HL-LHCでの新物理探索

Michihisa Takeuchi (Kobayashi-Maskawa Institute, Nagoya Univ, Japan)

at PPP2020, on 4th Sep 2020

Naturalness

$$-\mathcal{L}_{\mathrm{SM}} = -\mu^2 H^\dagger H$$

μ : only dimension full parameter ~ 100 GeV

d=2

$$+\mathcal{L}_{\mathrm{kin}} + g A_\mu \bar{f} \gamma^\mu f + y_{ij} \bar{f}_i H f_j + \lambda (H^\dagger H)^2$$

d=4

Naturalness

$$-\mathcal{L}_{\mathrm{SM}} = -\epsilon\Lambda^2 H^\dagger H$$

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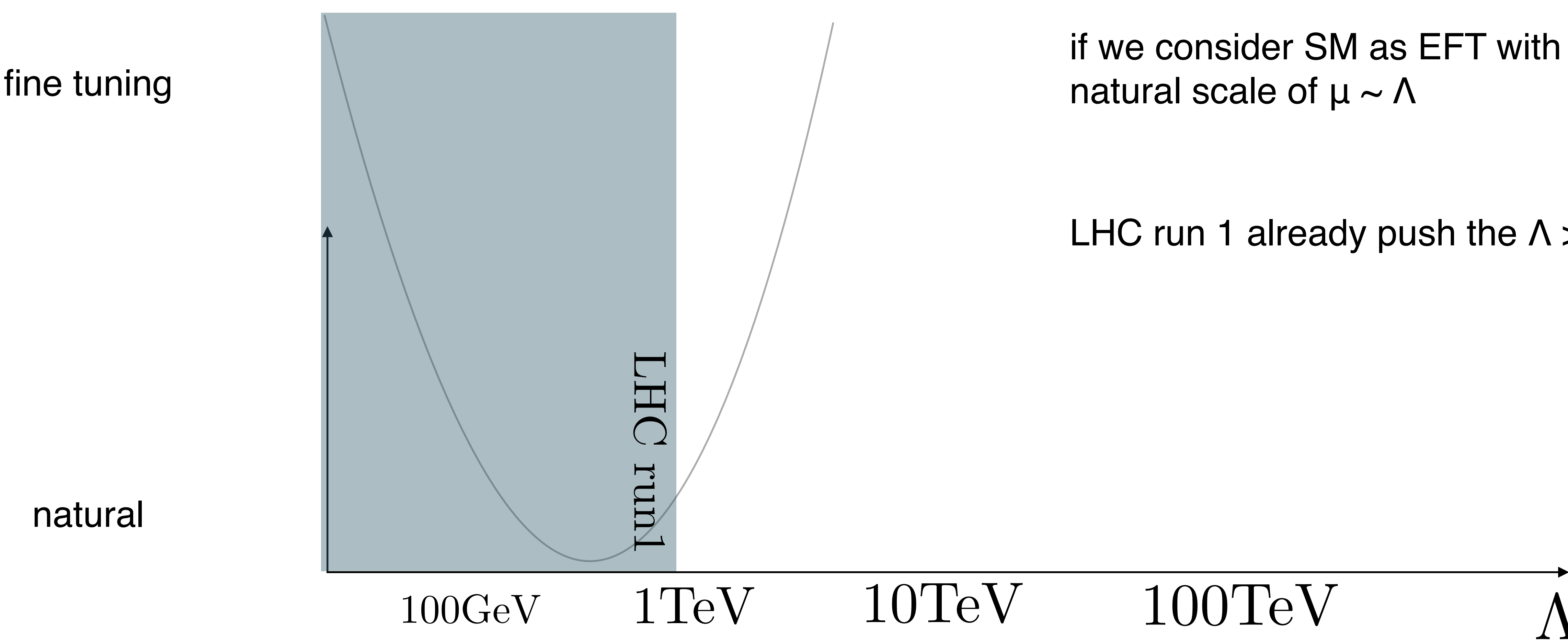

if we consider SM as EFT with NP scale Λ
natural scale of μ ~ Λ

LHC run 1 already push the Λ > 1 TeV

Naturalness

$$-\mathcal{L}_{\rm SM} = -\,\epsilon\Lambda^2 H^\dagger H$$

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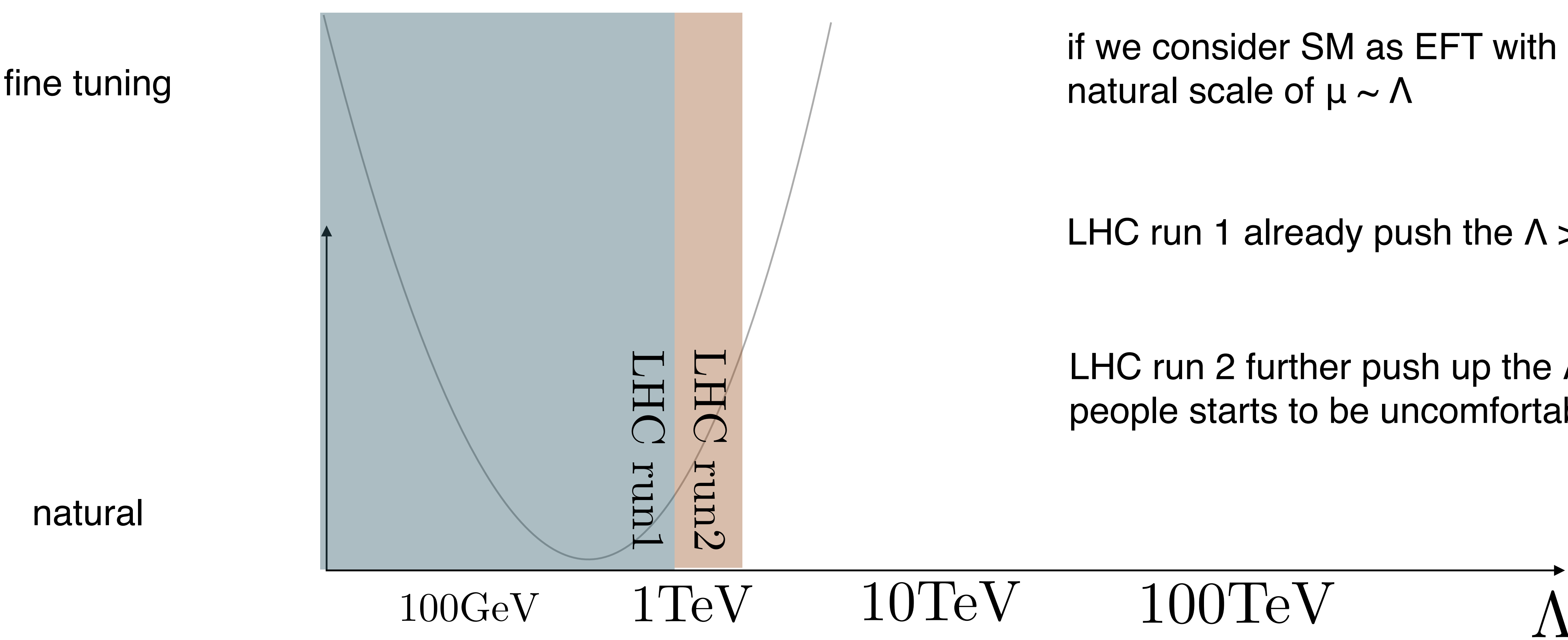


if we consider SM as EFT with NP scale Λ
natural scale of μ ~ Λ

LHC run 1 already push the Λ > 1 TeV

LHC run 2 further push up the Λ,
people starts to be uncomfortable

Naturalness

$$-\mathcal{L}_{\mathrm{SM}} = -\epsilon\Lambda^2 H^\dagger H$$

μ : only dimension full parameter ~ 100 GeV

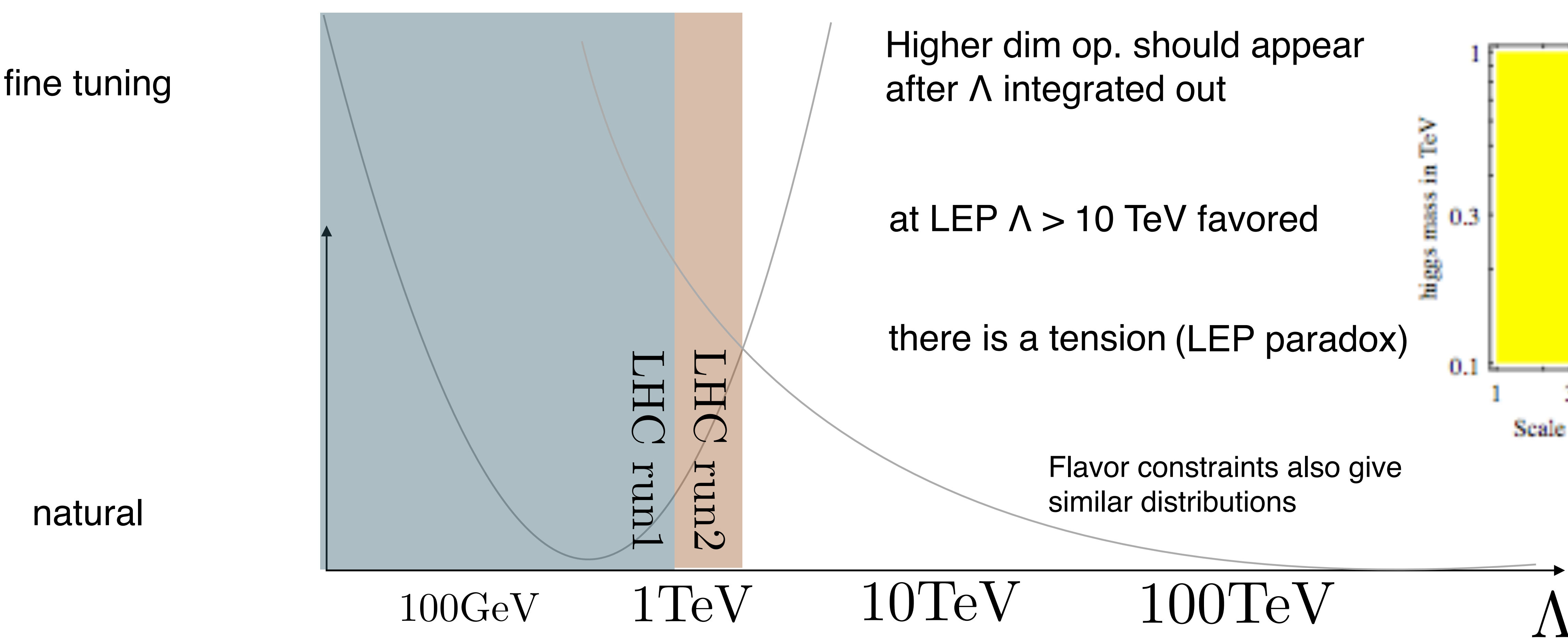
d=2

$$+\mathcal{L}_{\mathrm{kin}} + gA_\mu \bar{f}\gamma^\mu f + y_{ij}\bar{f}_i H f_j + \lambda(H^\dagger H)^2$$

d=4

$$+\frac{b_{ij}}{\Lambda}(LH)(LH) + \frac{c_{ij}}{\Lambda}(\bar{f}_i\sigma_{\mu\nu}f_j)G^{\mu\nu} + \frac{c_{ijkl}}{\Lambda^2}(\bar{f}_i f_j)(\bar{f}_k f_l)$$

d>4

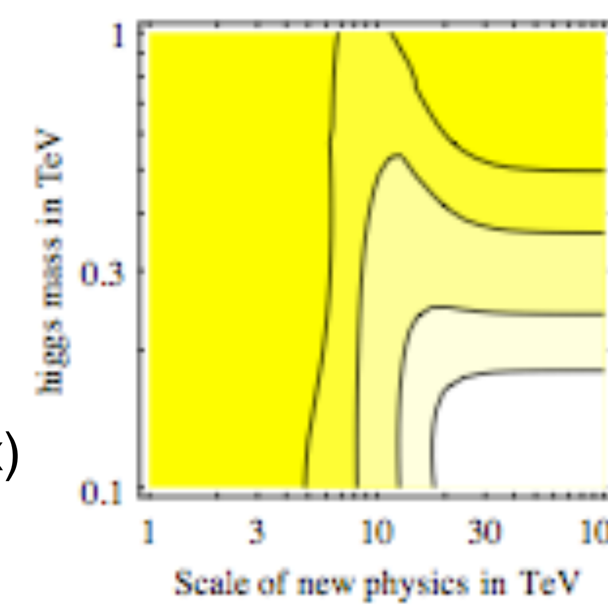


Higher dim op. should appear after Λ integrated out

at LEP Λ > 10 TeV favored

there is a tension (LEP paradox)

Flavor constraints also give similar distributions

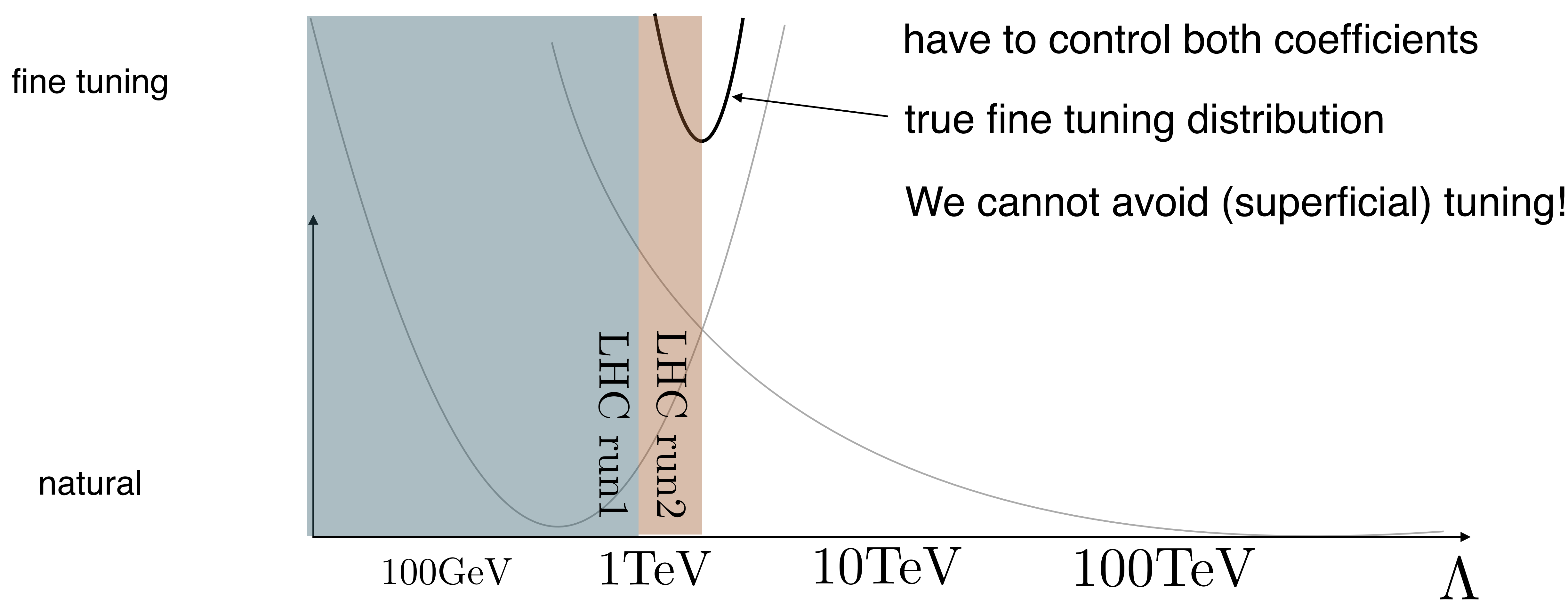


Naturalness

$$-\mathcal{L}_{\rm SM} = -\epsilon\Lambda^2 H^\dagger H$$ μ : only dimension full parameter ~ 100 GeV d=2

$$+\mathcal{L}_{\rm kin} + gA_\mu \bar{f}\gamma^\mu f + y_{ij}\bar{f}_i H f_j + \lambda(H^\dagger H)^2$$ d=4

$$+\frac{b_{ij}}{\Lambda}(LH)(LH) + \frac{c_{ij}}{\Lambda}(\bar{f}_i\sigma_{\mu\nu}f_j)G^{\mu\nu} + \frac{c_{ijkl}}{\Lambda^2}(\bar{f}_i f_j)(\bar{f}_k \bar{f}_l)$$ d>4



Naturalness

$$-\mathcal{L}_{\rm SM} = -\epsilon\Lambda^2 H^\dagger H$$

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$$+\mathcal{L}_{\rm kin} + gA_\mu \bar{f}\gamma^\mu f + y_{ij}\bar{f}_i H f_j + \lambda(H^\dagger H)^2$$

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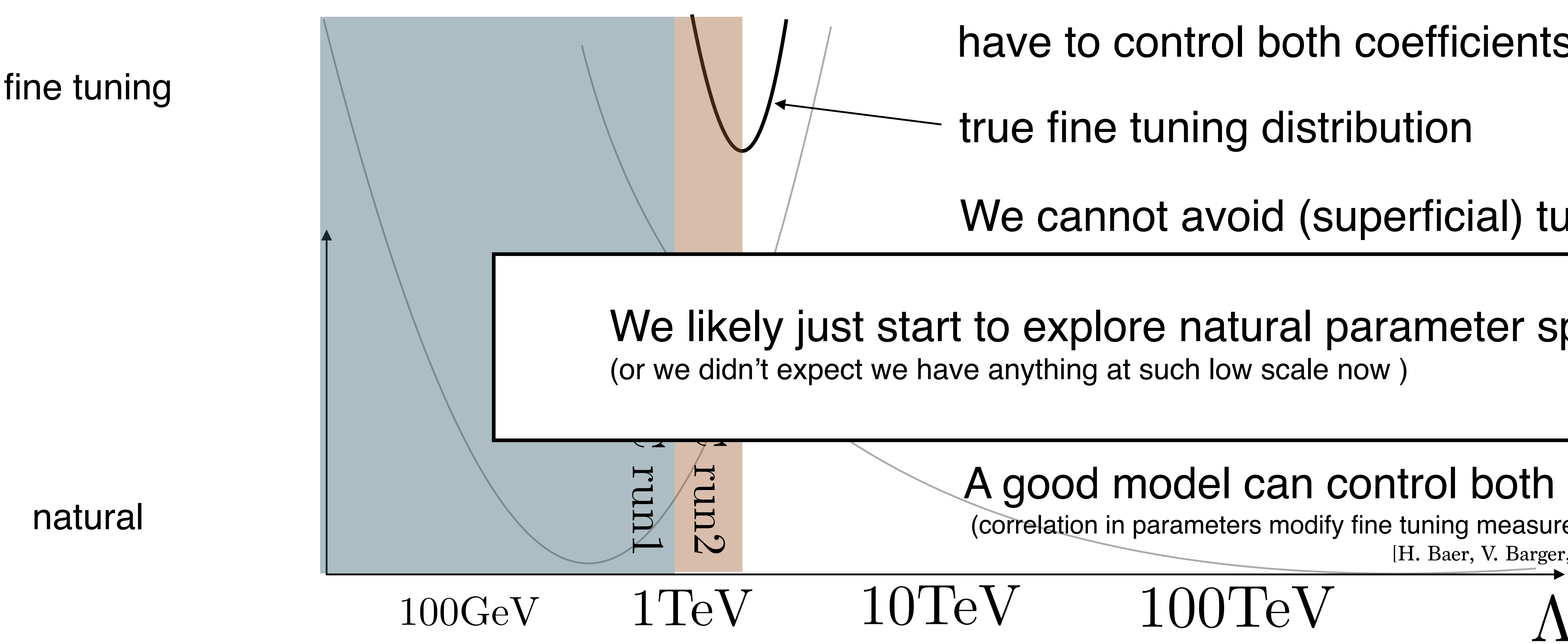
$$+\frac{b_{ij}}{\Lambda}(LH)(LH) + \frac{c_{ij}}{\Lambda}(\bar{f}_i\sigma_{\mu\nu}f_j)G^{\mu\nu} + \frac{c_{ijkl}}{\Lambda^2}(\bar{f}_i f_j)(\bar{f}_k f_l)$$

d>4



have to control both coefficients

true fine tuning distribution

We cannot avoid (superficial) tuning!

