search using ISR is 2008) So this was a “dead zone” of SUSY search.

- Therefore predicting a new lepton/photon signature was very important. (It is still clean and easy channel.)

- **Cosmology:** We already knew about “coannihilation” in degenerate SUSY, where dark matter density constraint is non-trivial. (Griest Seckel is 1991, Drees Nojiri 1993 for SUSY)

heavy scalar/fermion bound state as the origin of diphoton excess

- If the life time of **a heavy colored particle X** is longer than time scale forming XX bound state, there are a channel

- pp →X Xbar → S → gg, $\gamma\gamma$, ZZ

we take X SU(2) singlet

$$\sigma(pp \to S_0 \to \gamma\gamma) = \frac{K}{s\, m_{S_0}} \frac{\Gamma_{\gamma\gamma}\Gamma_{gg}}{\Gamma_{\rm tot}} \left[\frac{\pi}{8}\int dx_1 dx_2\, \delta(x_1 x_2 - m_{S_0}^2/s) f_g(x_1) f_g(x_2)\right]$$

$$\Gamma_{\rm tot} = \Gamma_{\gamma\gamma}/c_W^4 + \Gamma_{gg} + 2\Gamma_X,$$

$$\Gamma_{\gamma\gamma} = 48\pi Y_X^4 \alpha^2 |\psi_0(0)|^2/m_{S_0}^2,$$

$$\Gamma_{gg} = 32\pi\alpha_s^2 |\psi_0(0)|^2/(3m_{S_0}^2),$$

wave function of XX system at origin

4th power of hypercharge (…fit anything)

bound state of X

- wave function at origin

QED part+ linear part

$$\left[-\frac{\nabla_{\boldsymbol{r}}^2}{m_X}+V(\boldsymbol{r})-E_0\right]\psi_0(\boldsymbol{r})=0,$$

$$V(\boldsymbol{r})=-Y_X^2\frac{\alpha}{|\boldsymbol{r}|}+V_{\mathrm{QCD}}(|\boldsymbol{r}|).$$

- numerically solve and fit

(consistent with Hagiwara Kato Martine, Ng 1990 for Y=0)

$$|\psi_0(0)|=\sum_{n=0}^{4}a_n\,[\,\ln(m_{S_0}/750\,\mathrm{GeV})\,]^n,\qquad E_0=\sum_{n=0}^{4}b_n\,[\,\ln(m_{S_0}/750\,\mathrm{GeV})\,]^n,$$

Y_X	a_0	a_1	a_2	a_3	a_4	b_0	b_1	b_2	b_3	b_4
0	87.78	114.4	76.85	37.76	10.71	4.119	2.458	0.9314	0.2429	0.04078
1/3	88.44	115.3	77.54	38.14	10.82	4.145	2.481	0.9416	0.2461	0.04143
2/3	90.44	118.1	79.64	39.30	11.17	4.226	2.552	0.9726	0.2557	0.04341
1	93.82	122.9	83.20	41.25	11.76	4.363	2.672	1.026	0.2721	0.04682
4/3	98.64	129.8	88.28	44.05	12.61	4.559	2.845	1.102	0.2960	0.05180
5/3	105.0	138.8	95.01	47.76	13.73	4.822	3.077	1.206	0.3285	0.05858
2	112.6	150.7	104.5	51.83	14.40	5.162	3.366	1.322	0.3812	0.07999