We likely just start to explore natural parameter space!
(or we didn't expect we have anything at such low scale now)

A good model can control both cancelations
(correlation in parameters modify fine tuning measure dep. on models)
[H. Baer, V. Barger, N. Nagata, M. Savoy]

スケジュール

2021年5月~ run3

2027~2038年: HL-LHC

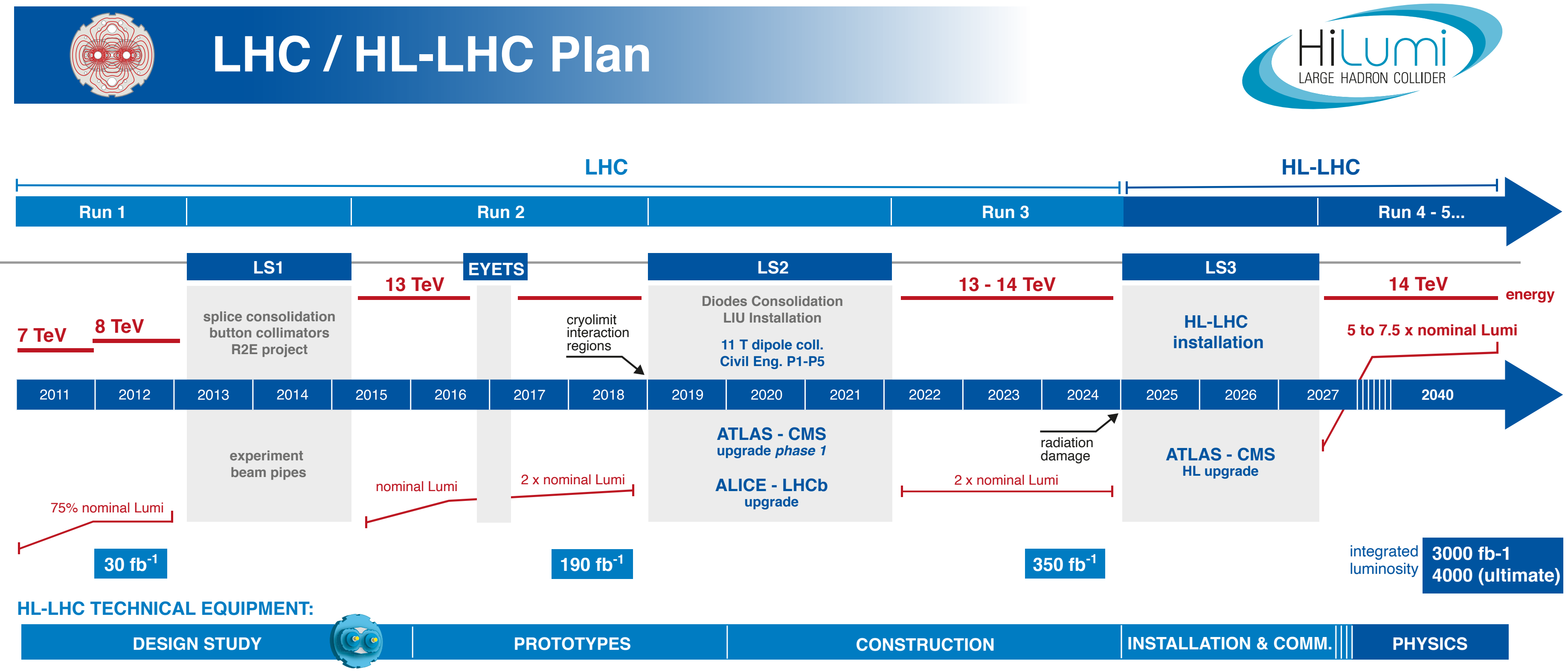
3 ab-1 の計画

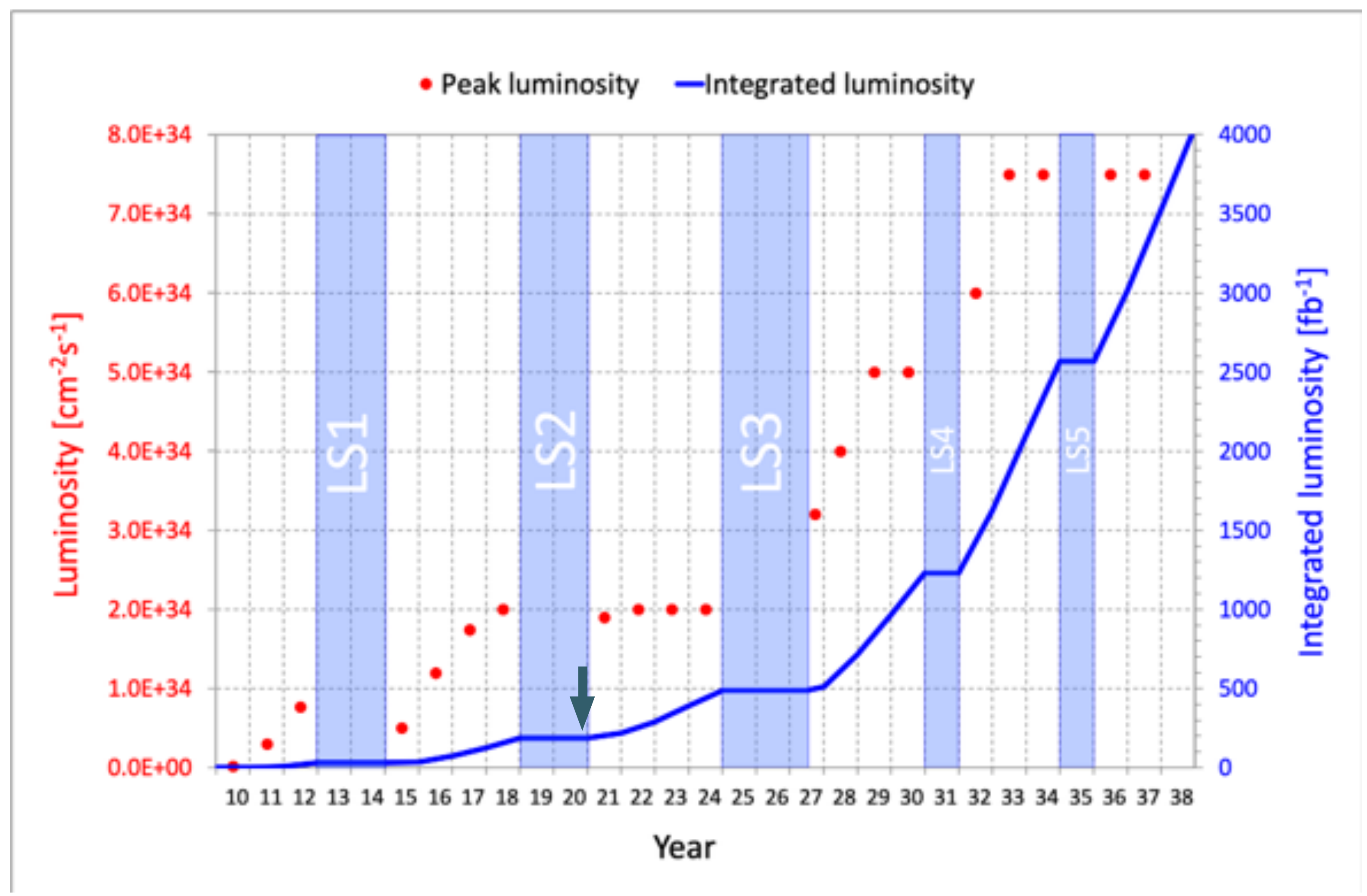
うまくいけば 4 ab-1

最終的な統計量は今の
O(20)倍程度 (18年後)

⇒ 粒子が20倍生成される

1. 重い粒子が見つかる可能性
2. 分布の精度が上がる
3. 稀崩壊の感度が上がる





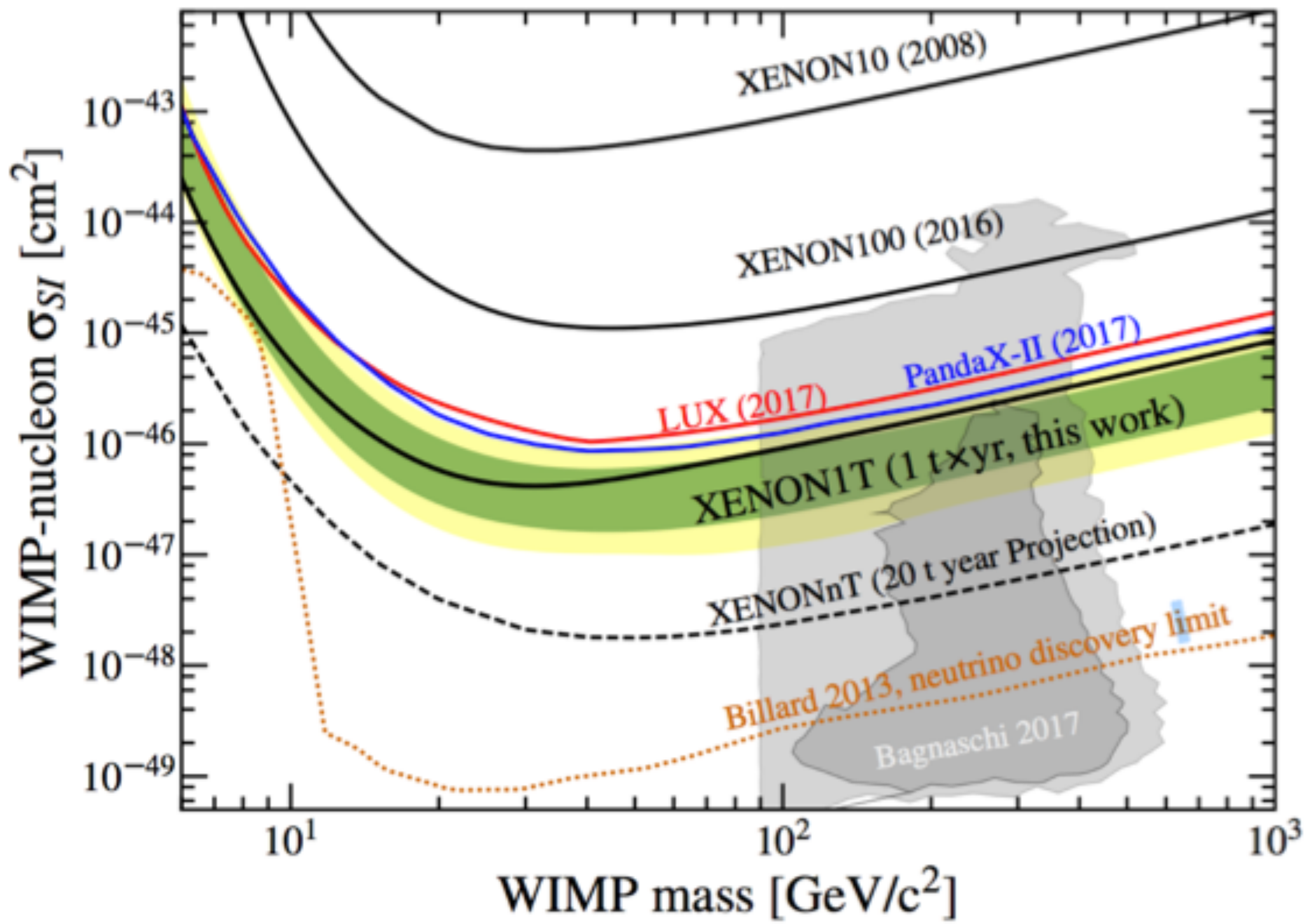
暗黒物質直接探索

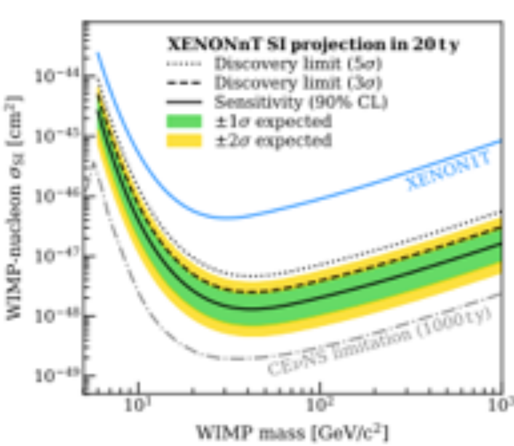
暗黒物質：存在が確定している。
　　　　　恐らく素粒子？

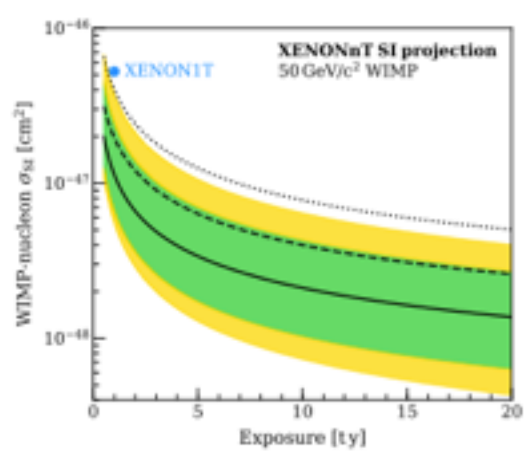
探索感度の向上スピードが早い

最初にシグナルが見つかる可能性

一方、シグナルが見つかったとしても、結局コライダー実験による検証が必要



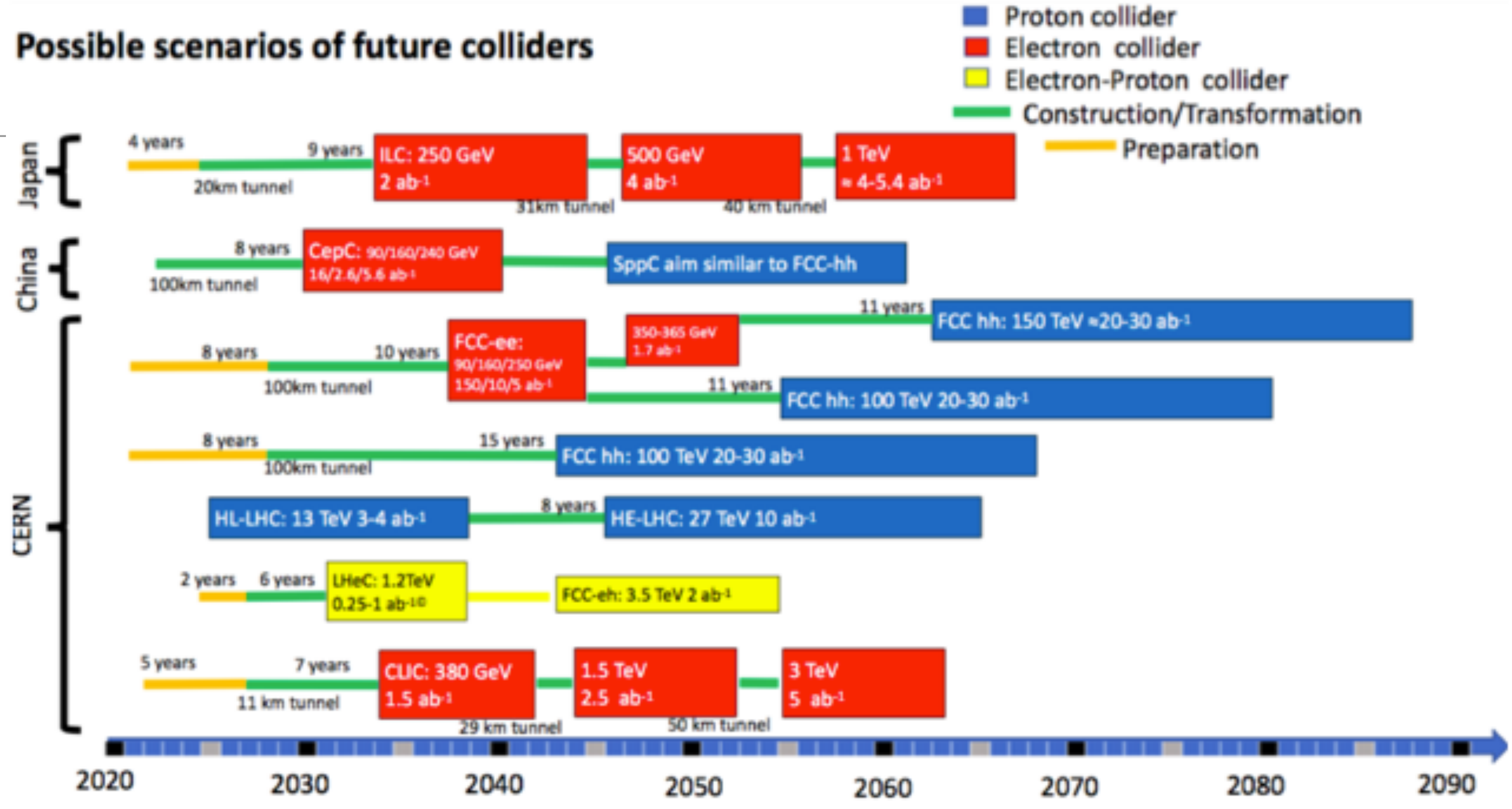




XENON10	XENON100	XENON1T	XENONnT
2005 – 2007	2008 – 2016	2011 – 2018	2019 – 2023
15 cm drift TPC	30 cm drift TPC	100 cm drift TPC	150 cm drift TPC
Total: 25 kg	Total: 161 kg	Total: 3 200 kg	Total: 8 000 kg
Target: **14** kg	Target: **62** kg	Target: **2 000** kg	Target: **6 000** kg
Fiducial: 5.4 kg	Fiducial: 34/48 kg	Fiducial: 1 300 kg	Fiducial: 4 500 kg
Achieved (2007)	Achieved (2016)	Achieved (2018)	Projected (2022)
σ_{SI} = 8.8 · 10^{-44} cm^2	σ_{SI} = 1.1 · 10^{-45} cm^2	σ_{SI} = 4.1 · 10^{-47} cm^2	σ_{SI} = 1.6 x 10^{-48} cm^2
@ 100 GeV/c^2	@ 55 GeV/c^2	@ 30 GeV/c^2	@ 50 GeV/c^2

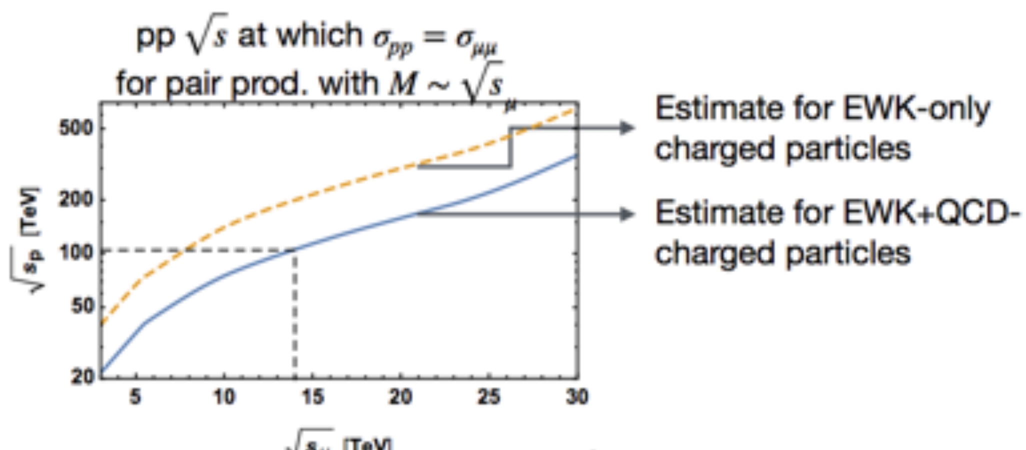
arXiv:2007.08796

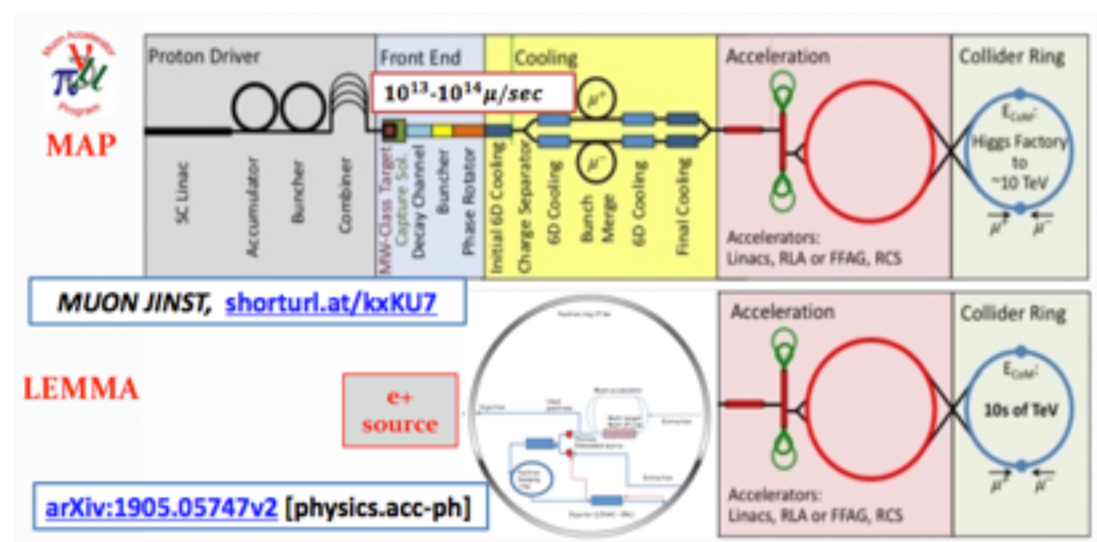
HL-LHCの後の将来計画



The timeline for different scenarios for future colliders.

ミューオンコライダー: e+e- promising?