1.65

Abnormal candidate remains

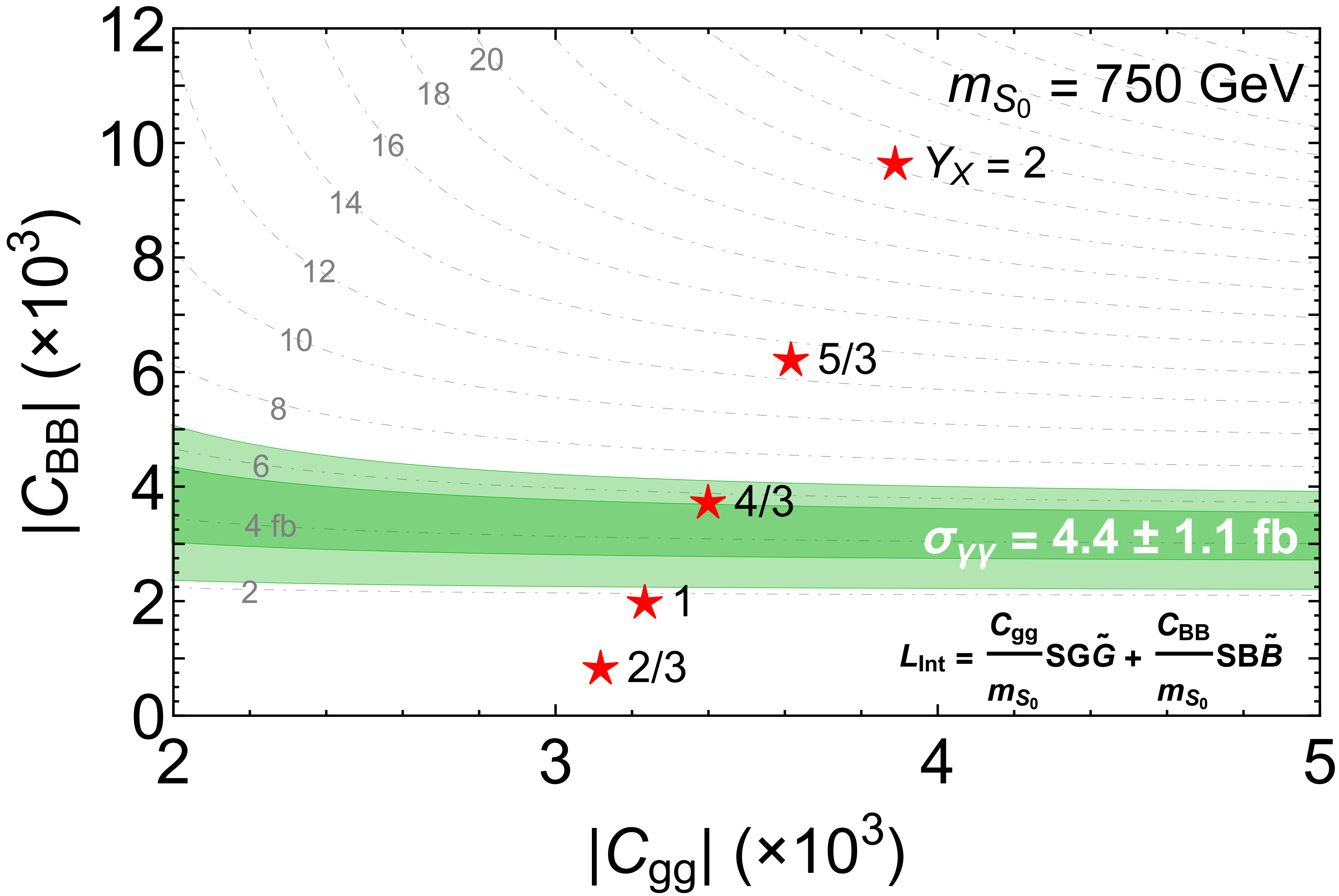


Figure 1: *Red stars are predictions of our model on the* $(|C_{gg}|, |C_{BB}|)$*-plane with* Y_X *being 2/3, 1, 4/3, 5/3 and 2, respectively. Contours of the diphoton cross section as a function of* $|C_{gg}|$ *and* $|C_{BB}|$ *are also shown by gray-dashed lines. Darker (lighter) green-shaded region corresponds to the cross section experimentally favored by the diphoton excess at 1σ (2σ) level [3].*