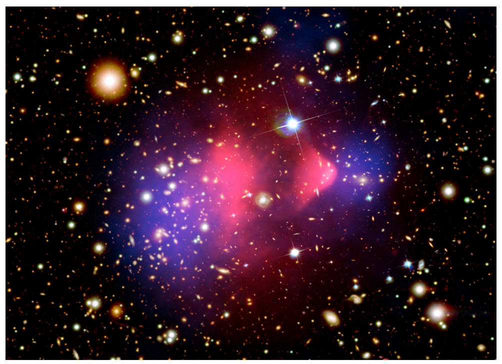
HL-LHCで何ができるか

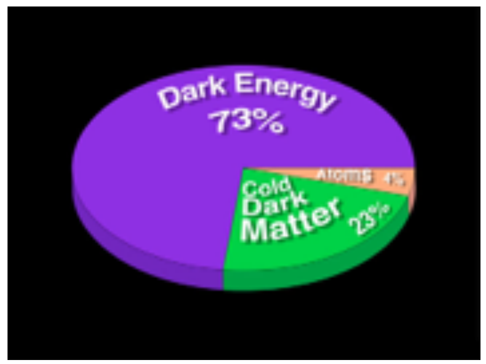
2027~2038年: HL-LHC　⇒ 粒子が20倍生成される

1. **重い粒子が見つかる可能性**
2. 分布の精度が上がる
3. 稀崩壊の感度が上がる

SUSY solves two big problems in particle physics

Existence of DM (serious problem)

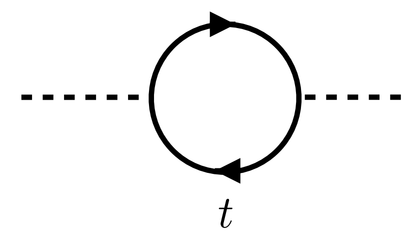




Naturalness (Fine tuning in Higgs sector)

$$m^2_{h,\mathrm{phys}} = m^2_{h,\mathrm{tree}} + \delta m^2_h \ \sim 125^2 \mathrm{GeV}^2 \sim 10^4 \mathrm{GeV}^2$$

$\delta m^2_h \sim$

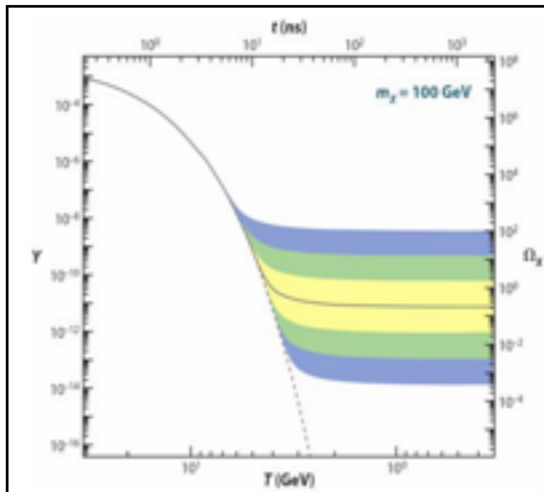


$$\sim -\frac{3}{4\pi} y_t^2 \Lambda^2_{\mathrm{SM}}$$

$$\sim 10^{38} \mathrm{GeV}^2 (\Lambda_{\mathrm{SM}} = M_{\mathrm{Planck}})$$

$$\sim 10^{6} \mathrm{GeV}^2 (\Lambda_{\mathrm{SM}} = 1\mathrm{TeV})$$

TeV scale SUSY elegantly solve both problems



WIMP miracle

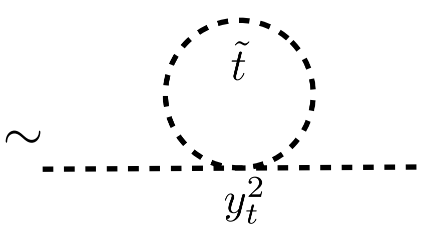
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{\alpha^2} \sim 10^9 \mathrm{GeV}^2$$

neutralino DM

perfect WIMP DM

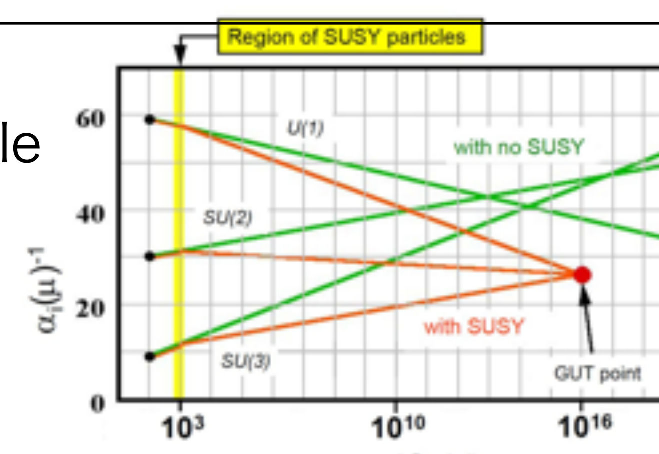
new partner particle, same coupling by symmetry

$\delta m^2_h \sim$



$$\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$$

TeV sparticles make the gauge coupling unification happen at one scale



Even though LHC doesn't find new particles yet,
TeV scale SUSY is still the most attractive BSM

latest SUSY search results at LHC 13TeV ~ 137 fb^{-1}

based on simplified models

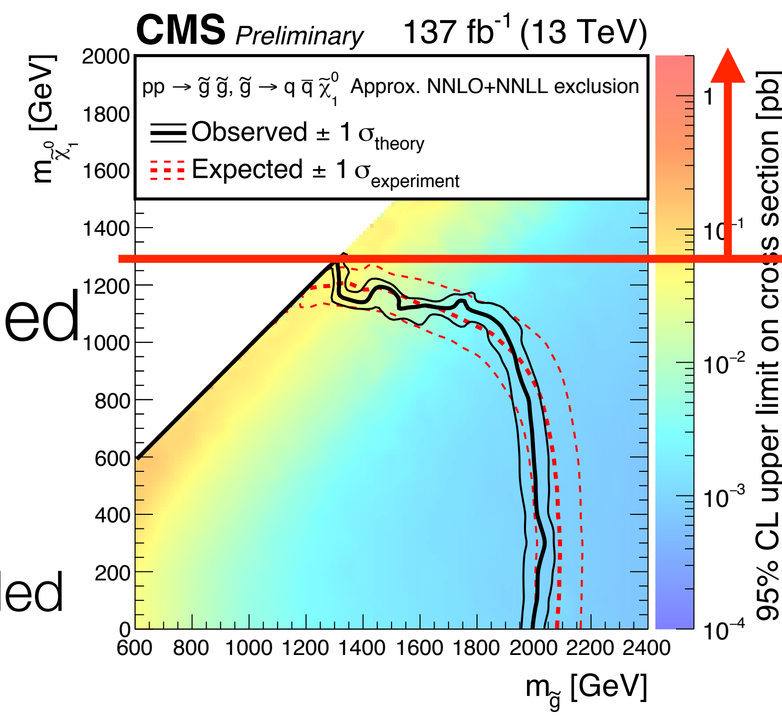
For massless LSP

~2 TeV gluino excluded

~1.8 TeV squarks excluded

~1.2 TeV stop excluded

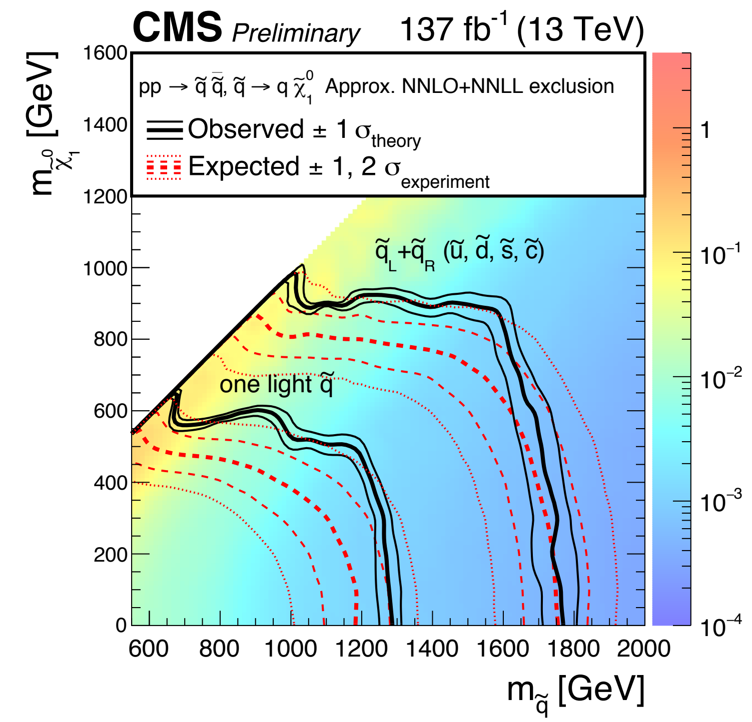
~700 GeV EWkino (W/Z) excluded
(highly depends on BR)

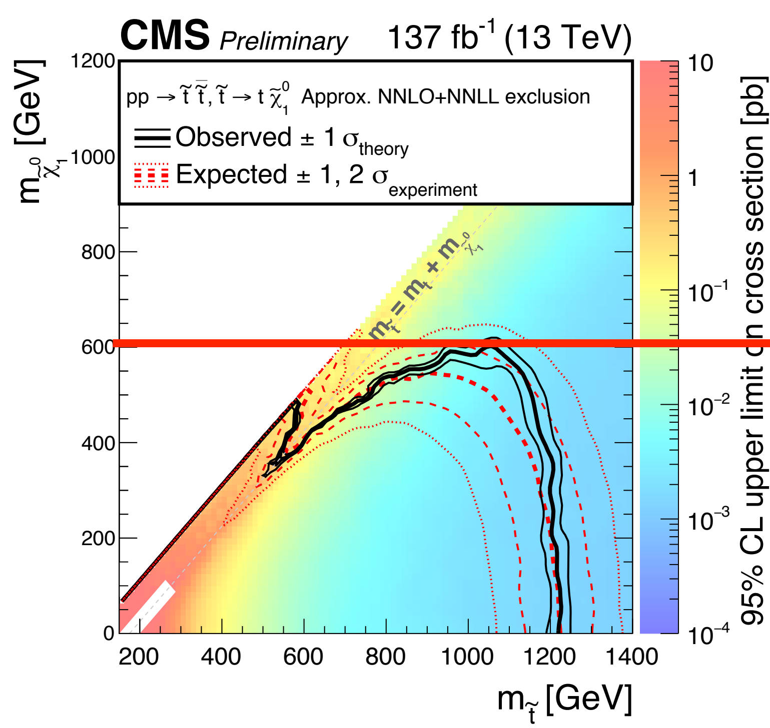


no constraint

LSP > 1.3TeV

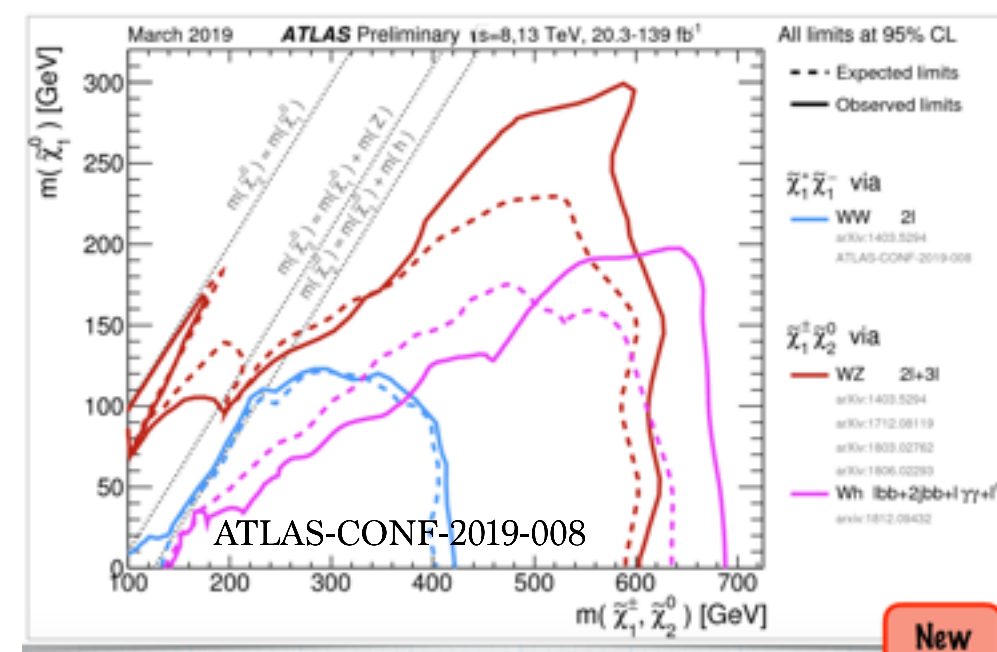
CMS-PAS-SUS-19-005





no constraint

LSP>600GeV



Notice: no constraints when LSP mass is heavy enough

[ATL-COM-PHYS-2014-555]

SUSY search projection at 3 ab^{-1}

based on simplified models

For massless LSP

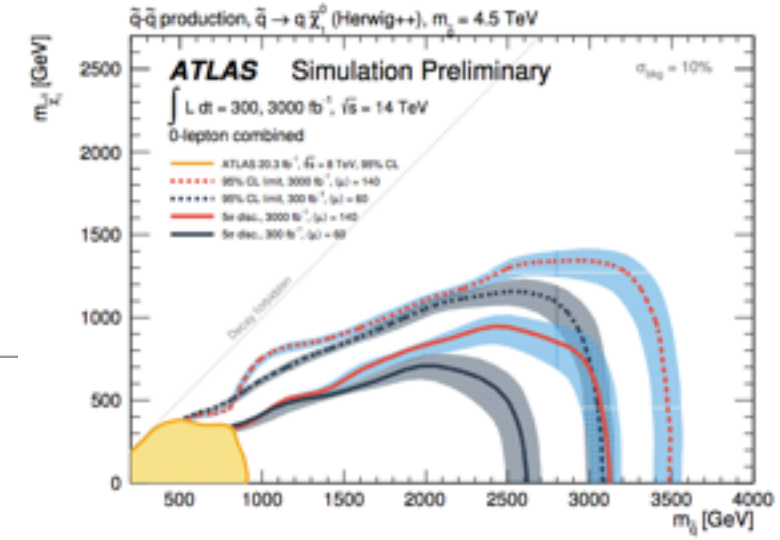
~3 TeV gluino excluded

~2.1-3.5 TeV squarks exclude

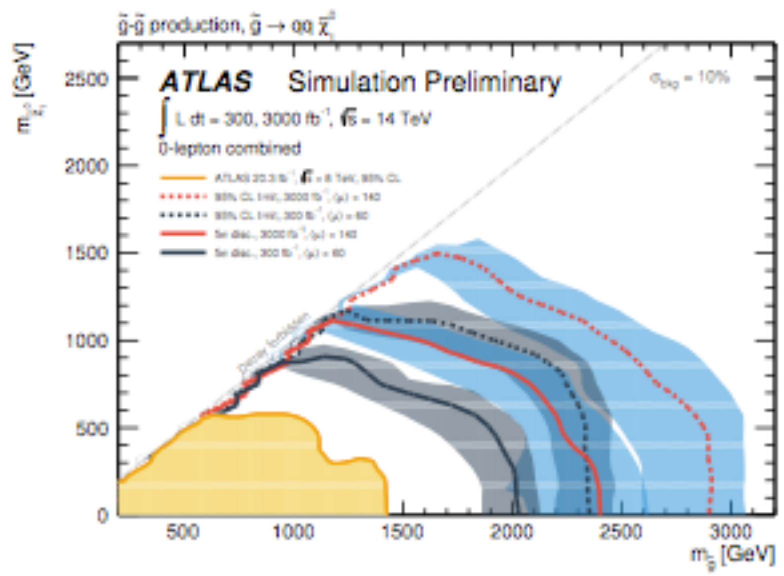
~1.6-1.7 TeV stop excluded

~1.1-1.3 TeV EWkino excluded
(highly depends on BR)

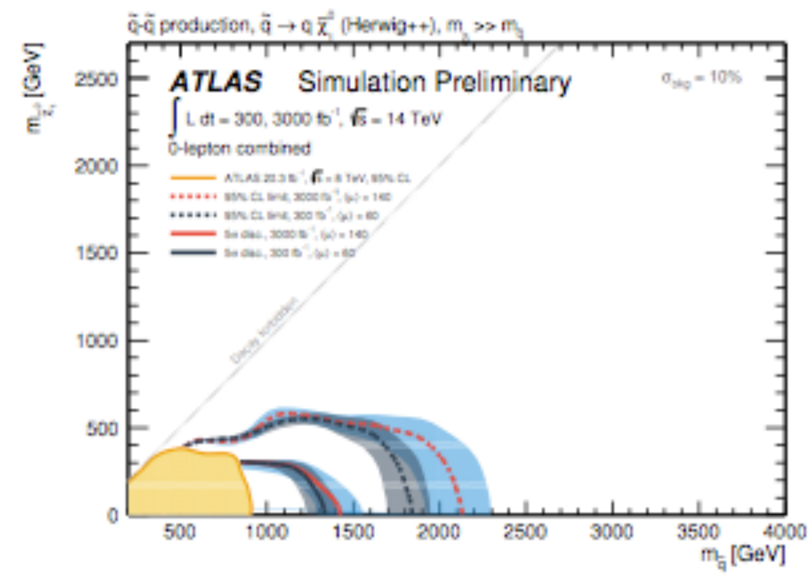
~0.7 TeV stau excluded



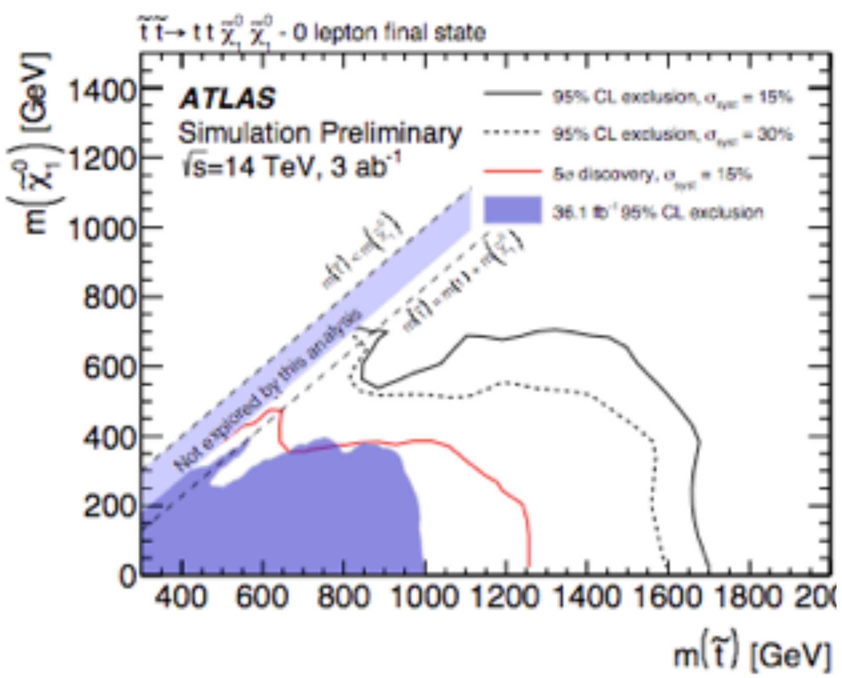
(c) $\tilde{q}\tilde{q}$, $m_{\tilde{g}}$ = 4.5 TeV

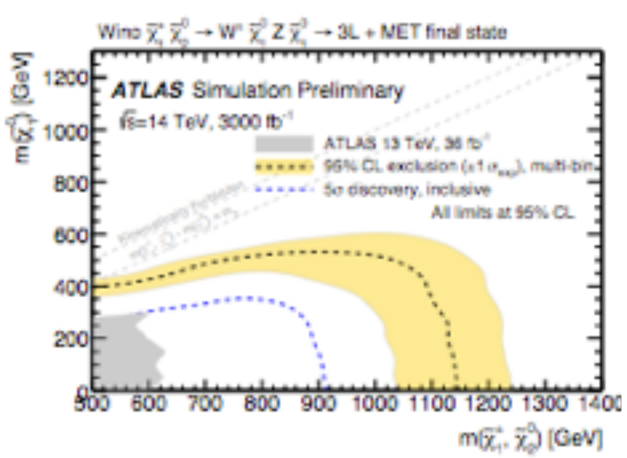


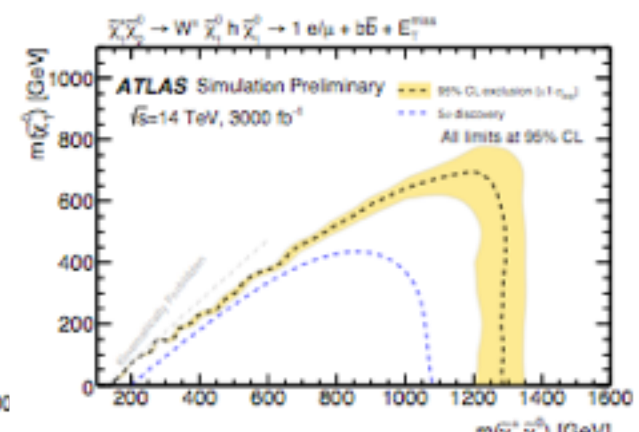
(a) $\tilde{g}\tilde{g}$

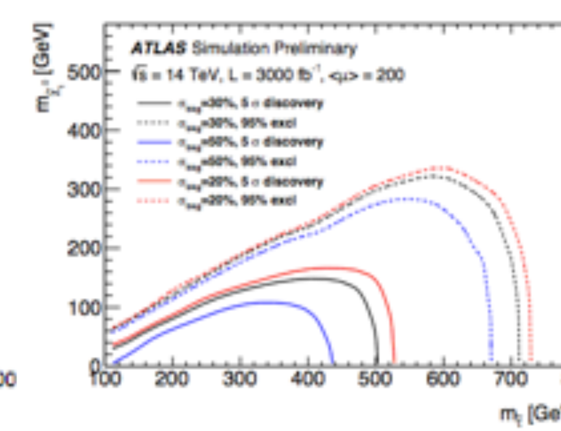


(b) $\tilde{q}\tilde{q}$, decoupled $\tilde{g}$









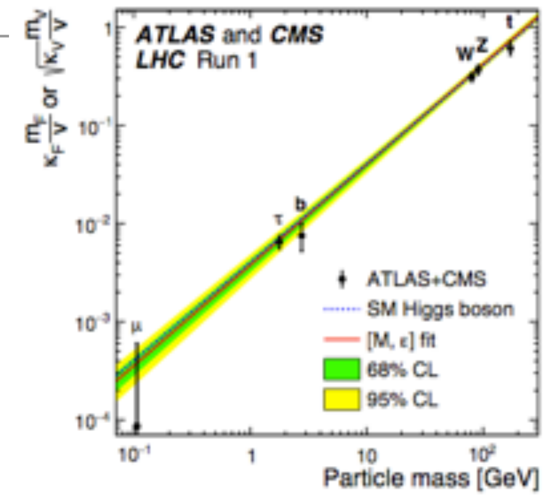
[arXiv:1812.07831]

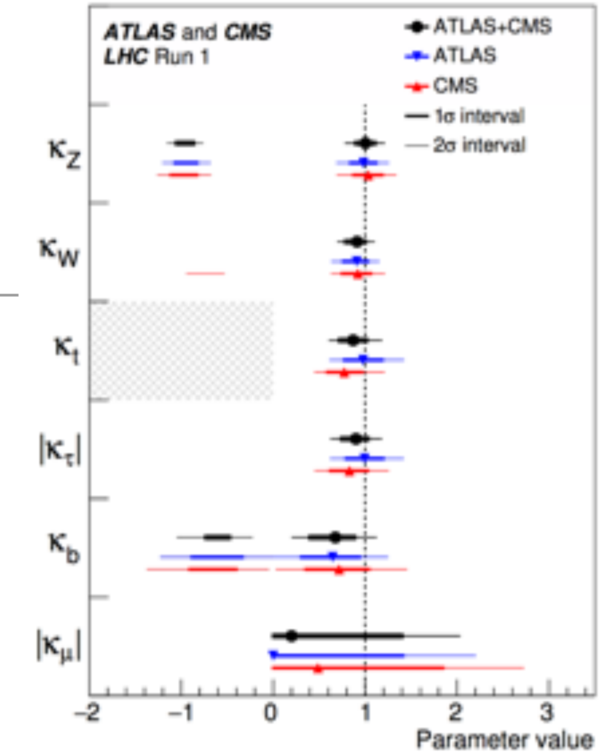
Notice: no constraints when LSP mass is heavy enough

SM like Higgs and no heavy Higgs

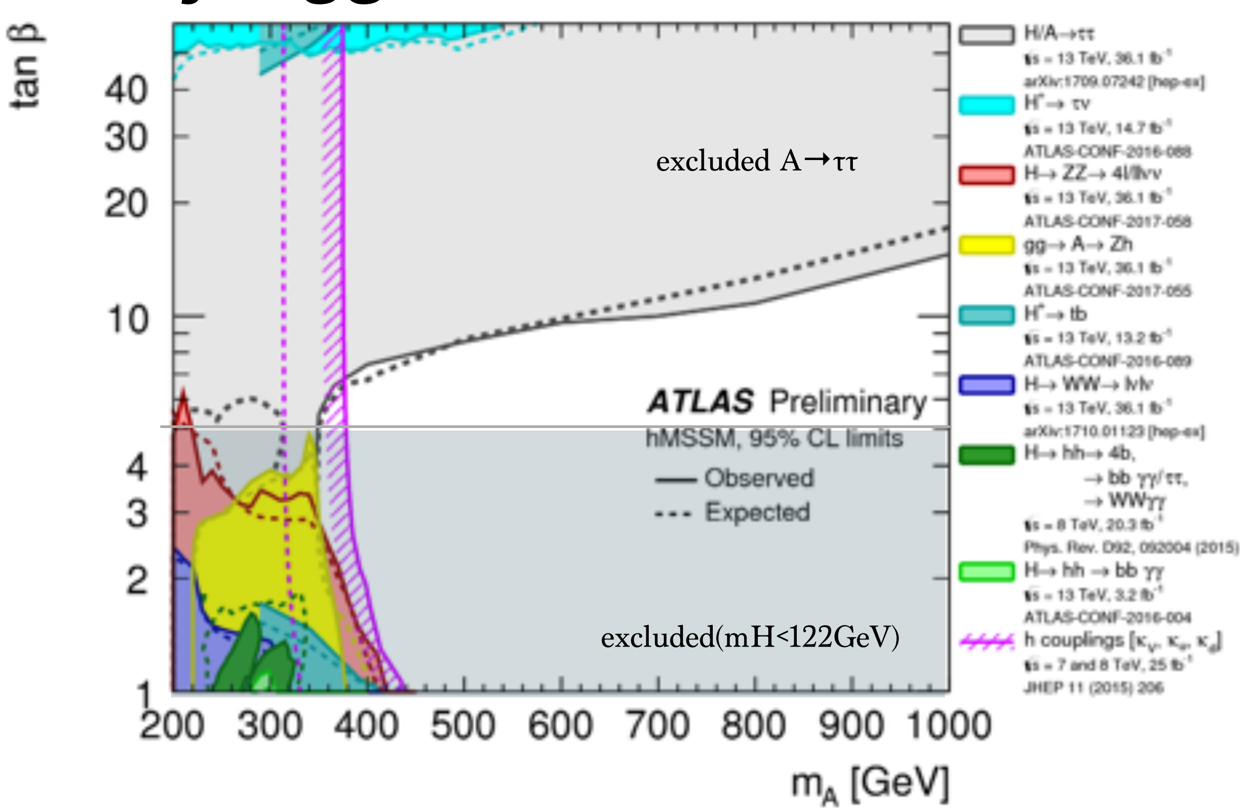
Higgs couplings measured
consistent to SM Higgs in 10-20%

also consistent to the MSSM higgs
in near decoupling limit





Heavy higgs searches



MSSM : 2HDM, additional Higgs expected

Unlike a general 2HDM, MSSM Higgs sector can be parameterized with $(m_A, \tan\beta)$

→ Light higgs coupling measurements already constrain $m_A \gtrsim 400\mathrm{GeV}$

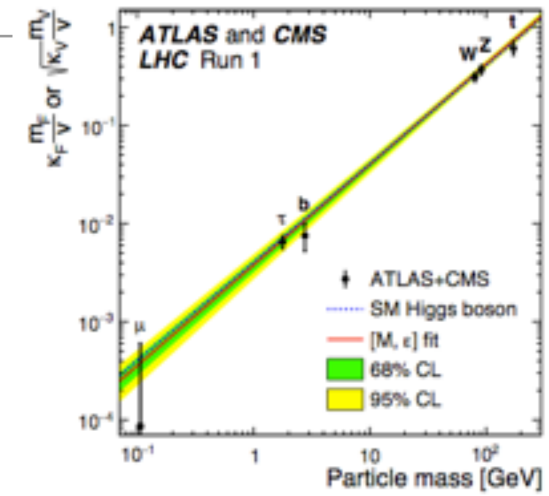
For large $\tan\beta$, bbA followed by $A \to \tau\tau$ dominates the sensitivity

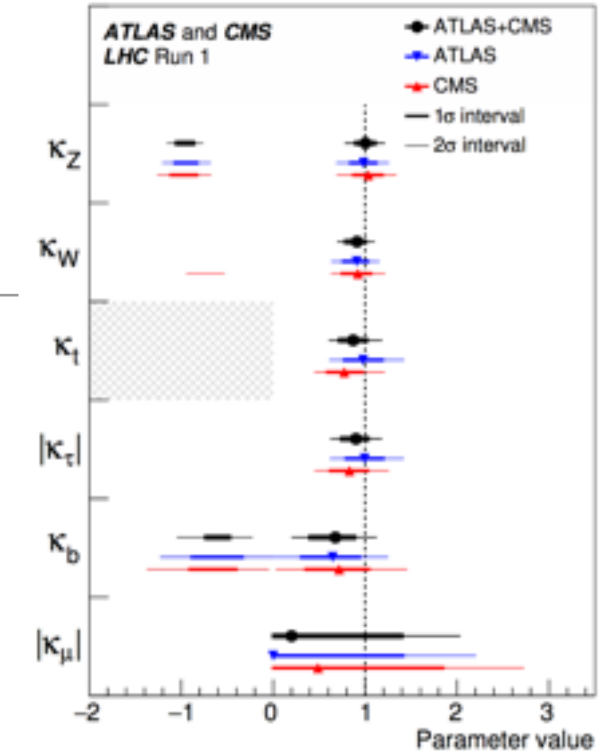
Large parameter space is excluded, but also large region is still available

SM like Higgs and no heavy Higgs

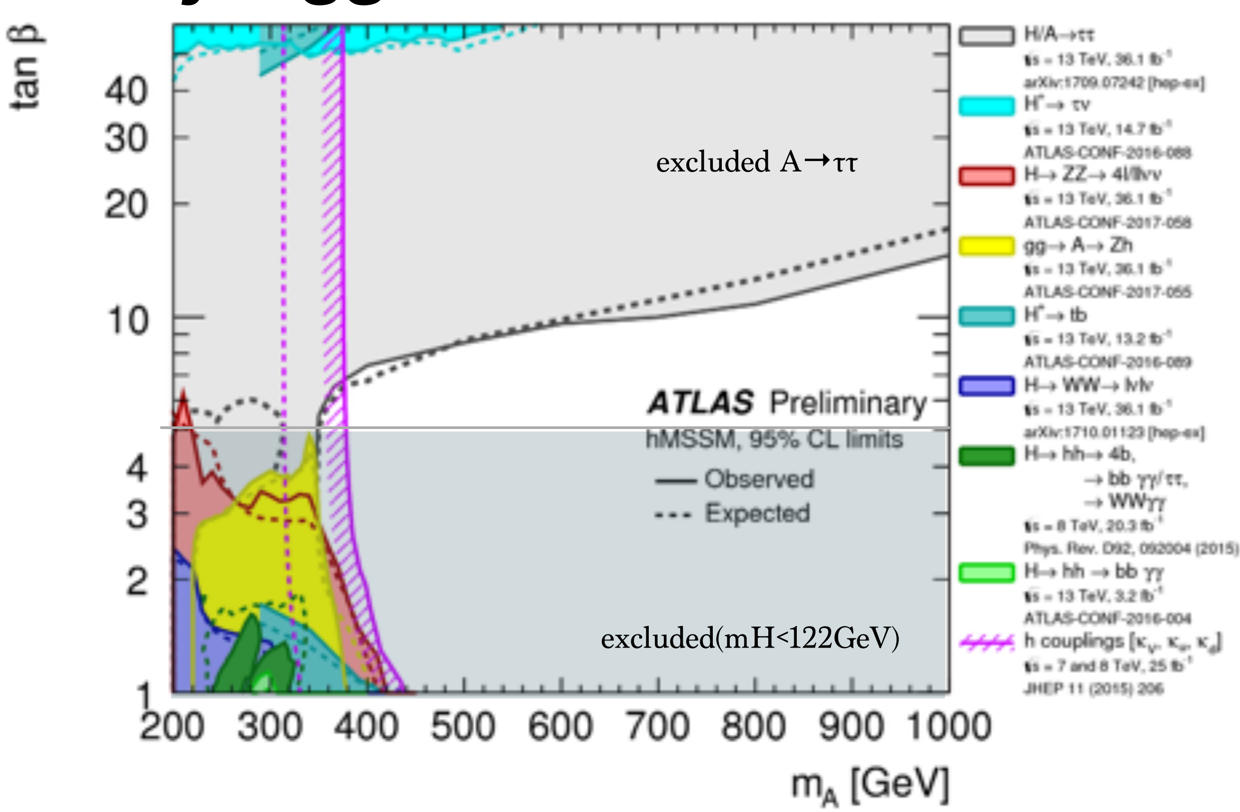
Higgs couplings measured
consistent to SM Higgs in 10-20%

also consistent to the MSSM higgs
in near decoupling limit





Heavy higgs searches



MS

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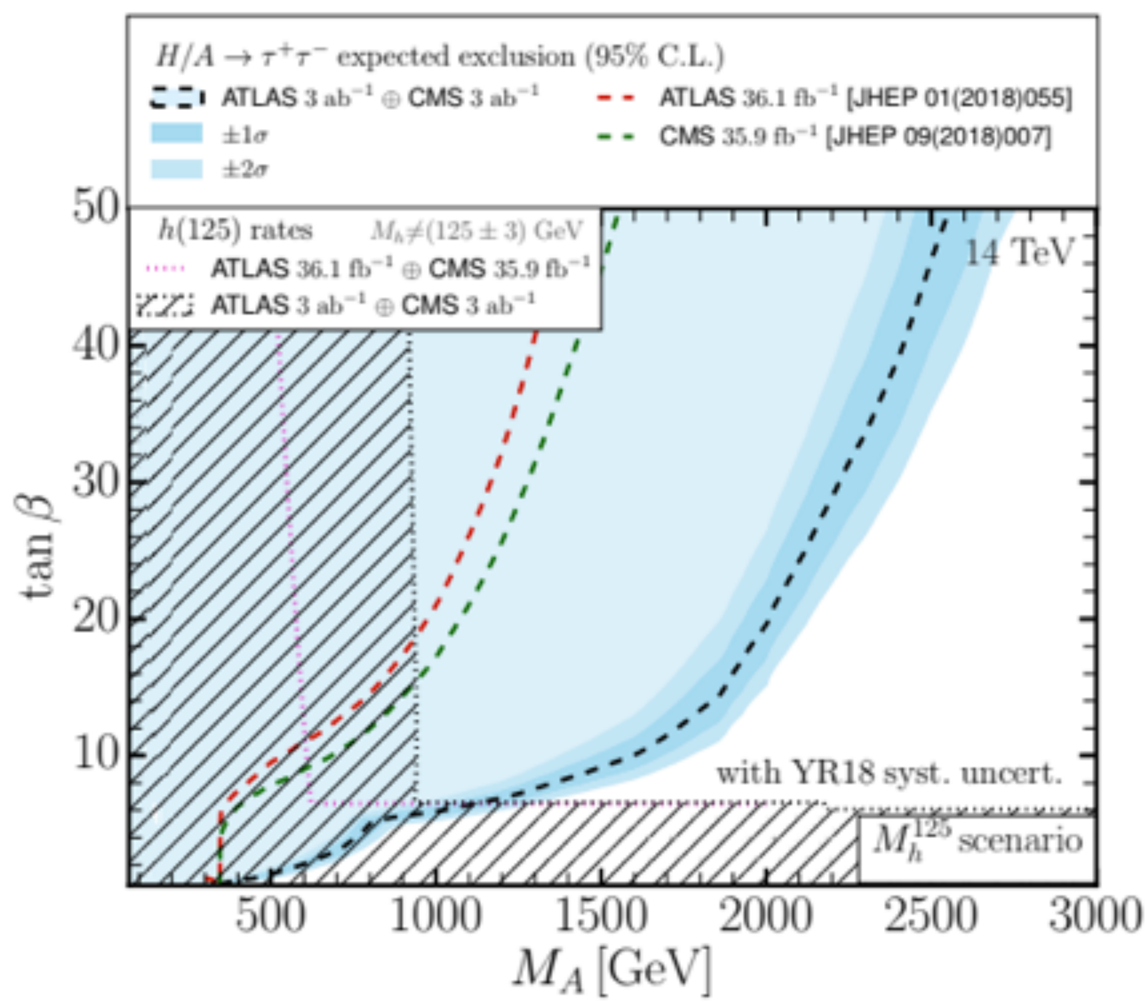


r

eady

For large $\tan\beta$, bbA followed by $A \to \tau\tau$

Large parameter space is excluded, but a

No evidence of SUSY anywhere yet

No evidence of SUSY at LHC, Higgs measurement, Direct-Detection…

Also consistent to the existence of SUSY below TeV scale
TeV scale SUSY still the most attractive solution for big hierarchy problem and DM

Where to hide SUSY?

- just heavy, just above the current search reaches
- relatively light but compressed spectrum
  - reduced missing momentum
  - compatible to co-annihilation, null DM-DD
- RPV, Stealth SUSY [J. Fan, M. Reece, J. Ruderman]

(g-2)μ deviation : long standing indication of low scale new physics?

$$a_\mu(\mathrm{exp}) = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$$

$$a_\mu(\mathrm{SM}) = \begin{cases} (11\,659\,182.8 \pm 4.9) \times 10^{-10} & \text{[K. Hagiwara, R. Liao, A. D. Martin, D. Nomura, T. Teubner]} \\ (11\,659\,180.2 \pm 4.9) \times 10^{-10} & \text{[M. Davier, A. Hoecker, B. Malaescu, Z. Zhang]} \end{cases}$$

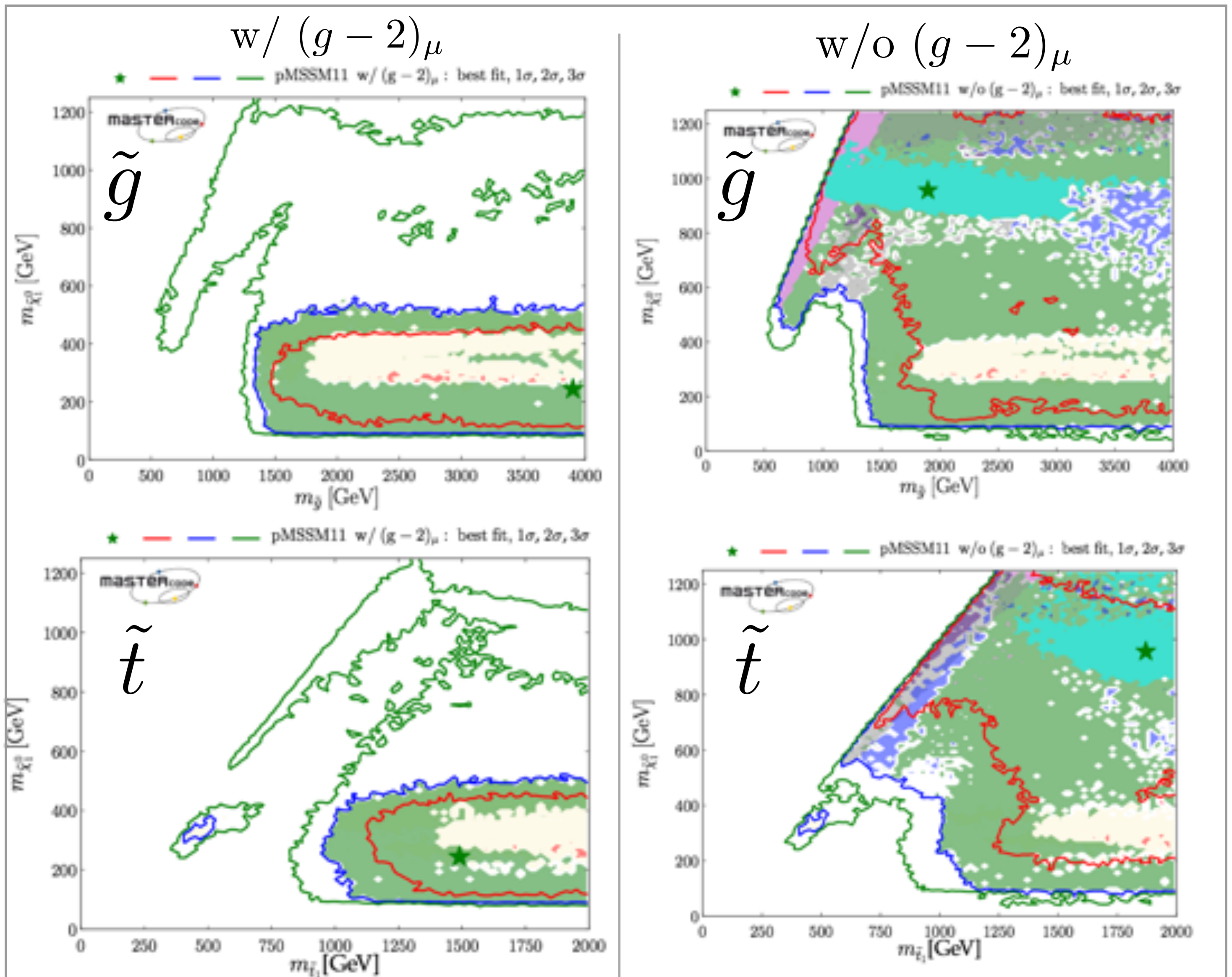
In MSSM, at least three of $\tilde{B}, \tilde{H}, \tilde{\mu}_L, \tilde{\mu}_R$ must be at $\mathcal{O}(100\mathrm{GeV})$

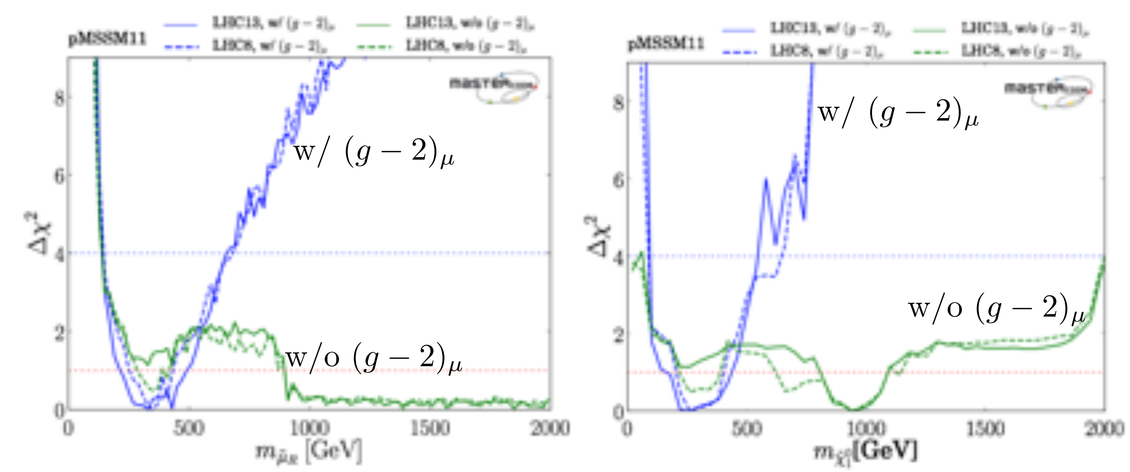
global fit with pMSSM11

Likelihood analysis of pMSSM11 [arXiv:1710.11091: E. Bagnaschi, et. al]

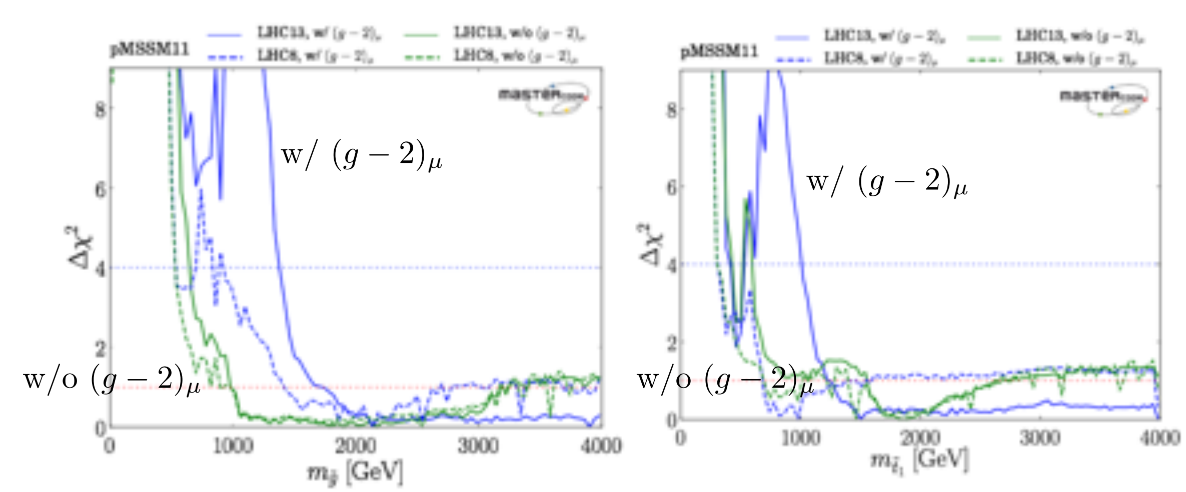
11 param. : $M_{1,2,3}, m_{\tilde{q}}, m_{\tilde{q}_3}, m_{\tilde{\ell}}, m_{\tilde{\ell}_3}, A, \mu, m_A, \tan\beta$