Numerically tough calculation, completely relay on Ishikawa-san

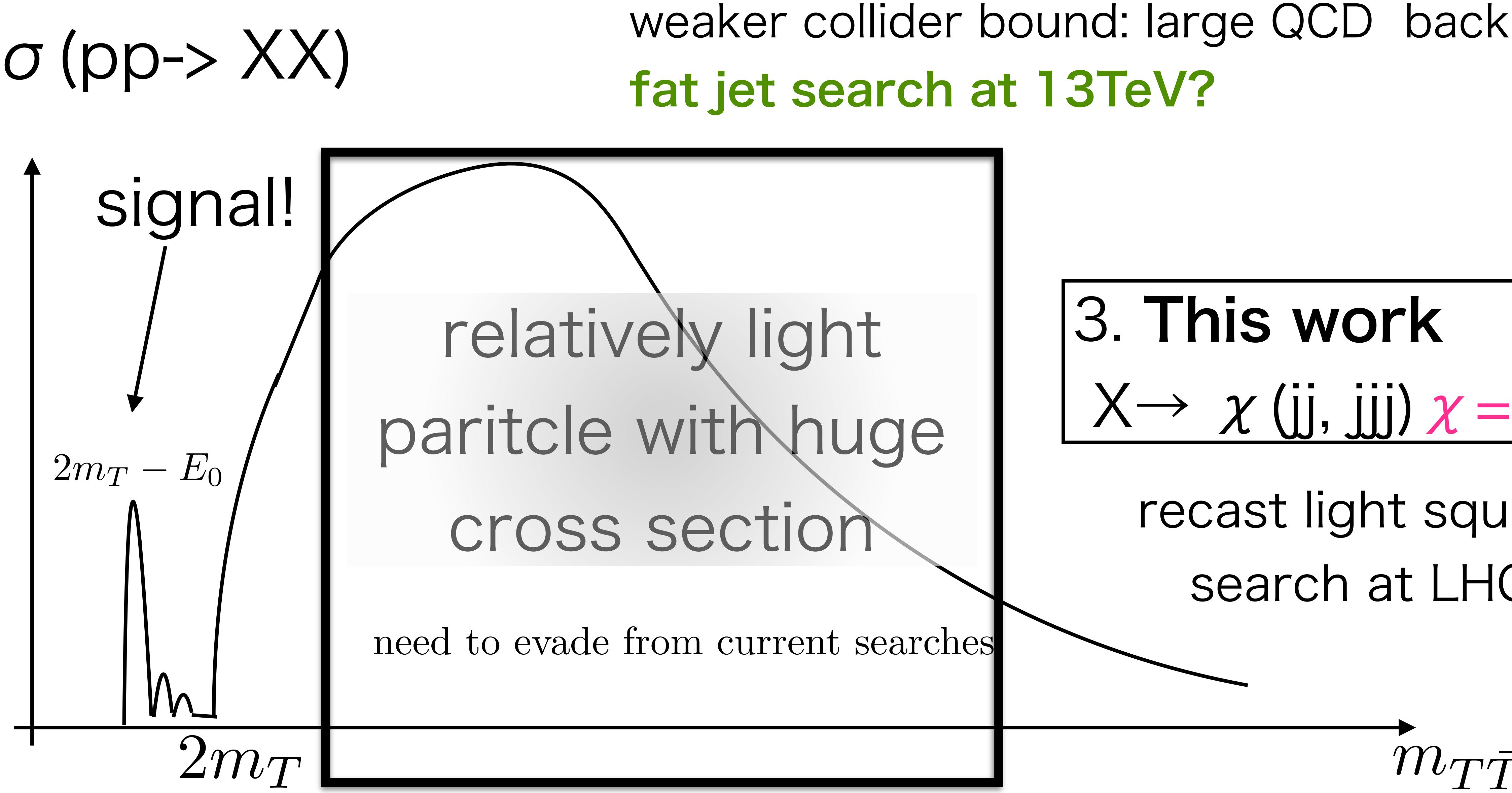
This is nice

- There are no dim 4 operator involving X and SM particles
- The X decay is suppressed by some cutoff scale Λ
- Consistent with small width assumption to get signal

Collider bound from open production

X decay pattern

1. X-> W j, Zj Hj etc
   is not allowed because of Q=4/3
2. X-> 2j, 3j (Kats and Strassler 1602.08819)
   weaker collider bound: large QCD background
   fat jet search at 13TeV?



3. **This work**
X→ χ (jj, jjj) χ =DM

recast light squark search at LHC

Quick consideration on the dark matter χ

- Z_2 odd
  - X: strongly interaction particle (3,0,4/3)
  - χ: weakly interacting partile
- X and χ interact through some higher dim operators such as

$$\mathcal{O}_F \sim (\bar{X}u^c)(\bar{\chi}u^c)/\Lambda^2 \quad \mathcal{O}_S \sim (\bar{X}d^c)(\bar{u^c}d^c)\chi/\Lambda^3$$