LHC, B-physics, Higgs, EWPO, DM, with/without $(g-2)_\mu$



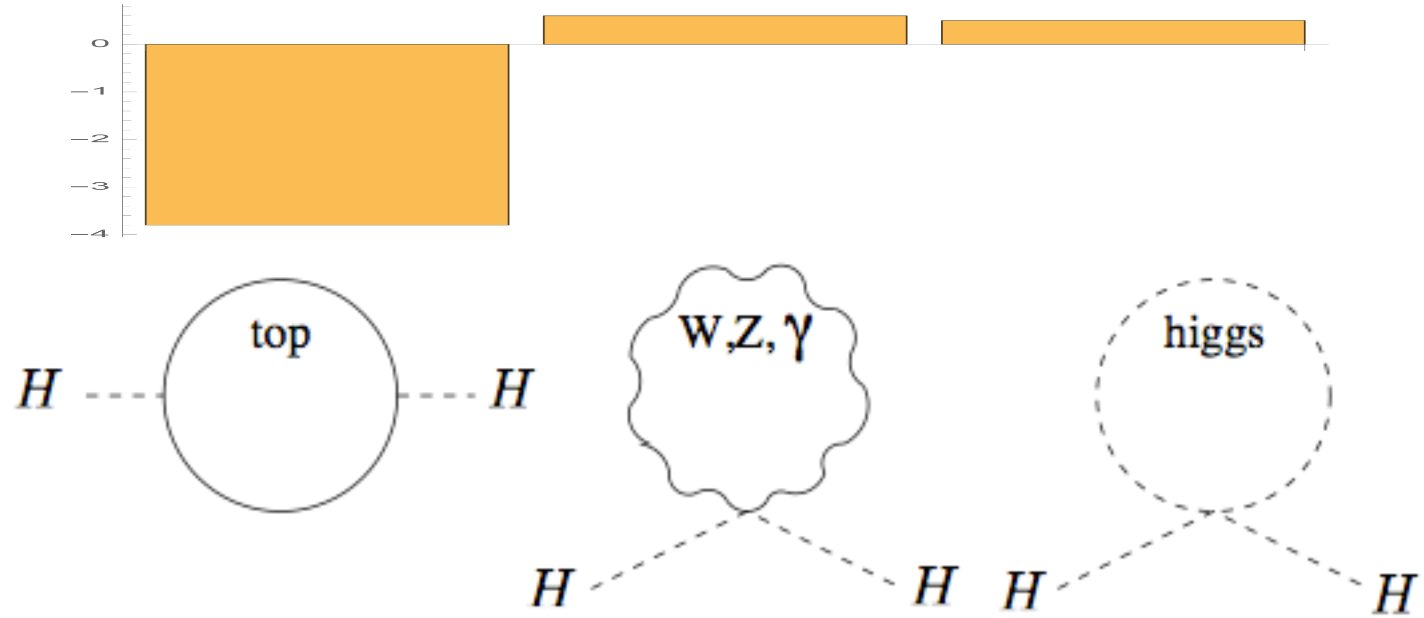


with g-2, only light DM acceptable



w/o $(g-2)_\mu$ allows lighter colored mass spectrum, because heavy DM allowed and compressed DM co-annihilation important. heavy stops, partly compressed spectrum favored.

Naturalness



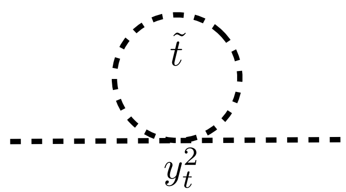
$$-\frac{3y_t^2}{8\pi^2}\Lambda^2 \qquad \frac{9g^2}{64\pi^2}\Lambda^2 \qquad \frac{3\lambda}{8\pi^2}\Lambda^2$$

~3.8% ~0.6% ~0.5%

After accepting fine tuning,
what we expect next?

top contribution is the largest among radiative corrections in Higgs mass

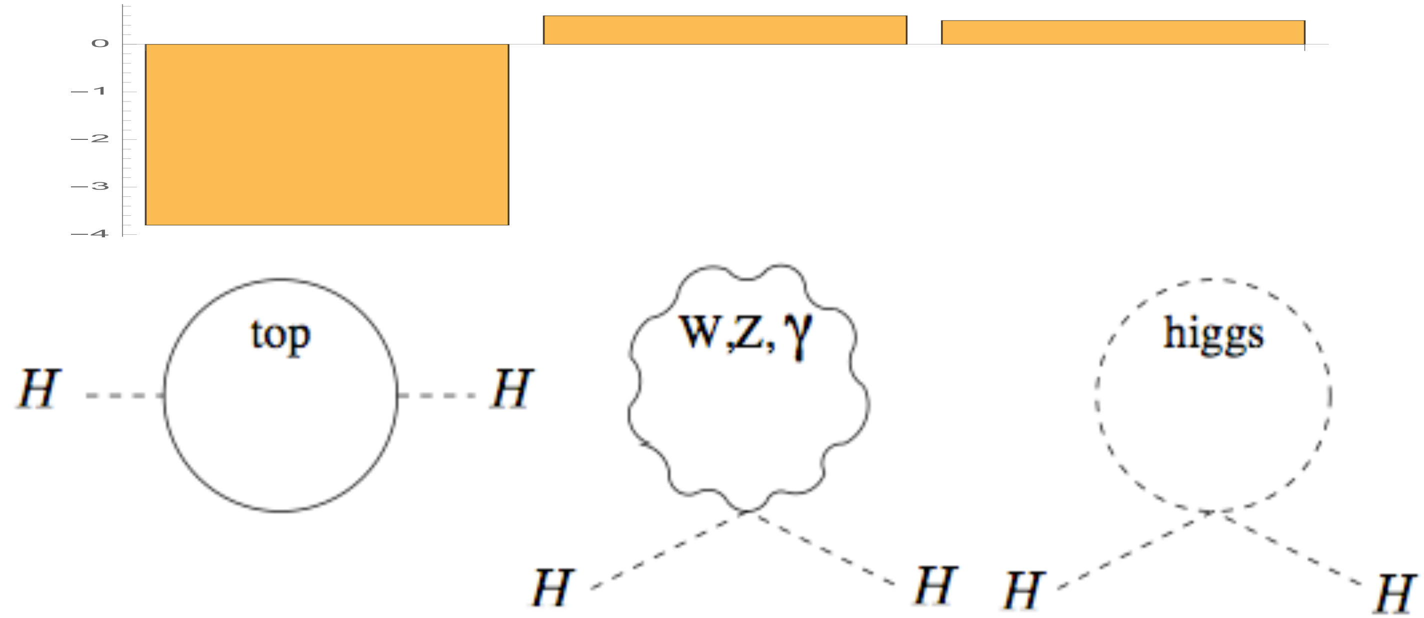
→ light stop

$\delta m_h^2 \sim$  $\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$

Naturalness

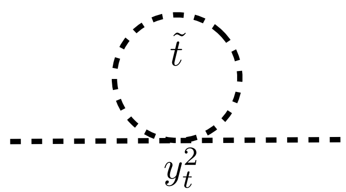
After accepting fine tuning,
what we expect next?

top contribution is the largest among
radiative corrections in Higgs mass



$$-\frac{3y_t^2}{8\pi^2}\Lambda^2 \qquad \frac{9g^2}{64\pi^2}\Lambda^2 \qquad \frac{3\lambda}{8\pi^2}\Lambda^2$$

~3.8% ~0.6% ~0.5%

→ light stop $\delta m_h^2 \sim$  $\sim +\frac{3}{4\pi}y_t^2\Lambda^2$

problem: the observed Higgs mass 125 GeV

before higgs discovery, MSSM successfully predicts

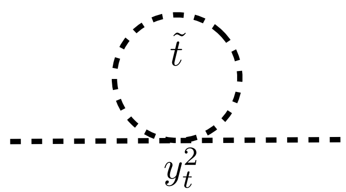
$m_h \lesssim 130\text{GeV}$ unless stops are not too heavy

This is one of the collateral evidences of the SUSY

Naturalness

After accepting fine tuning,
what we expect next?

top contribution is the largest among
radiative corrections in Higgs mass

→ light stop $\delta m_h^2 \sim$  $\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$

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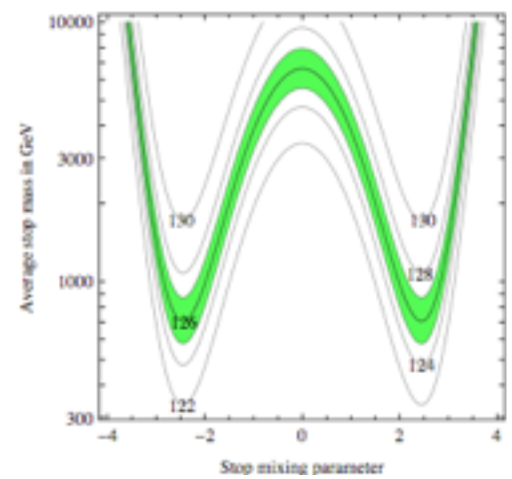
$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} y_t^2 m_t^2 \sin^2\beta \left[\log \frac{m_S^2}{m_t^2} + X_t^2 \left(1 - \frac{X_t^2}{12} \right) \right] + \dots$$

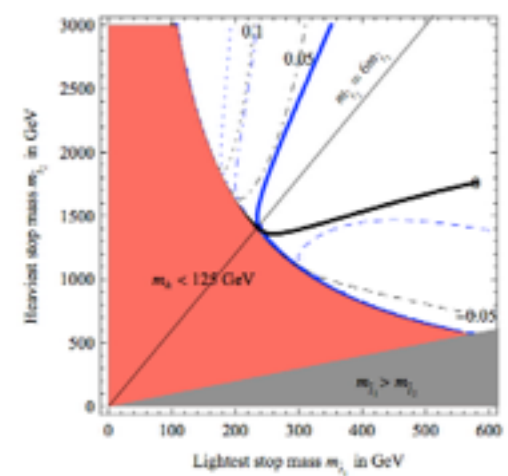
We need **heavy** or light but **highly mixed** stops

$5 \sim 10$ TeV

m_S as low as 600 GeV

m_{t_1} as low as 200 GeV





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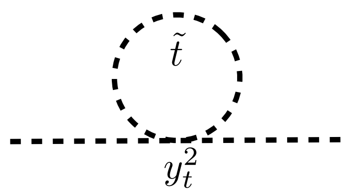
$\delta m_h^2 \sim$  $\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$

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$\quad$ m_{t_1} as low as 200 GeV

anywhere in $200\text{GeV} < m_{\tilde{t}_1} < 10$ TeV possible

Considering such light stops requires a tuning
to avoid S,T,U, Higgs couplings constraints
→ stop blind spot (lighter stop-higgs coupling vanish)

$$\mathcal{L}_{\rm eff} = \left(y_t^2 - \frac{y_t^2 X_t^2}{m_{\tilde{t}_h}^2 - m_{\tilde{t}_l}^2}\right)|H_u|^2 |\tilde{t}_l|^2. \quad X_t^* = \left(m_{\tilde{t}_h}^2 - m_{\tilde{t}_l}^2\right)^{1/2}$$

[J. Fan, M. Reece, L-T Wang]

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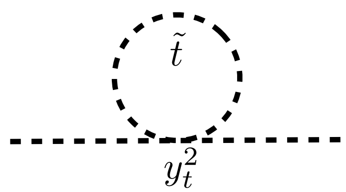
→ light stop $\delta m_h^2 \sim$ 

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[J. Fan, M. Reece, L-T Wang]

no one can guarantee that next new physics looks not superficially fine tuned

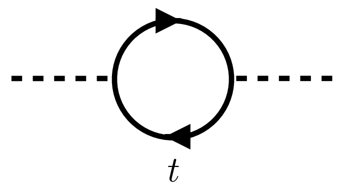
Further tuning welcome:

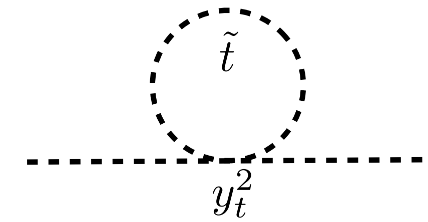
fine tuning found → more chance to go beyond 1%*99%
 ||
natural parameter found → less chance to reveal underlining theory 99%*1%

lighter stop can exist just outside the current reach

Stop searches

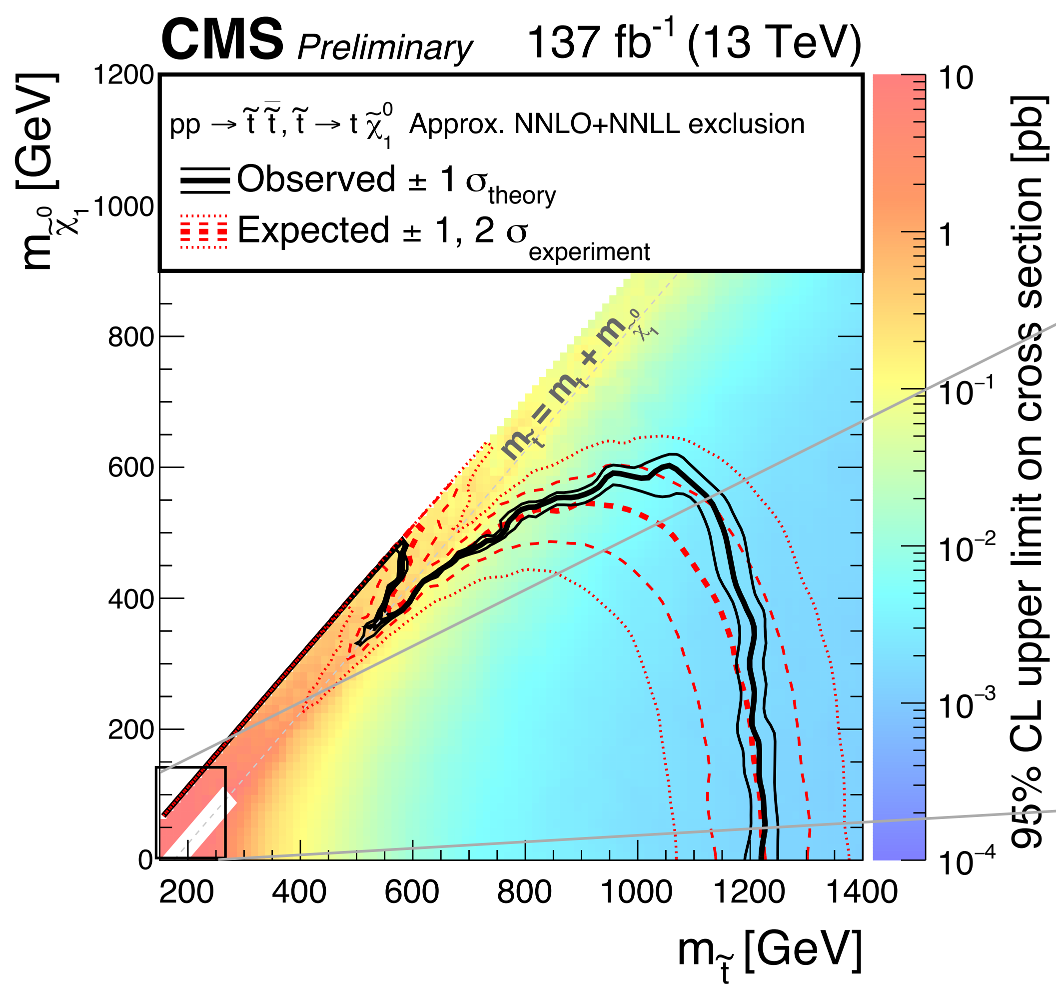
Solving hierarchy problem requires top partner: stop

$\delta m_h^2 \sim$  $\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\rm SM}^2 \quad \sim 10^{38}{\rm GeV}^2 (\Lambda_{\rm SM} = m_{\rm Pl})$

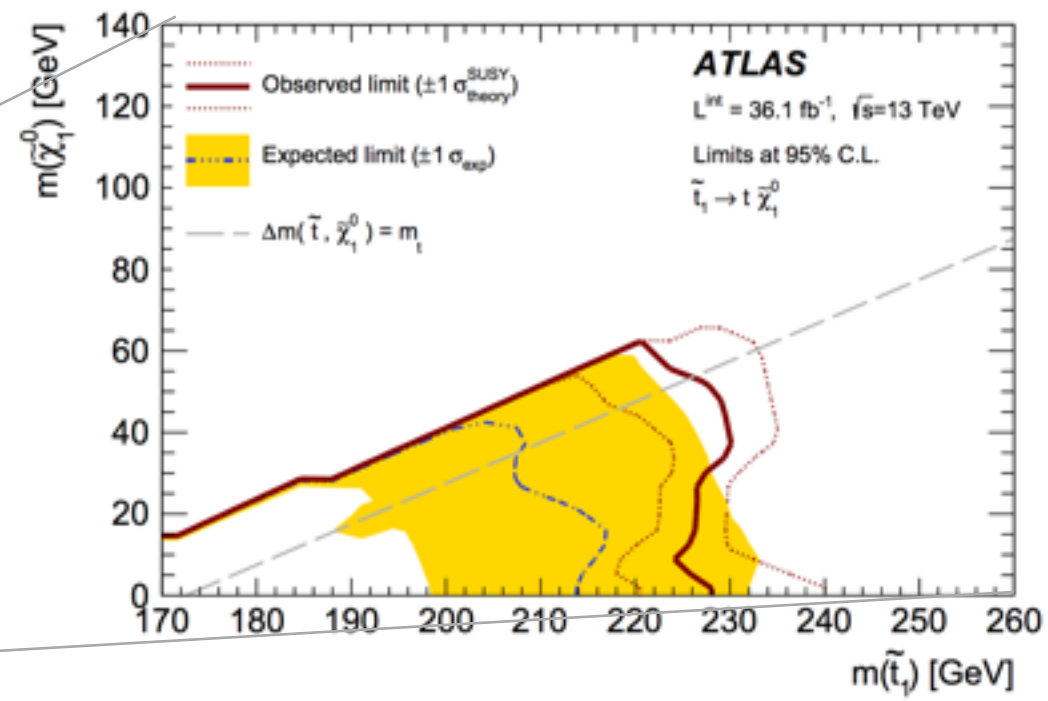
$\delta m_h^2 \sim$  $\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$

current status (Bino LSP: tt+missing)

up to ~1.2 TeV excluded ?



CMS-PAS-SUS-19-005

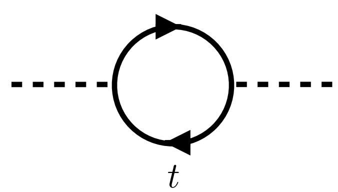


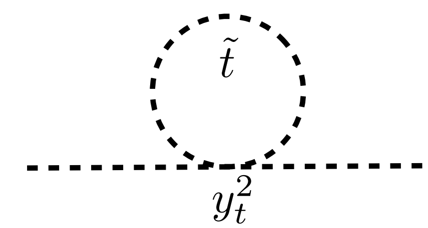
arXiv:1903.07570

spin correlation finally filled the gap

Stop searches

Solving hierarchy problem requires top partner: stop

$\delta m_h^2 \sim$  $\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\mathrm{SM}}^2 \quad \sim 10^{38}\mathrm{GeV}^2 (\Lambda_{\mathrm{SM}} = m_{\mathrm{Pl}})$

$\delta m_h^2 \sim$  $\sim + \frac{3}{4\pi} y_t^2 \Lambda^2$

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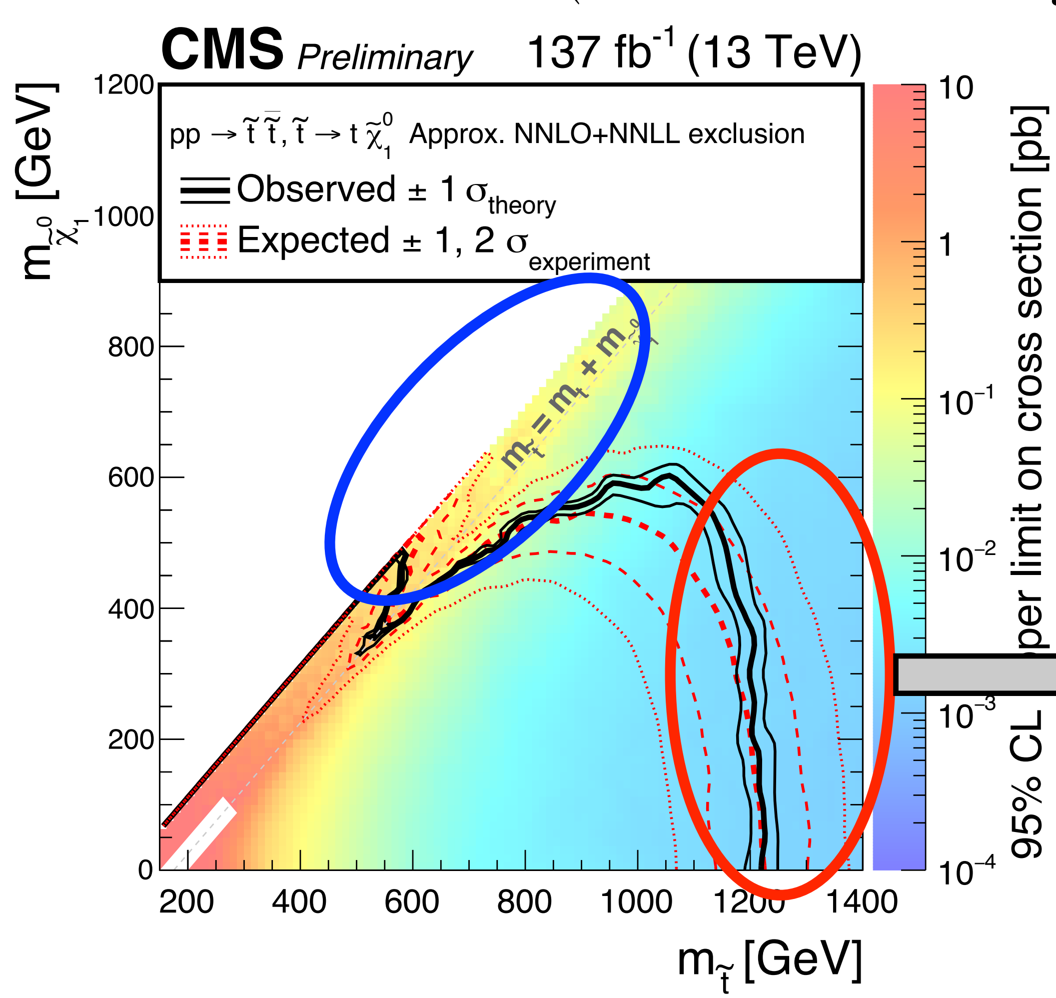