(nearly model independent) Ω_χ

strongly interacting X work as the cleaner of dark matter

- Early Universe (T~ mX)
- XX⇄ gg large cross section: rapid annihilation

  density is small
- $\chi\chi$ ⇄ SM particles: maybe small and suppressed
- χSM ⇄ X SM rapid because so many SM particles in the thermal bath: leading small $\Omega\chi$

dark matter density $\Omega \propto 1/\langle \sigma v \rangle$

effective pair annihilation cross section

$$\langle \sigma v \rangle = \sum_{ij} \langle \sigma_{ij} v \rangle \frac{g_i g_j}{g_{\rm eff}^2} (1+\Delta_i)^{3/2} (1+\Delta_j)^{3/2} \exp[-x(\Delta_i + \Delta_j)],$$

$$x = m_\chi / T$$

Griest and Seckel Phys. Rev. D43, 3191(1991)

"Three exceptions in the calculation of relic abundance"

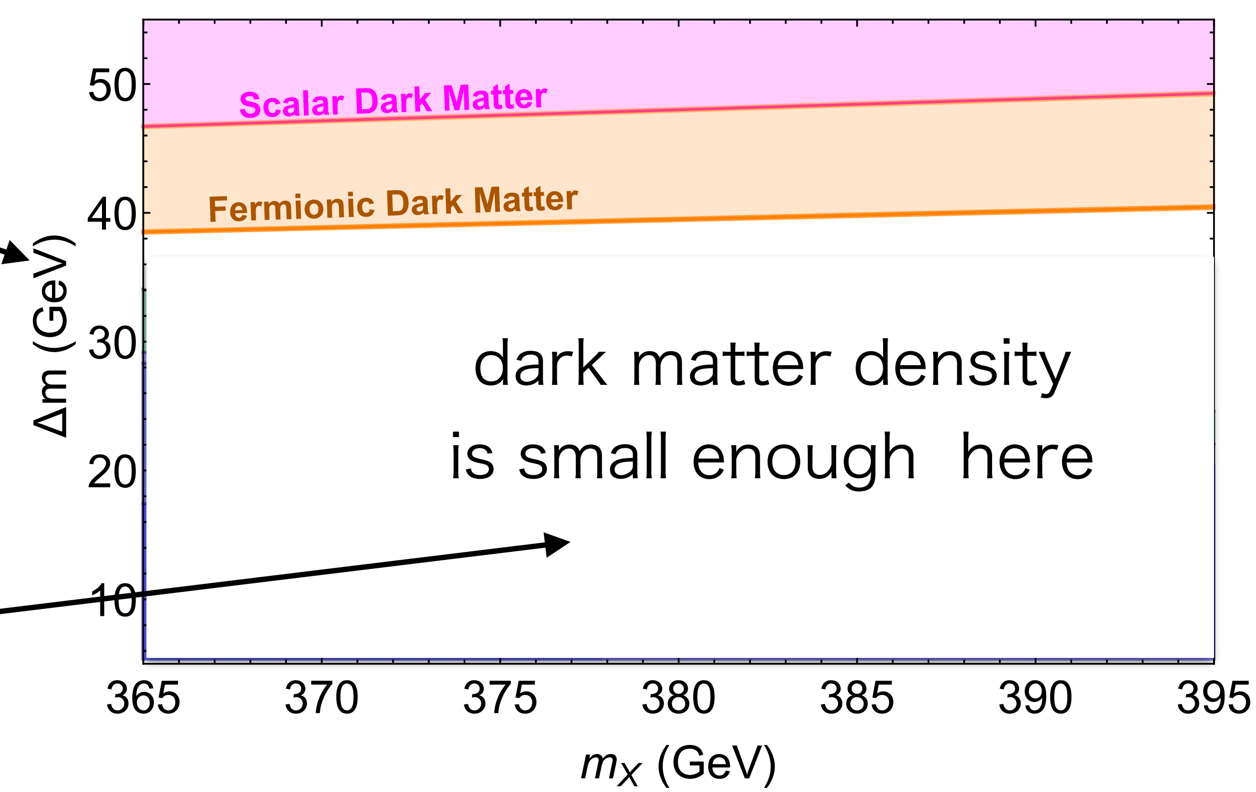
$$\Delta_i = (m_i - m_\chi)/m_\chi$$ mass difference

for our case

$$\langle \sigma v \rangle \simeq 2 \frac{43 \pi \alpha_s^2}{27 m_X^2} \frac{36 (1+\Delta_X)^3 \exp(-2x\Delta_X)}{\left[g_\chi + 12 (1+\Delta_X)^{3/2} \exp(-x\Delta_X) \right]^2}.$$

dark matter density is the function of X mass and χ X mass difference only XX and mass

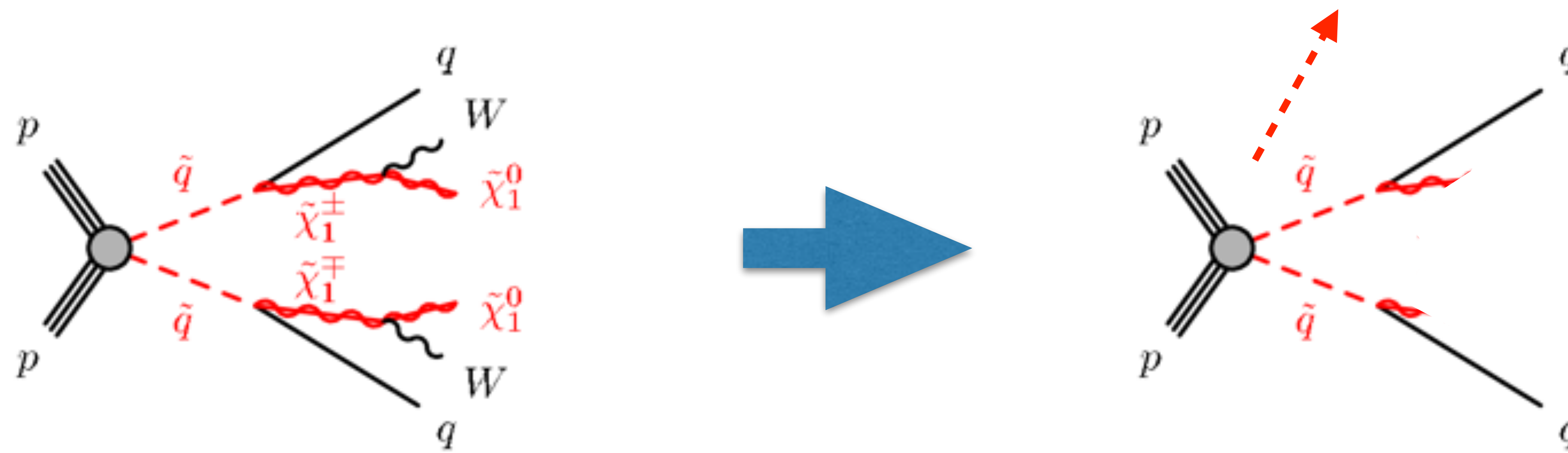
It is enough to exclude this region



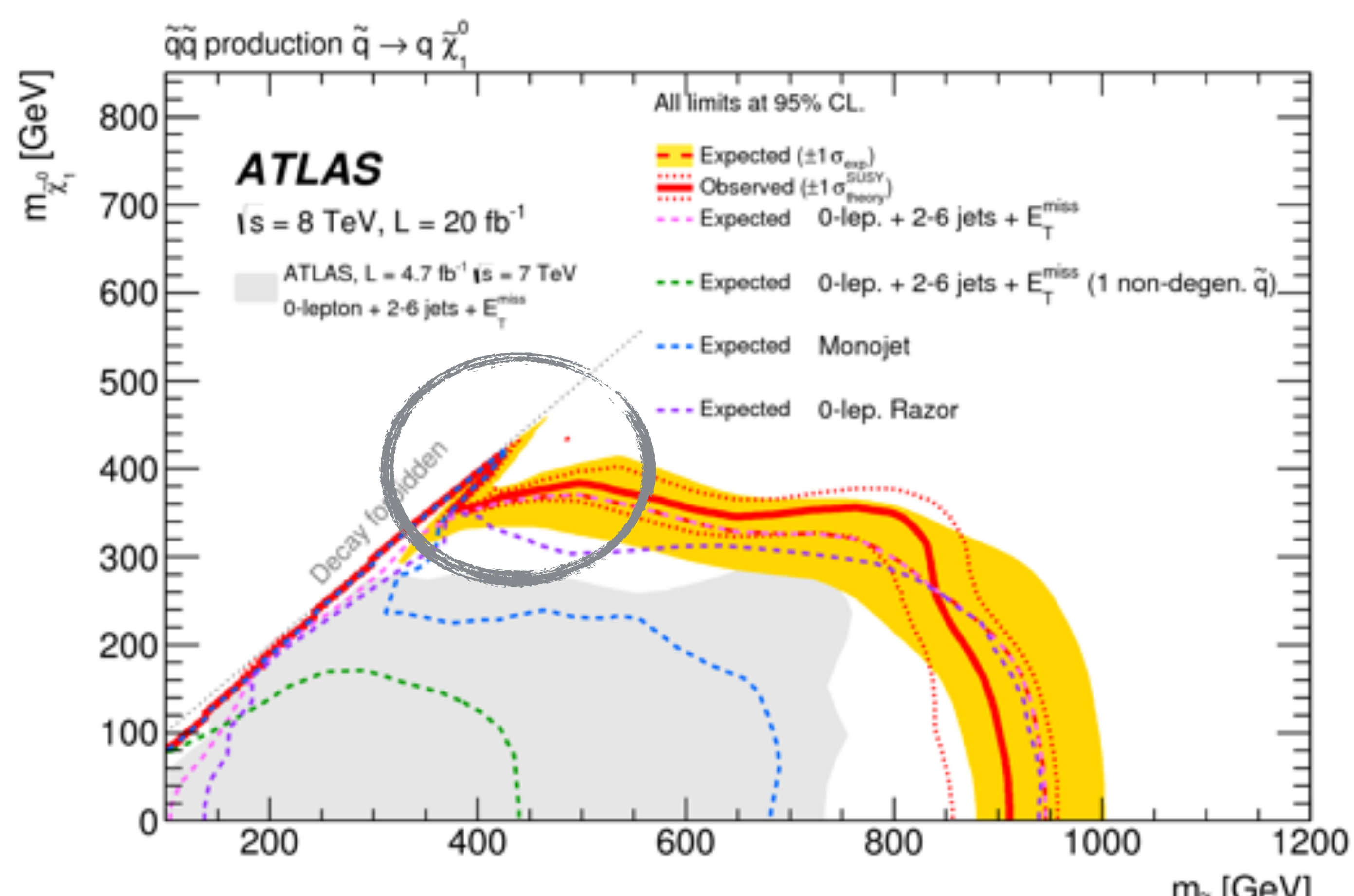
Collider constraints

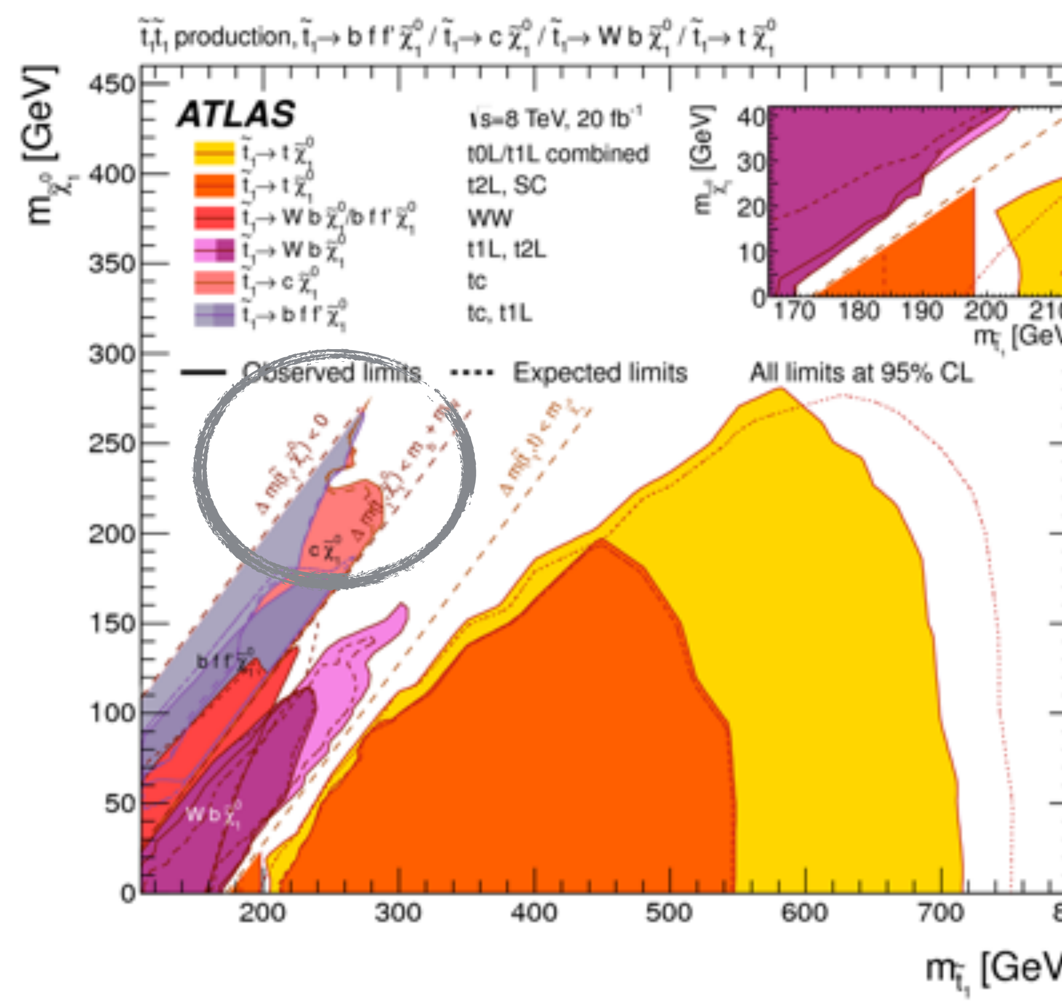
degenerate BSM search

hard ISR (better prediction)



too soft to contorol





degenerate heavy fermion search at LHC

- generate p p → X X upto 2jet matched sample.
- force X to decay into X-> χ jj or χ jjj to obtain efficiency.
- signature is therefore jet (ISR , hard) + missing + soft activities
- compare with ATLAS and CMS SUSY searches results using checkmate

8TeV stop -LSP degenerate

more general missing pT search

	$\not{E}_T$ [GeV]	$p_{T\,j_1}$ [GeV]	$\Delta\phi\,(j, \not{p}_T)$	n_j	$\not{E}_T/\sqrt{H_T}$	$m_{\rm eff}$ (incl.)	$\sigma^{95\%}_{\rm obs}$	Ref.
M2	340	340	0.4	≤ 3	-	-	28.4 fb	[44]
SR5	350	$0.5\not{E}_T$	1.0	-	-	-	21 fb	[45]
SR6	400	$0.5\not{E}_T$	1.0	-	-	-	12 fb	[45]
SR2jm	200	300	0.4	≥ 2	15 GeV$^{1/2}$	1.2 TeV	21 fb	[46]

Table 3: *Signal regions and upper bounds on the signal cross sections at 95% C.L. Here,* p_{T,j_1}, H *and* $m_{\rm eff}$ *(incl.) are the leading jet* p_T*, the scalar* p_T *sum of all jets and* $H_T + \not{E}_T$*, respectively.*

13TeV data