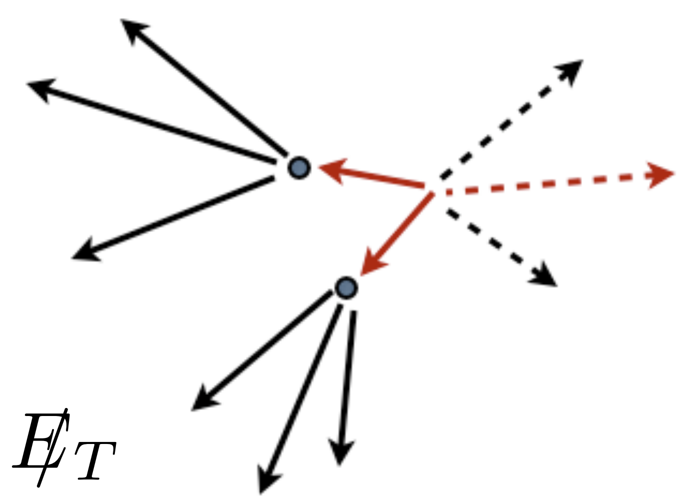
CMS-PAS-SUS-19-005

At the search frontier, special efforts must be taken

heavy region: boosted top reconstruction

compressed region: mono-jet, soft-leptons

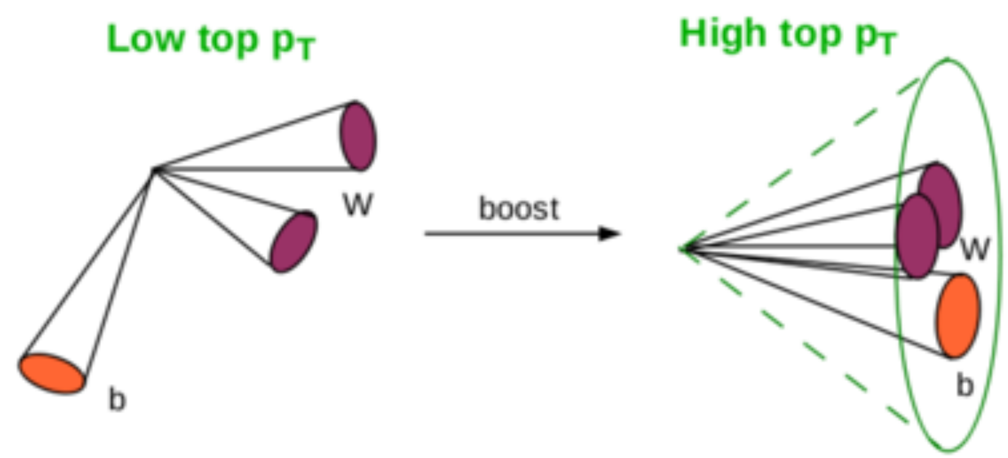
more boosted in future



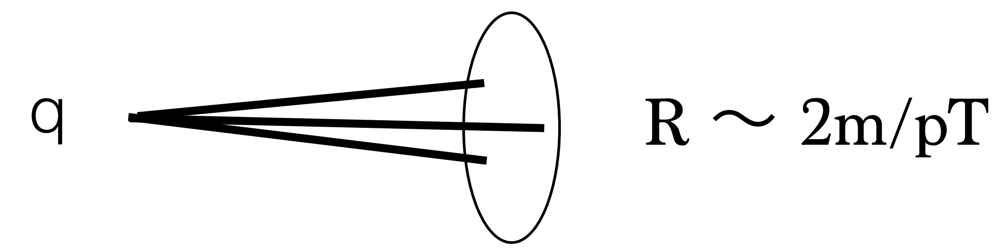
$$\text{high } p_{T,t} = \text{high } \not{E}_T$$

the heavier the stop is, the more boosted the top is

What changes with a boost?



jets start overlapping, cannot observe separate 3j



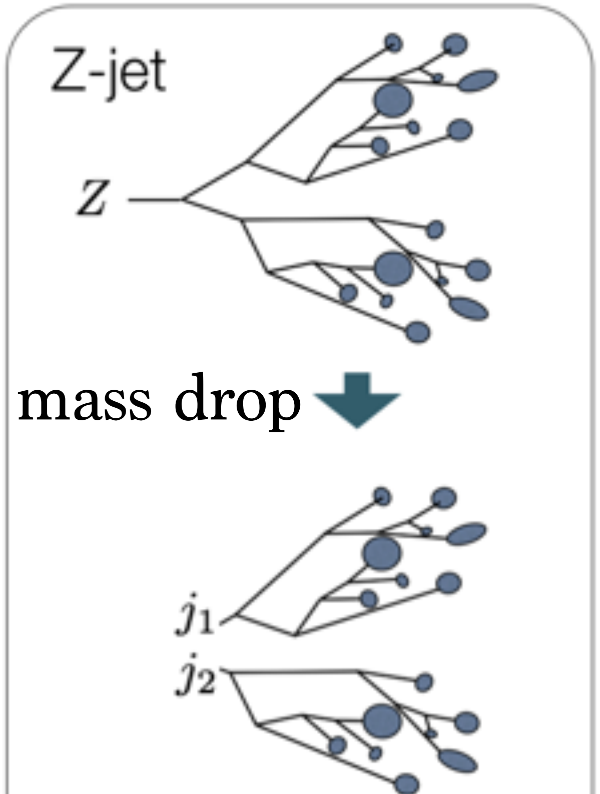
difficult to distinguish from q/g-initiated jets

this problem can be solved by looking into **jet substructure**

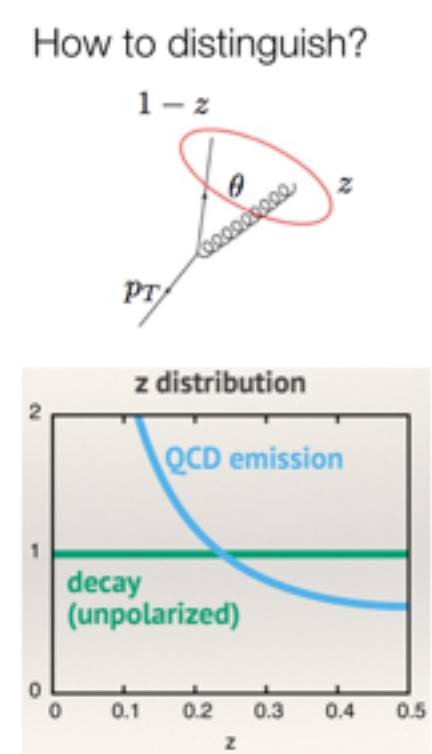
split a jet into 2 subjets, **mass drop** observed for heavy particle decay but not for QCD jets

(soft-collinear singularity everywhere)

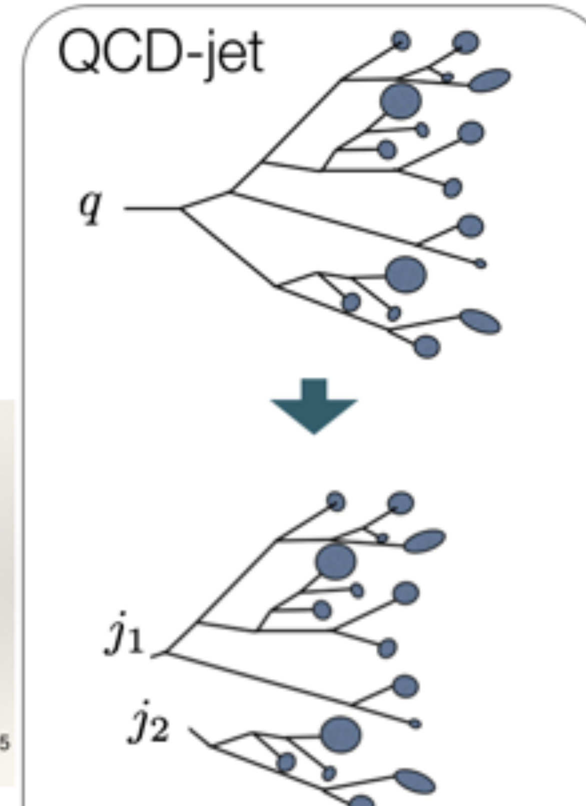
[J. M. Butterworth, A. R. Davison, M. Rubin, G. P. Salam Phys. Rev. Lett. 100, 242001 (2008)]



$m_j \gg m_{j1}, m_{j2}$ (decay)



$\mathcal{P} = \frac{2\alpha_s C}{\pi} \frac{dz}{z} \frac{d\theta}{\theta}$

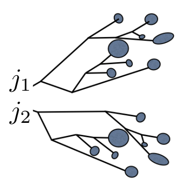


$m_j \sim m_{j1} \gg m_{j2}$ (QCD)

HEPTopTagger Algorithm

JHEP 1010 (2010) 078
[T. Plehn, M. Spannowsky, MT, D. Zerwas]

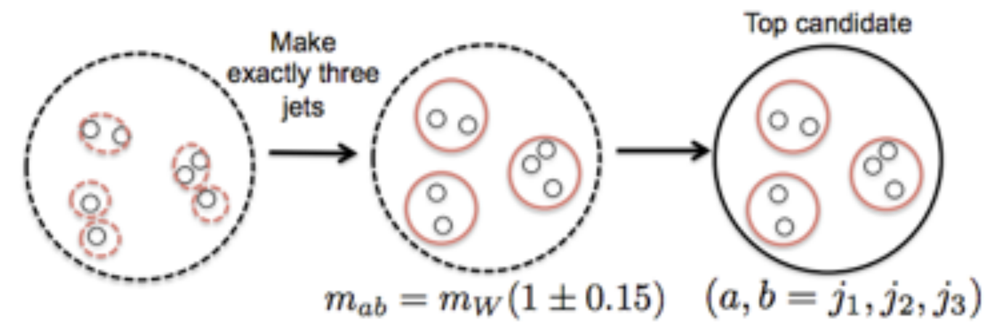
the top-identification algorithm based on jet substructures (mass drop)



$m_j \gg m_{j1}, m_{j2}$ (decay) $\quad m_j \sim m_{j1} \gg m_{j2}$ (QCD)

split a jet into 2 sub-jets

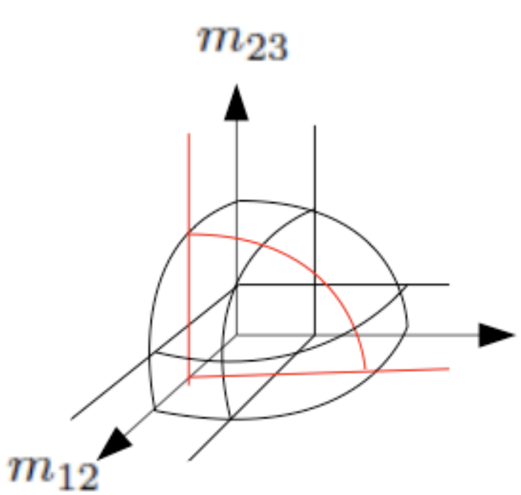
when it is from heavy particle decays, sudden mass drop observed



by using mass drop criteria recursively, we extend the algorithm usable for 3 subjets case

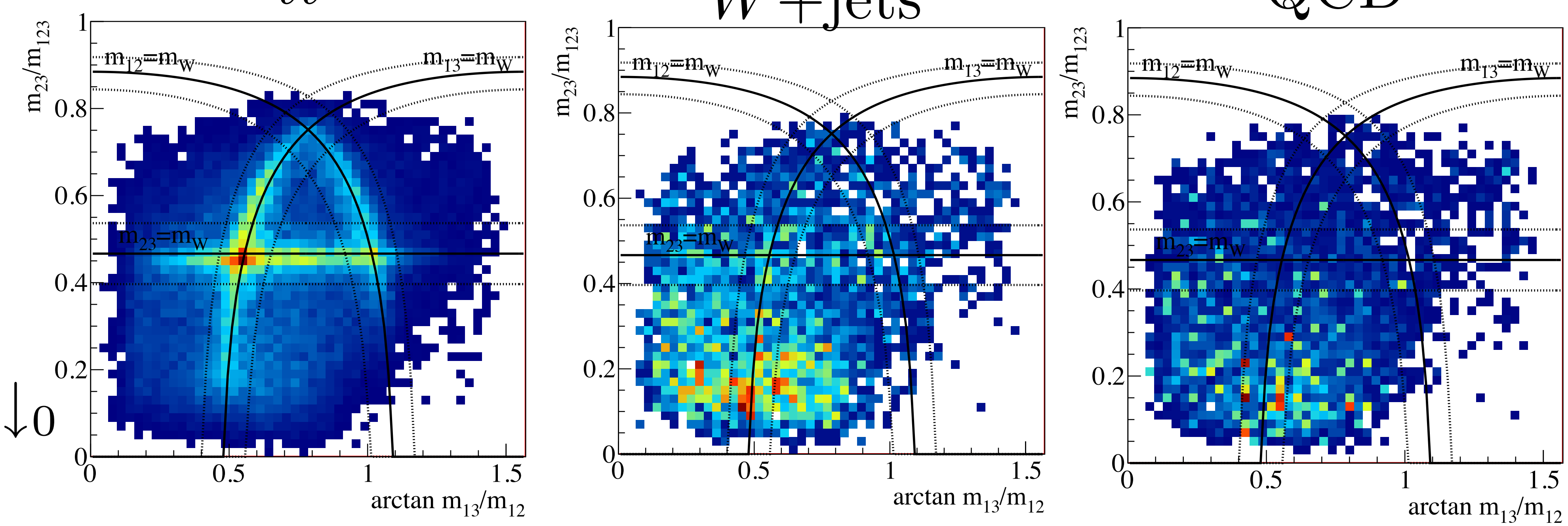
3 subjets: $p_1, p_2, p_3 \to m_{12}, m_{13}, m_{23}$

$m_t^2 \simeq m_{123}^2 \simeq m_{12}^2 + m_{13}^2 + m_{23}^2 \to$ 2D mass ratios



$m_{23} \downarrow 0$

$t\bar{t}$ $\quad W$+jets $\quad$ QCD



cut on the 2-dim plane, we can efficiently distinguish top-jet from the QCD-jets

similar methods used for the stop search frontier

Machine Learning/Deep Learning on Jet images

[J. Cogan, M. Kagan, E. Strauss, A. Schwartzman, JHEP02(2015)118]

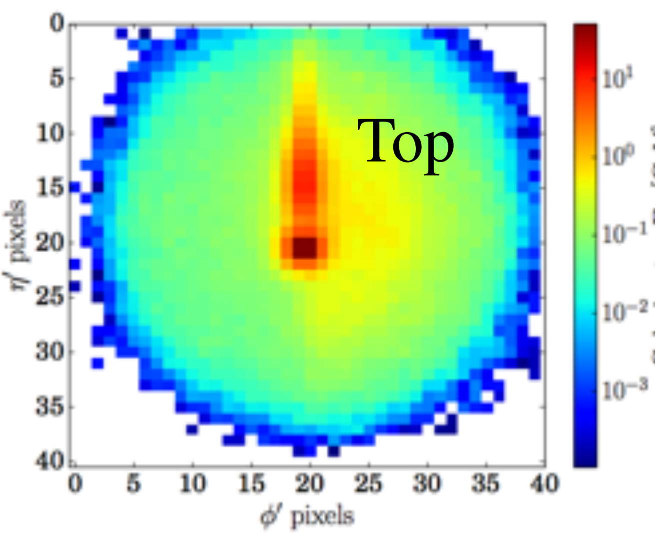
[G. Kasieczka, T. Plehn, M. Russell and T. Schell, JHEP 1705 (2017) 006.]

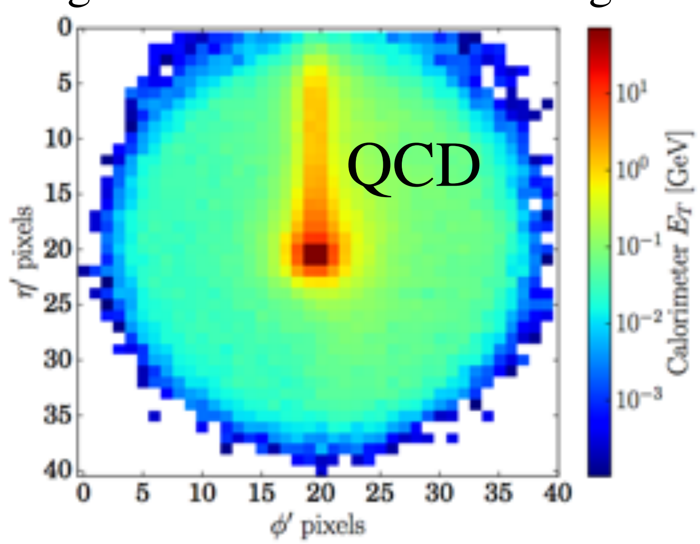
Top tagging : classification problem, suitable to extend ML/DL

viewed as image recognition task on Jet Image (energy deposits in calorimeters = pixels of a grayscale image)

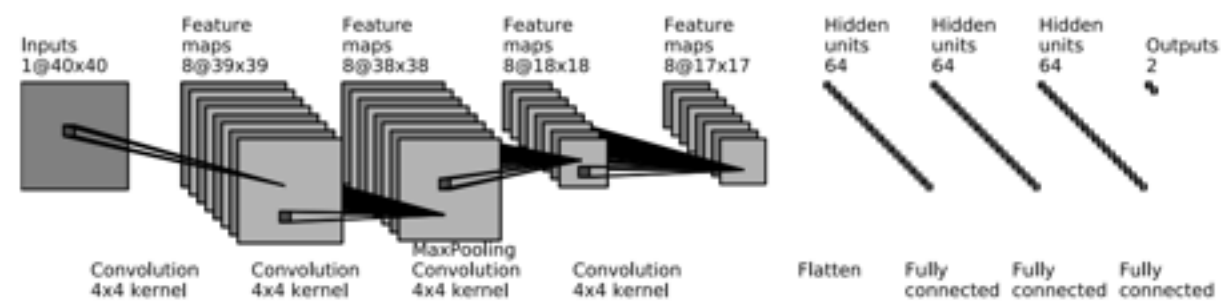
Image recognition : Convolutional Neural Networks (CNNs) very powerful

the weights to be learned are arranged in convolutional kernels applied to different parts of the image.





DeepTop algorithm



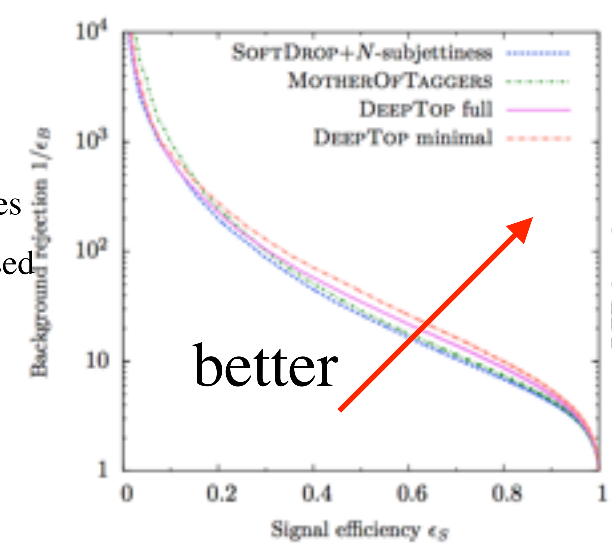
Comparison between DeepTop and multivariate BDT of

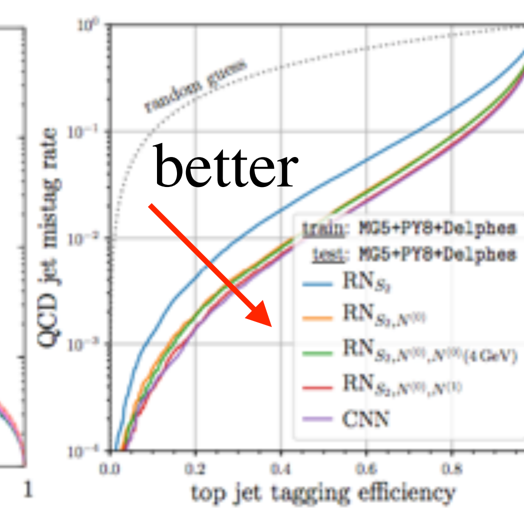
$\{\, m_{\rm sd}, m_{\rm fat}, \tau_2, \tau_3, \tau_2^{\rm sd}, \tau_3^{\rm sd} \,\}$ (SoftDrop + N-subjettiness) basic QCD based jet substructures

$\{\, m_{\rm sd}, m_{\rm fat}, m_{\rm rec}, f_{\rm rec}, \Delta R_{\rm opt}, \tau_2, \tau_3, \tau_2^{\rm sd}, \tau_3^{\rm sd} \,\}$ (MotherOfTaggers) . HEPTopTagger2 based

performances of the two approaches are comparable

multivariate QCD-based top-tagging ⇔ data-based ML





we have similar comparison, found difference comes from non-perturbative counting variables,

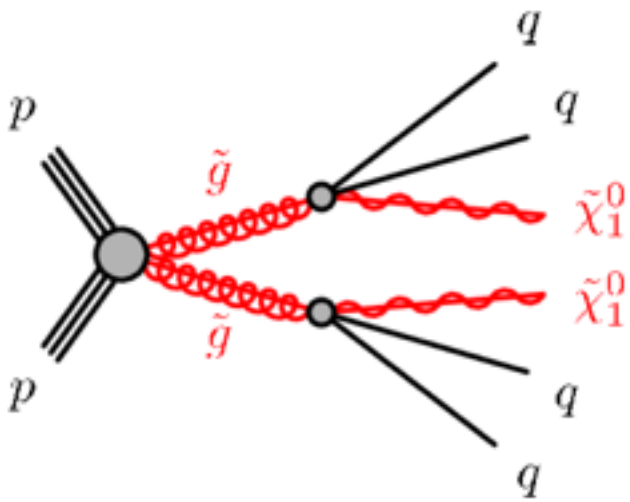
[A. Chakraborty, S.H. Lim, M. Nojiri, MT, JHEP07(2020)111]

Minkowski functionals $N^{(0)}, N^{(1)}$ to parametrize how dense the calorimeter hits distribute.