all the other limits included in Checkmate are investigated.

background modeling at 13TeV

Table 1: The Standard Model background Monte Carlo simulation samples used in this paper. The generator the order in α_s of cross-section calculations used for yield normalization (leading order (LO), next-to-leading order (NLO), next-to-next-to-leading order (NNLO), next-to-next-to-leading logarithm (NNLL)), PDF sets, parton showers, and tunes used for the underlying event are shown.

Physics process	Generator	Cross-section normalisation	PDF set	Parton shower	Tune
$W(\to \ell\nu)$ + jets	Sherpa 2.1.1	NNLO	CT10	Sherpa	Sherpa default
$Z/\gamma^*(\to \ell\bar{\ell})$ + jets	Sherpa 2.1.1	NNLO	CT10	Sherpa	Sherpa default
γ + jets	Sherpa 2.1.1	LO	CT10	Sherpa	Sherpa default
$t\bar{t}$	Powheg-Box v2	NNLO+NNLL	CT10	Pythia 6.428	Perugia2012
Single top (t-channel)	Powheg-Box v1	NLO	CT10f4	Pythia 6.428	Perugia2012
Single top (s- and Wt-channel)	Powheg-Box v2	NLO	CT10	Pythia 6.428	Perugia2012
$t\bar{t} + W/Z/WW$	MadGraph 5.2.2.2	NLO	NNPDF2.3LO	Pythia 8.186	A14
WW, WZ, ZZ	Sherpa 2.1.1	NLO	CT10	Sherpa	Sherpa default
Multi-jet	Pythia 8.186	LO	NNPDF2.3LO	Pythia 8.186	A14

NNLO cross section and +NLO multijet

Table 3: Control regions used in the analysis. Also listed are the main targeted background in the SR in each case, the process used to model the background, and the main CR requirement(s) used to select this process. The transverse momenta of high-purity leptons (photons) used to select CR events must exceed 25 (130) GeV.