Jet substructure for SUSY searches

[B. Bhattacharjee, S. Mukhopadhyay, M. M. Nojiri, Y. Sakaki, B. R. Webber] JHEP 1701 (2017) 044

gluino pair production signal : 4 quarks ⇔ BG Z+jets : gluon rich   q/g separation will help



Process	$f_q^{j_1}$	$f_q^{j_2}$	$f_q^{j_3}$	$f_q^{j_4}$
$\tilde{g}\tilde{g}$+jets	0.92	0.87	0.77	0.64
Z+jets	0.64	0.55	0.27	0.16

in QCD, q/g difference : C_F/C_A

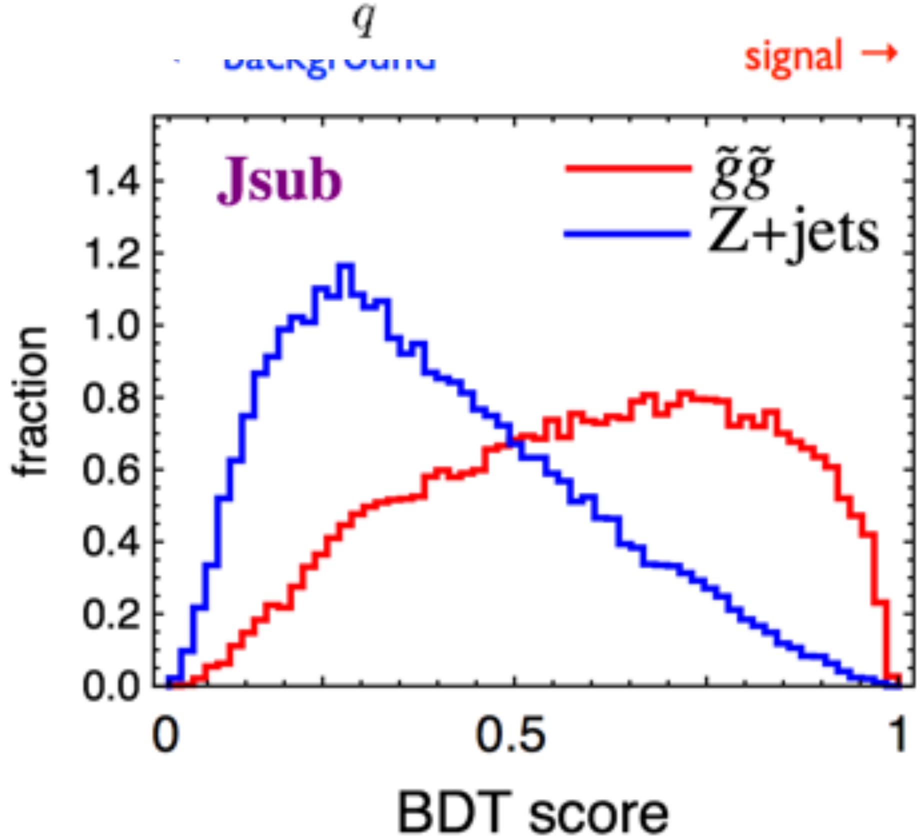
for each jet, quark score:

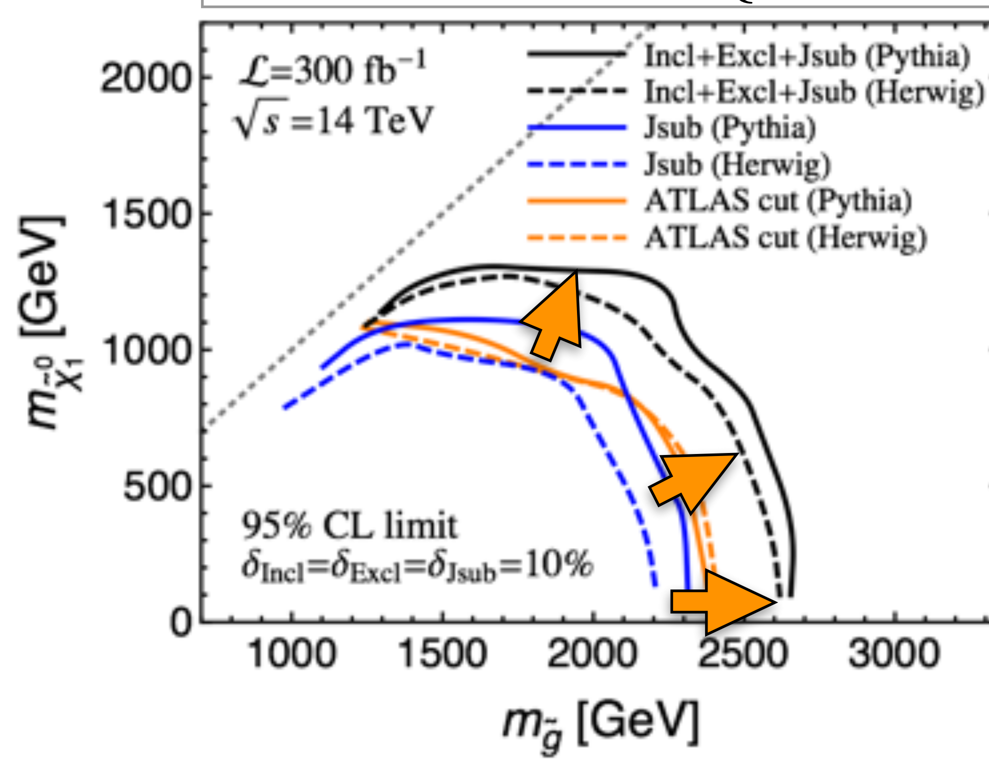
$$B_i = \mathrm{BDT}\{n_{\mathrm{ch}}, C_1^{\beta}, m_j\}$$

charged tracks, jet width, jet mass

for each events:

$$\mathrm{J_{sub}} = \mathrm{BDT}\{B_1, B_2, B_3, B_4\}$$



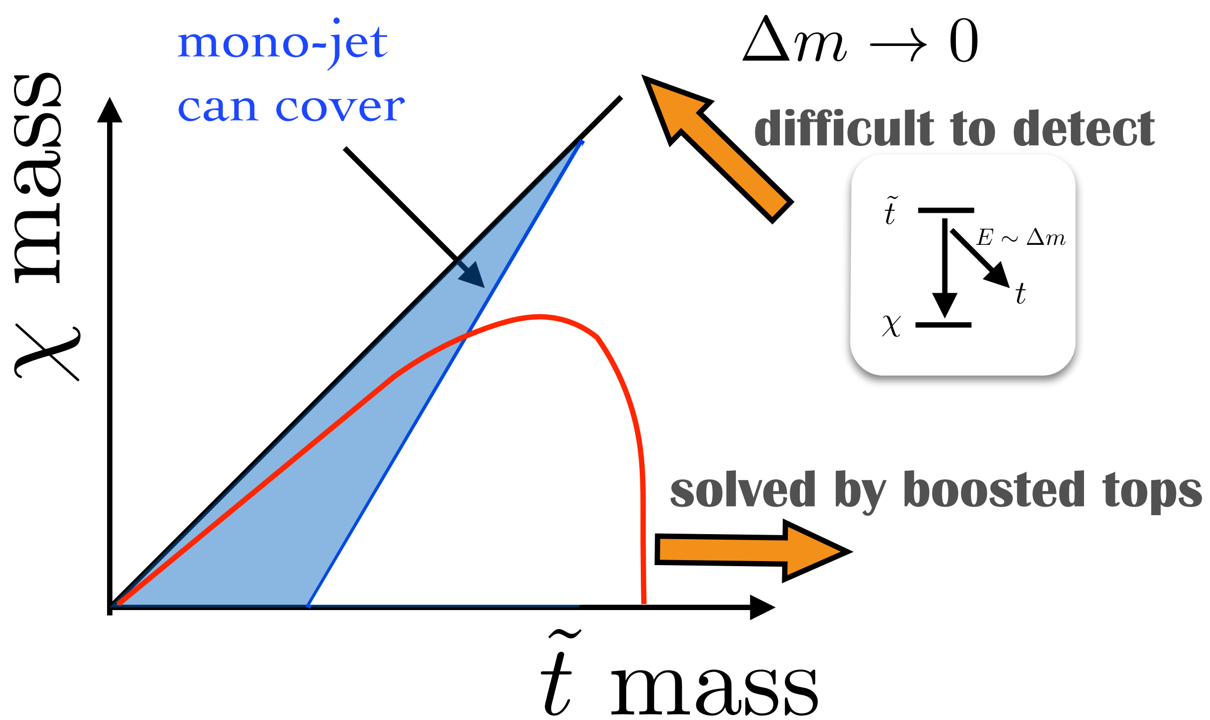


explicitly show adding the orthogonal Jsub information improves the reach

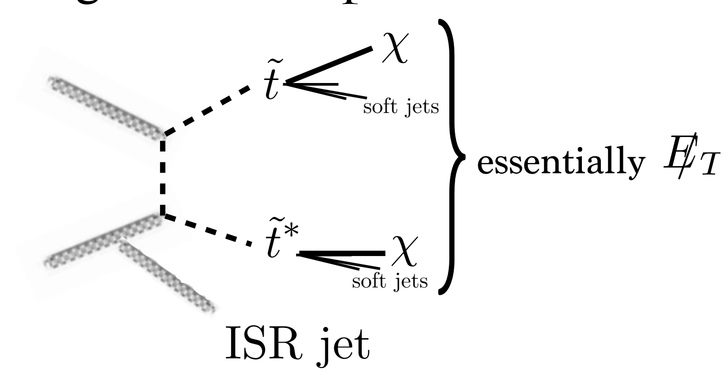
use of jet substructure, extension to ML/DL etc. is very rapidly developing field

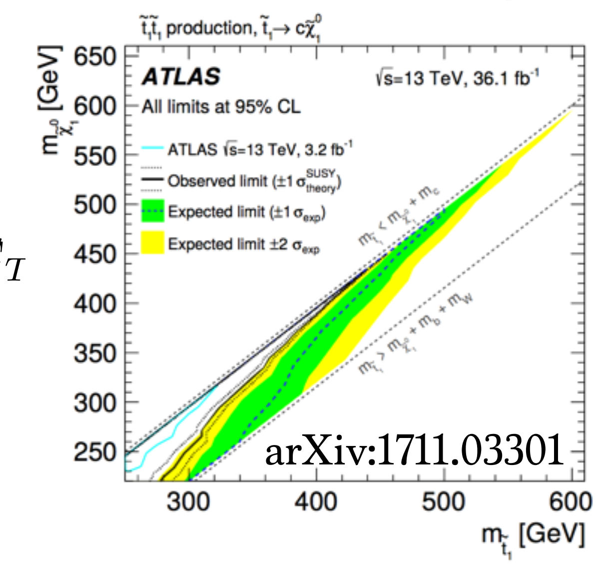
Degenerate stop searches

D. Goncalves, K. Sakurai, MT [Phys.Rev. D94 (2016) 075009]
D. Goncalves, K. Sakurai, MT [Phys.Rev. D95 (2017) no.1, 015030]
D. Goncalves, K-C.Kong, K. Sakurai, MT [Phys.Rev. D97 (2018) no.1, 015002]



degenerate stops





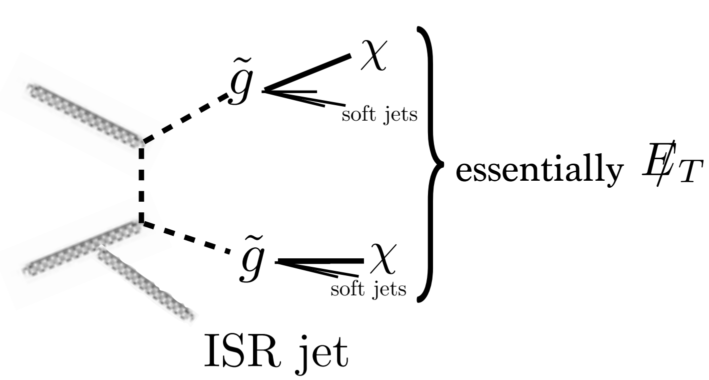
well known solution:
NLO process provides
mono-jet signature

$$j + \not{E}_T$$

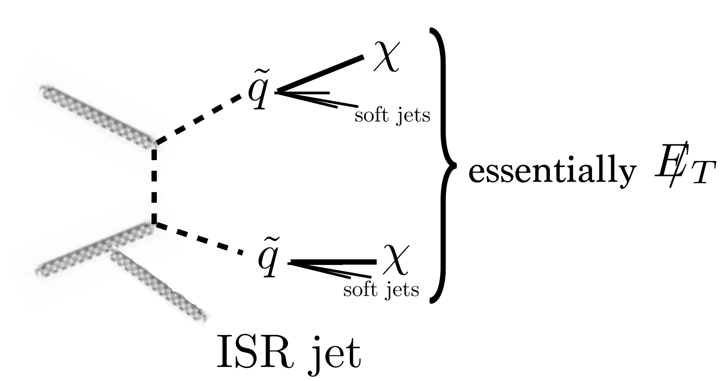
However,
once mono-jet signatures are found

As mono-jet signatures are predicted from
any degenerated spectrum,
it wouldn't be the distinctive signature
of degenerate scalar tops

degenerate gluinos



degenerate squarks



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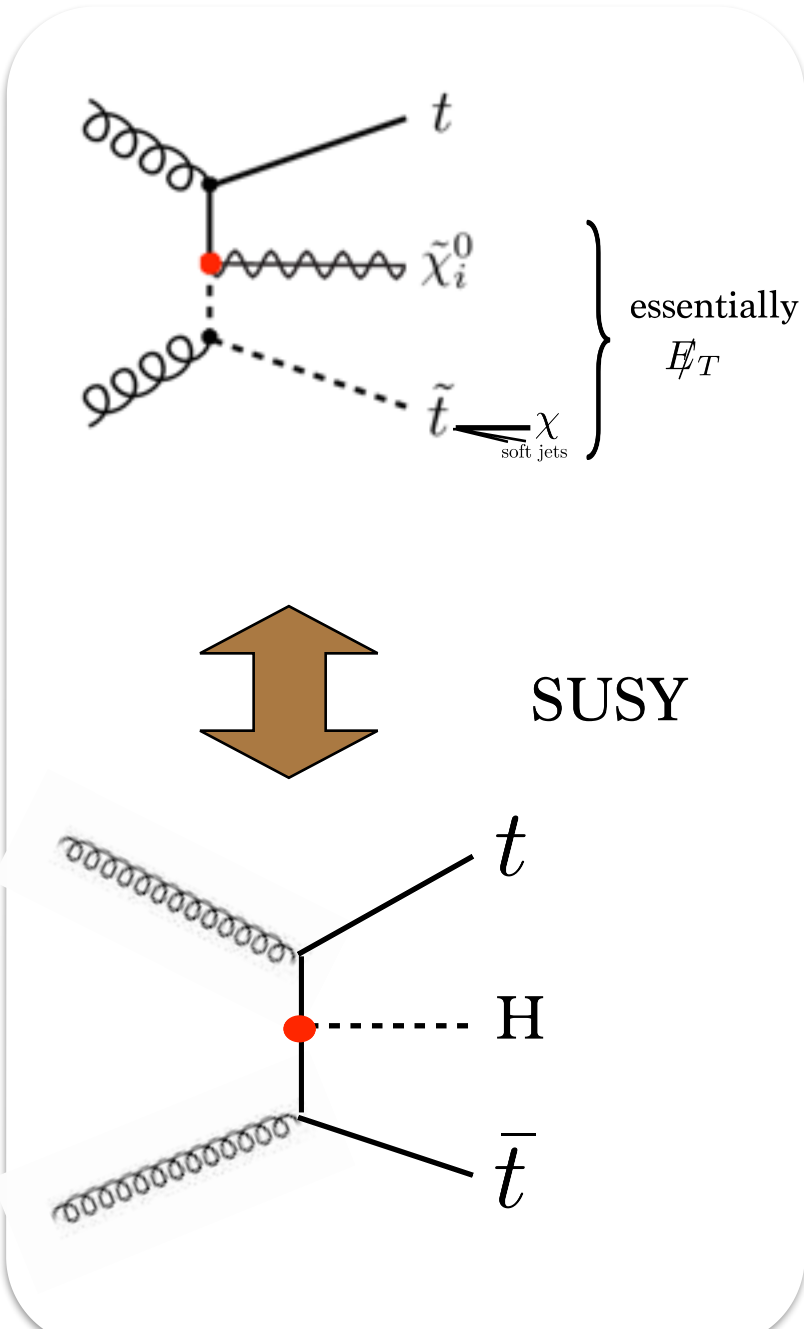
Mono-top signature as a smoking-gun signature for the degenerate stops

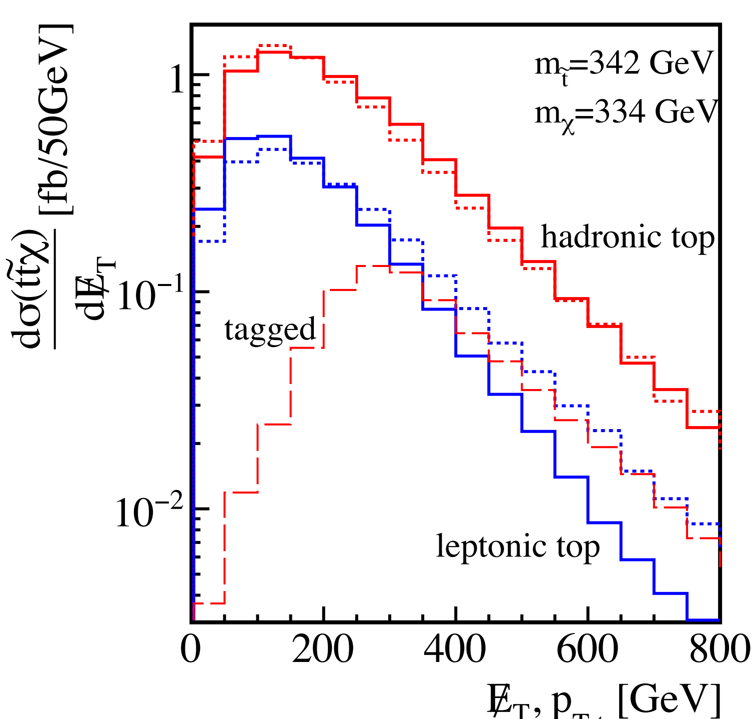


SUSY ttH production — stop-top-higgsino — is not too small (a few fb)

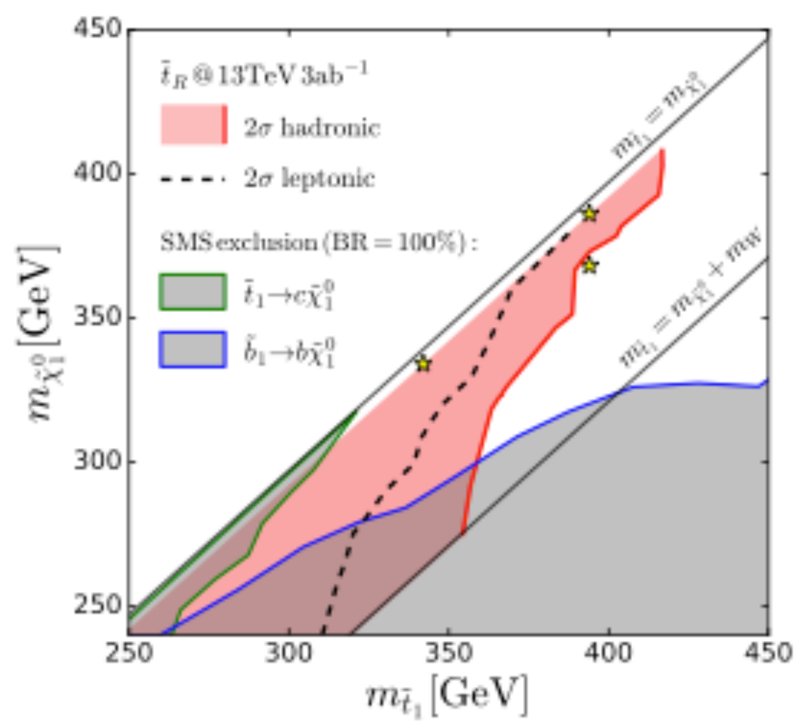
$t + \not{E}_T$ in degenerate stop spectrum

Measuring this process provides first verification of non-trivial SUSY relation (both controlled by super-potential)

large $\not{E}_T$/boost needed → Top Tagging (HEPTopTagger)



hadronic mode ($\not{E}_T$ fully usable)
leptonic mode ($\not{E}_T$ canceled by ν)



mono-top search reach at LHC
interesting at future colliders

EWkino as thermal relic DM

Colored sparticles mass bounds are already heavy, split SUSY type spectrum gets popular

10TeV SUSY (stop) still successfully solves the big gauge hierarchy problem of $\sim 10^{-30}$ tuning