CR	SR background	CR process	CR selection
CRγ	$Z(\to \nu\bar{\nu})$+jets	γ+jets	Isolated photon
CRQ	Multi-jet	Multi-jet	SR with reversed requirements on (i) $\Delta\phi(\text{jet}, \boldsymbol{E}_{\text{T}}^{\text{miss}})_{\text{min}}$ and (ii) $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}(N_{\text{j}})$ or $E_{\text{T}}^{\text{miss}}/\sqrt{H_{\text{T}}}$
CRW	$W(\to \ell\nu)$+jets	$W(\to \ell\nu)$+jets	30 GeV $< m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) <$ 100 GeV, b-veto
CRT	$t\bar{t}$(+EW) and single top	$t\bar{t} \to b\bar{b}qq'\ell\nu$	30 GeV $< m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) <$ 100 GeV, b-tag

CR

Channel	**2jl**	**2jm**
Total bkg	237	163
Total bkg unc.	±22 [9%]	±20 [12%]
MC statistics	–	±1.8 [1%]
$\Delta\mu_{Z+\text{jets}}$	±6 [3%]	±5 [3%]
$\Delta\mu_{W+\text{jets}}$	±4 [2%]	±4 [2%]
$\Delta\mu_{\text{Top}}$	±1.2 [1%]	±1.6 [1%]
$\Delta\mu_{\text{Multi-jet}}$	±0.05 [0%]	±0.09 [0%]
CRγ corr. factor	±8 [3%]	±6 [4%]
Theory W	±1.4 [1%]	±2.3 [1%]
Theory Z	±6 [3%]	±3.2 [2%]
Theory Top	±2.7 [1%]	±2.1 [1%]
Theory Diboson	±16 [7%]	±16 [10%]
Jet/$E_{\text{T}}^{\text{miss}}$	±1.5 [1%]	±2.1 [1%]

Our case: signal cross section is known in NNLO level(QCD)

m_X [GeV]	360	365	370	375	380	385	390	395	400
σ @ 8 TeV [pb]	4.35	4.01	3.70	3.41	3.15	2.91	2.69	2.49	2.31
σ @13 TeV [pb]	20.34	18.86	17.51	16.26	15.12	14.07	13.10	12.21	11.39

Table 2: *Pair production cross sections of the heavy fermion X at NNLO for various m_X.*

cross section error 25%(NLO)→less than 10% (NNLO)

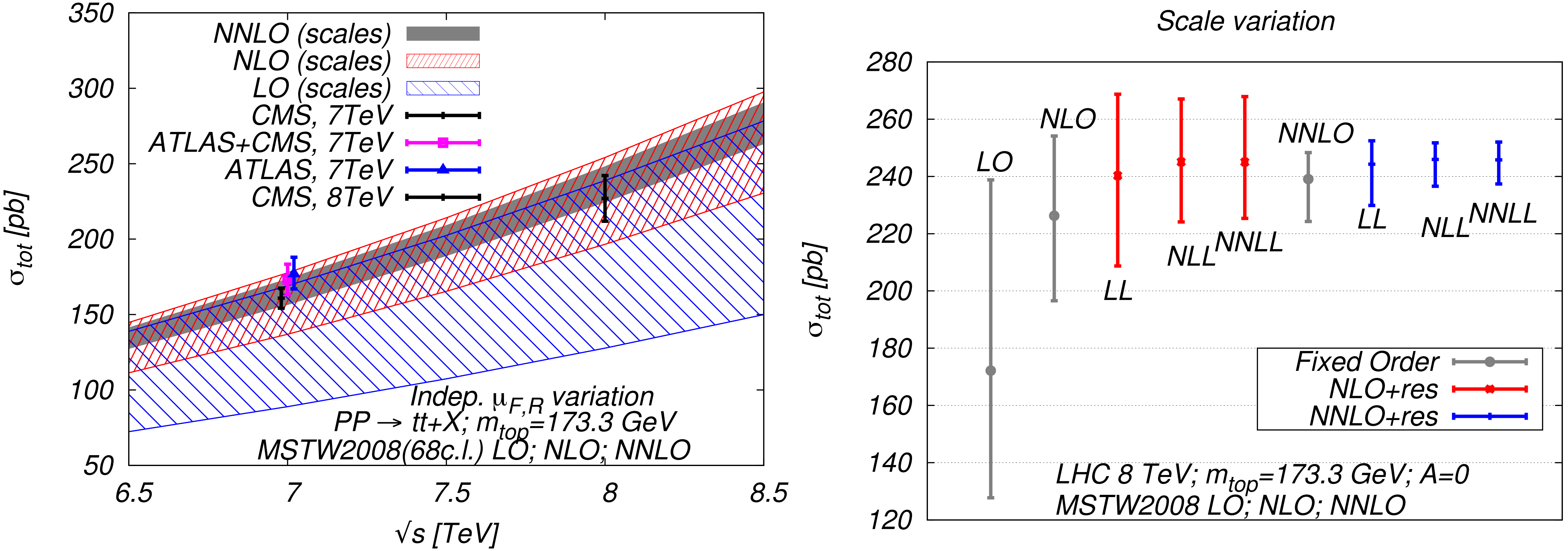


Fig. 2. – Scale dependence of the predicted cross-section at LO, NLO and NNLO at the LHC as a function of $\sqrt{s}$ (left). On the right plot: detailed breakdown of scale uncertainty for LHC 8 TeV at LO, NLO and NNLO including also soft-gluon resummation at LL, NLL and NNLL.

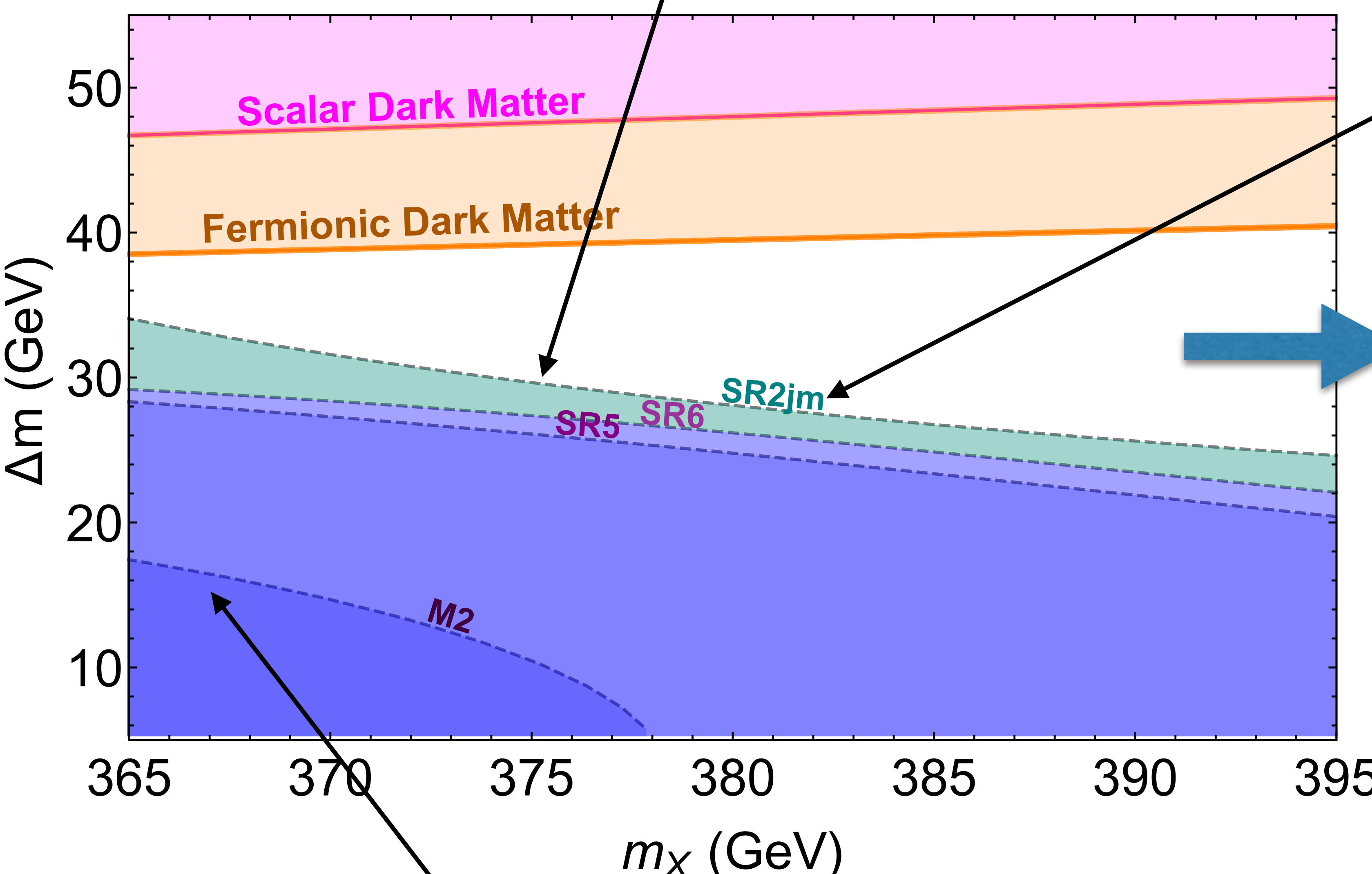
Systematic error on efficiency

- **ATLAS SUSY analysis (for SIGNAL)**
  - NLO total cross section,
  - SUSY + ISR jets (matched tree) for signal efficiency: varying **scale, factorization scale, and emission scale** from 0.5 to 2. cross section times efficiency error is **16%** for degenerate stop and **<u>we use this number</u>**
  - **CheckMate scheme (allow up to two sigma deviation-> 32%**
- **NLO cross section uncertainty is large** for our case (25% for scale and pdf) . NNLO available + NLO multi-jet calculation is desirable(faking Sherpa tt + multi-jet?) Regret we have not done this(too competitive d**xxx** new resonance)
- Tight cuts might improve the limit significantly provided controlled systematics with higher order generators

results

The limit depends on signal error assumptions (we take 16%)

13TeV data gives best limit, and the limit is weaker than expected



limit is weaker here because mono-jet condition (pT1 vs ETmiss) two body decay case (X-> jχ) is excluded by multi-jets+ missing search

Tight mono-jet requirement leads worse sensitivity for heavy quark: (more ISR). Stop search is optimize for M2

(personal) summary

- **It is a responsibility of elderlies to tell ideas and disasters in the past to younger generations**
- **Heavy quark and dark matter for 750 GeV diphoton :** We proposed a effective theory with rather few number of particles **with a DM**, Almost Model independent upper limit of the DM density.
- The LHC is not safe playground as it was in 1993, **when we did not think about using ISR to search for the particle degenerate with dark matter. (Alwall et al PRD 79 (2009) 015005)**
- **Our case** still survives(for narrow width) . Checkmate scheme is very conservative. More stringent constraint this year.
- LHC will exclude narrow width heavy fermion though $\gamma\gamma$ channel.