Attractive point of SUSY : neutralino as a good DM candidate

Assuming thermal relic neutralino explain the observed DM abundance set the upper bound on the DM mass

pure Higgsino : 1.1TeV

pure Wino : 3 TeV with Sommerfeld Enhancement

cf.) squark co-annihilation: 3 TeV

stop co-annihilation: 6 TeV

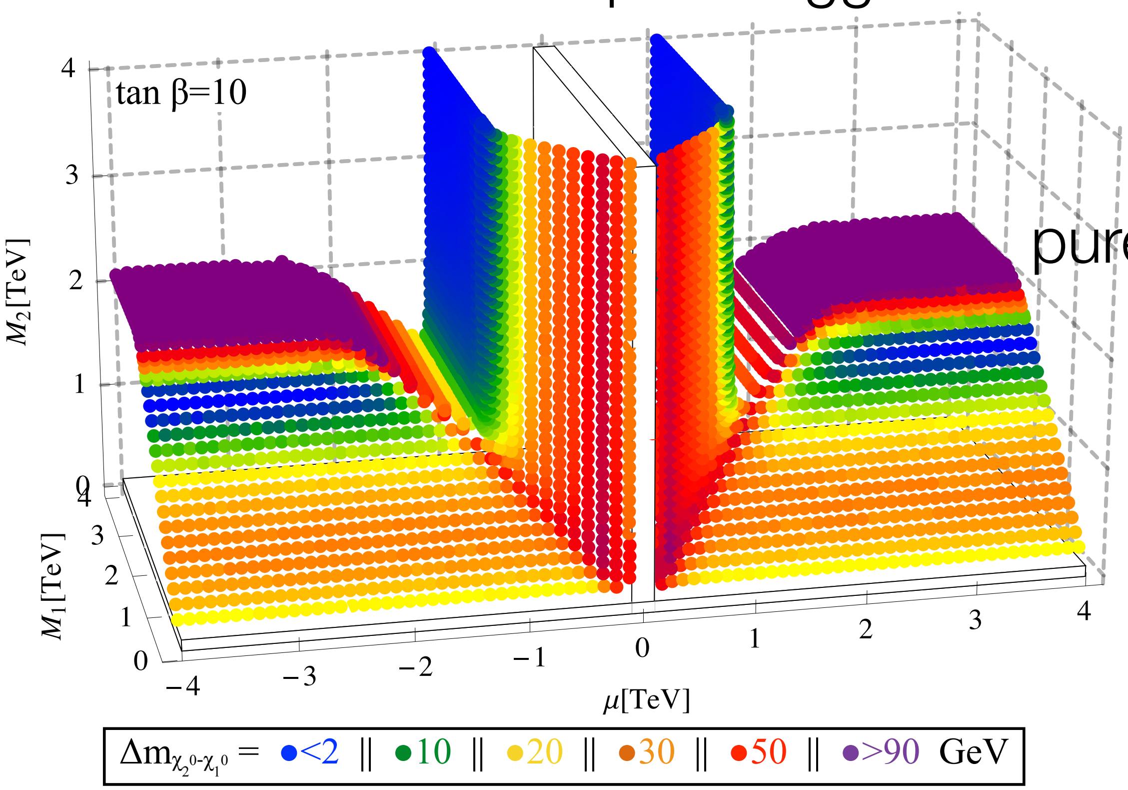
gluino co-annihilation: 8 TeV

If all scalar particles decoupled other than EWkinos $\tilde{B}, \tilde{W}, \tilde{H}$, EWkino sector parametrized by (M_1, M_2, μ)

requiring $\Omega_\chi h^2 = 0.12$ provides **“Relic neutralino surface”**

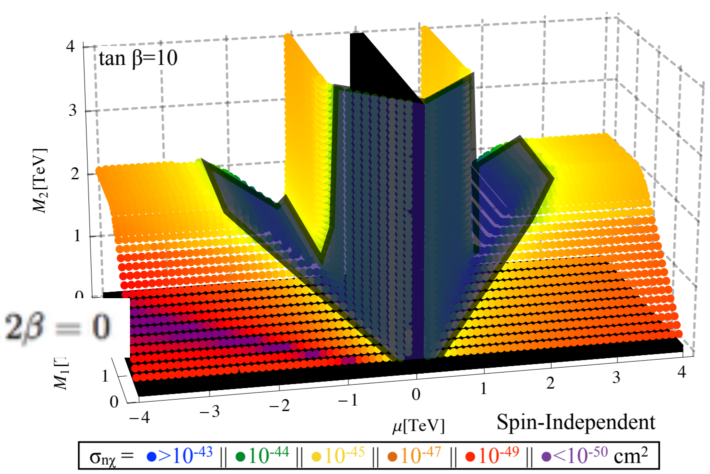
pure Higgsino DM

pure Wino DM



[J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell, MT]

DMDD SI constraints



$m_{\chi_1} + \mu \sin 2\beta = 0$

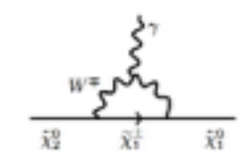
pure wino, higgsino, wino-bino mixture remain

mass difference always small

$m_{\chi_2^0} - m_{\chi_1^0}, m_{\chi_1^\pm} - m_{\chi_1^0}$ $\Delta m \lesssim 30$ GeV

EWkino search strategies at LHC depend on Δm

$\Delta m = m_{NLSP} - m_{LSP}$

$\Delta m > m_Z, m_W$	$\not{E}_T + 3\ell$	$\chi_2^0 \to \chi_1^0 Z, \chi_1^\pm \to \chi_1^0 W^\pm$
$0.2\text{GeV} < \Delta m < m_W$	$j^{\rm ISR} + \not{E}_T + 2^+\ell^{\rm soft}$ For the same trigger ISR jet pT, BG is more boosted.	$\chi_2^0 \to \chi_1^0 \ell^+\ell^-$ via Z^*  [Z. Han, G. Kribs, A. Martin, A. Menon]
	$\not{E}_T + 2^+\ell^{\rm soft} + \gamma$ $j^{\rm ISR} + \not{E}_T + \ell^{\rm soft} + \gamma$	$\chi_2^0 \to \chi_1^0 \gamma$ (1-loop)  [J. Bramante, A. Delgado, F. Elahi, A. Martin, B. Ostdiek] [C. Han, L. Wu, J-M. Yang, M. Zhang, Y. Zhang]
	$j^{\rm ISR} + \not{E}_T$ (mono-jet)	too soft decay products
$\Delta m < 0.2\text{GeV}$	Disappearing tracks $+j^{\rm ISR} + \not{E}_T$	long-lived $\chi^\pm$

more compressed

less powerful

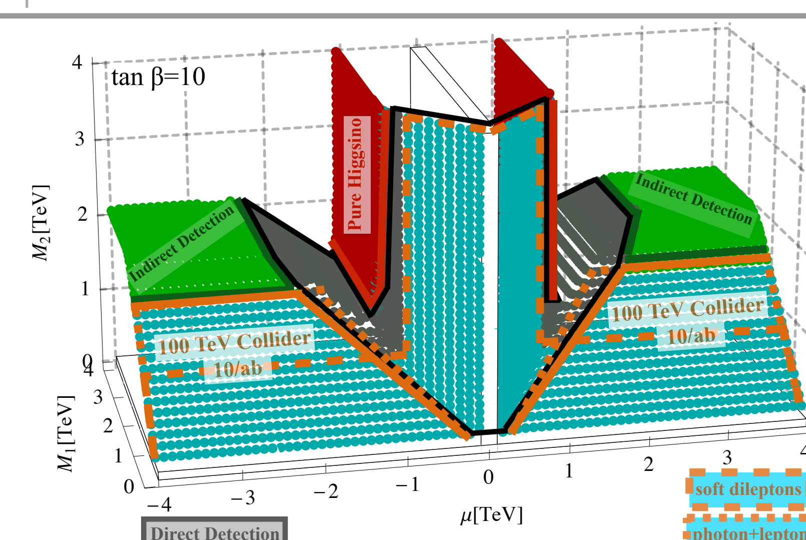
loose sensitivity

At 100TeV collider, Bino-Wino mixed case would be discovered at 5σ up to 1.5 TeV via $j^{\rm ISR} + \not{E}_T + 2^+\ell^{\rm soft}$

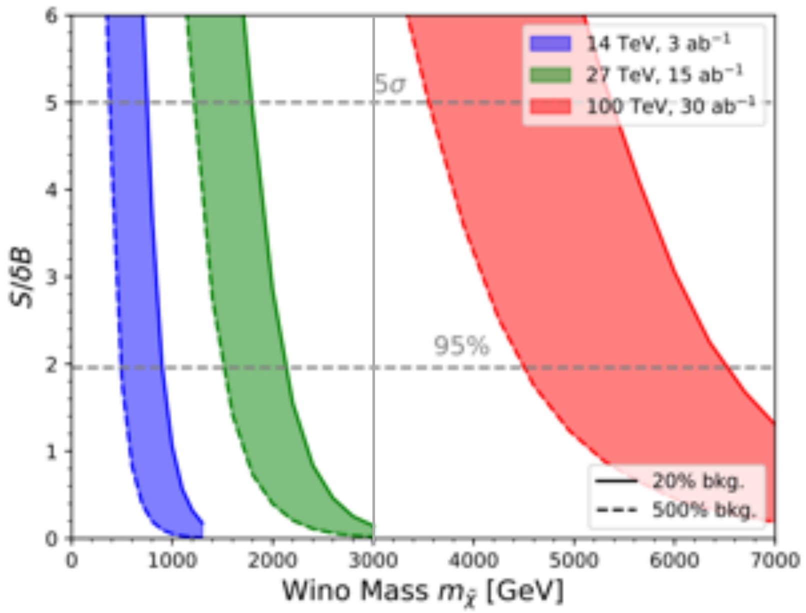
$j^{\rm ISR} + \not{E}_T + \ell^{\rm soft} + \gamma$

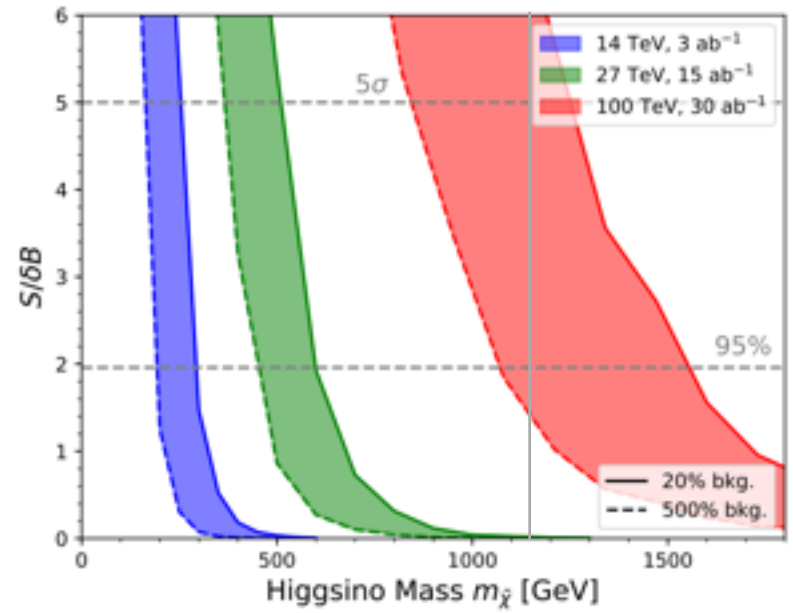
[J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell, MT]

pure-wino, pure-higgsino would rely on DT, and mono-jet



EWkino at HE-LHC (27TeV), 100 TeV collider

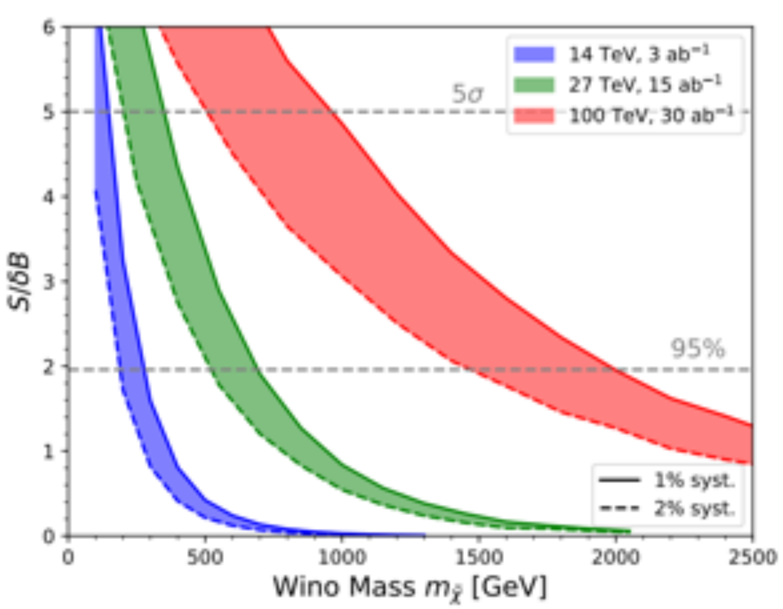


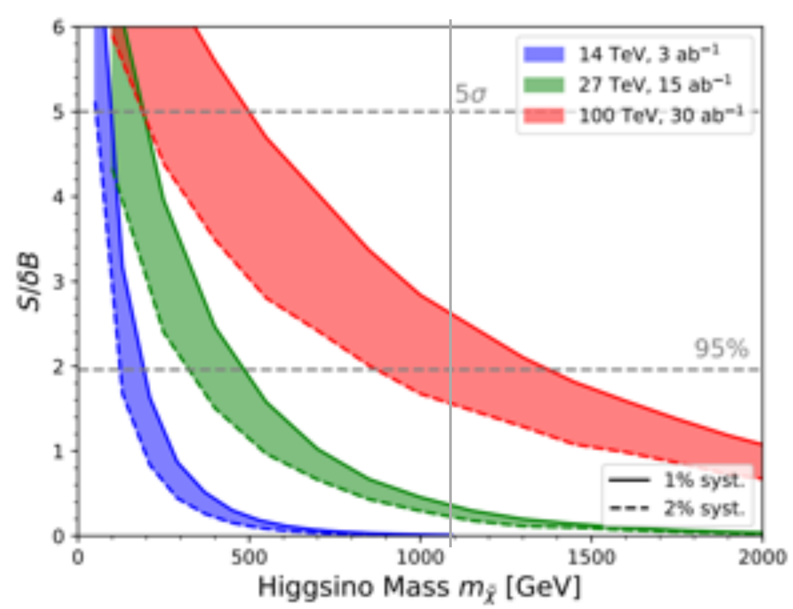


disappearing tracks

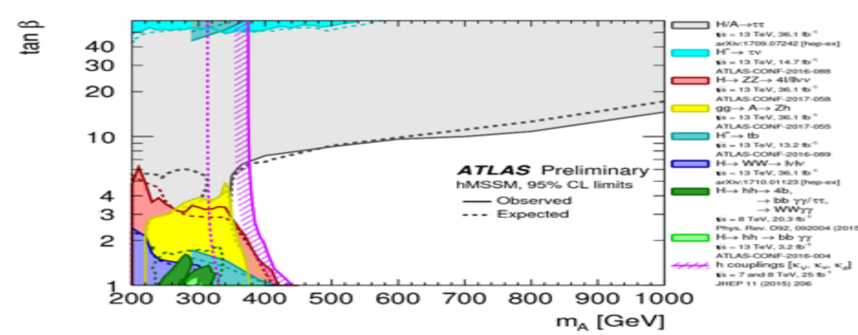
working group report
for prospect of HL-, HE-LHC
arXiv:1812.07831

at 100 TeV,
3 TeV wino detectable
1.1 TeV higgsino marginal



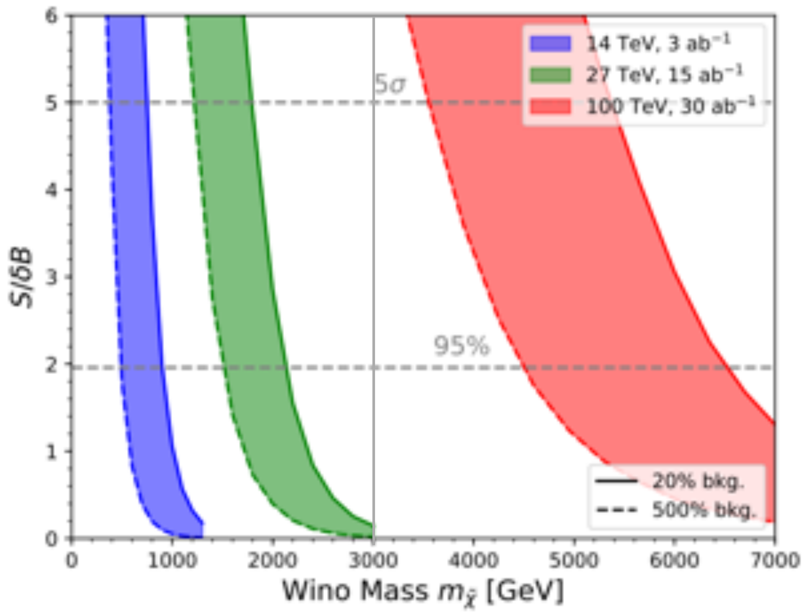


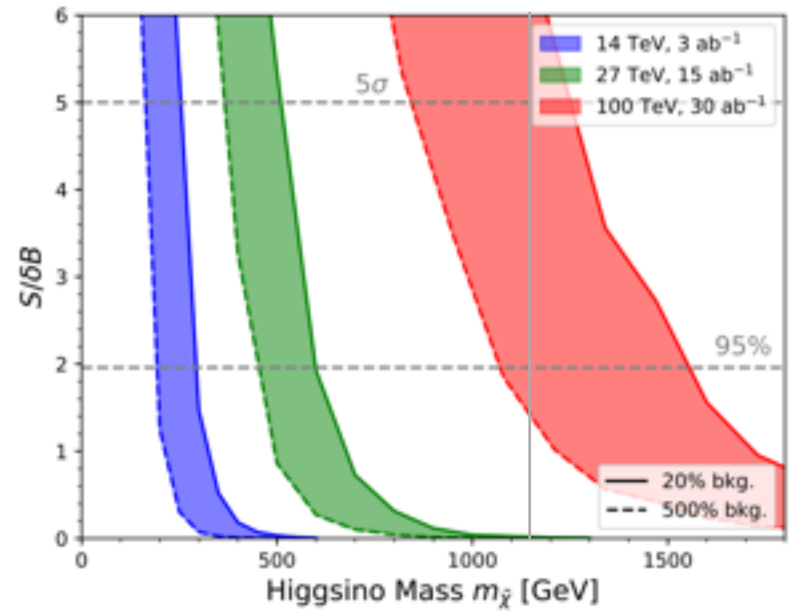
mono-jet searches



for wino-bino mixed case, DT is not usable
the sensitivity would be
better than mono-jet with soft-leptons

EWkino at HE-LHC (27TeV), 100 TeV collider



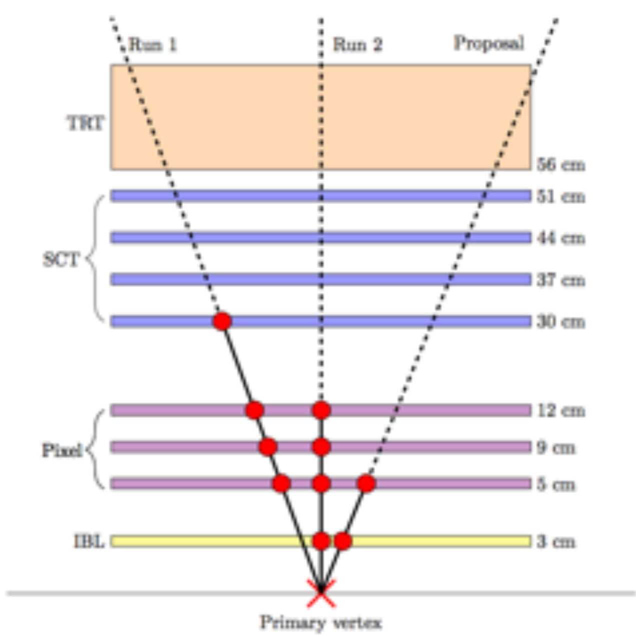


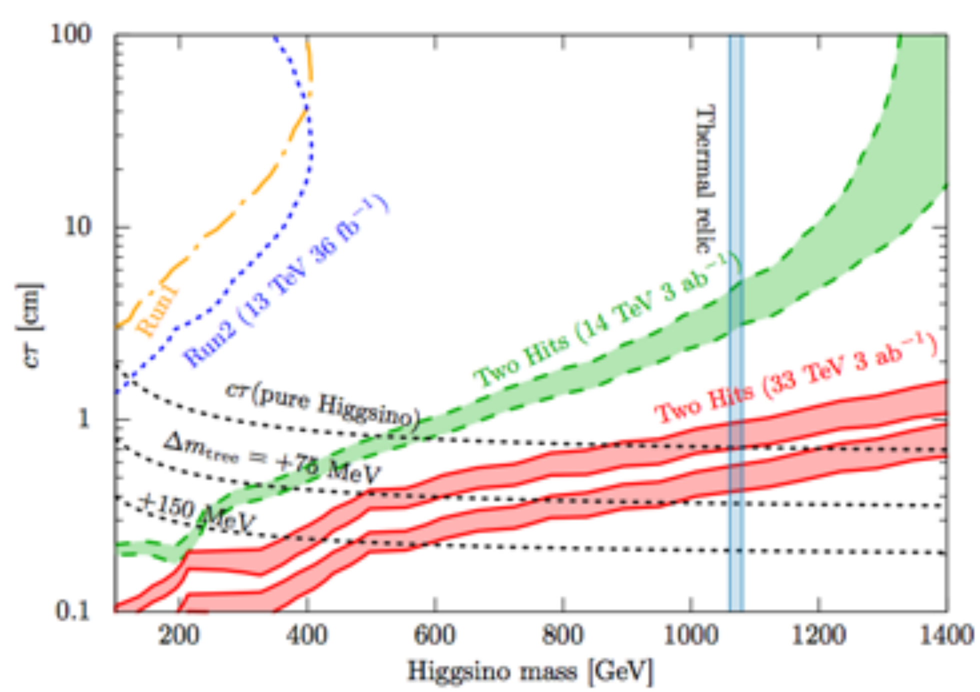
disappearing tracks

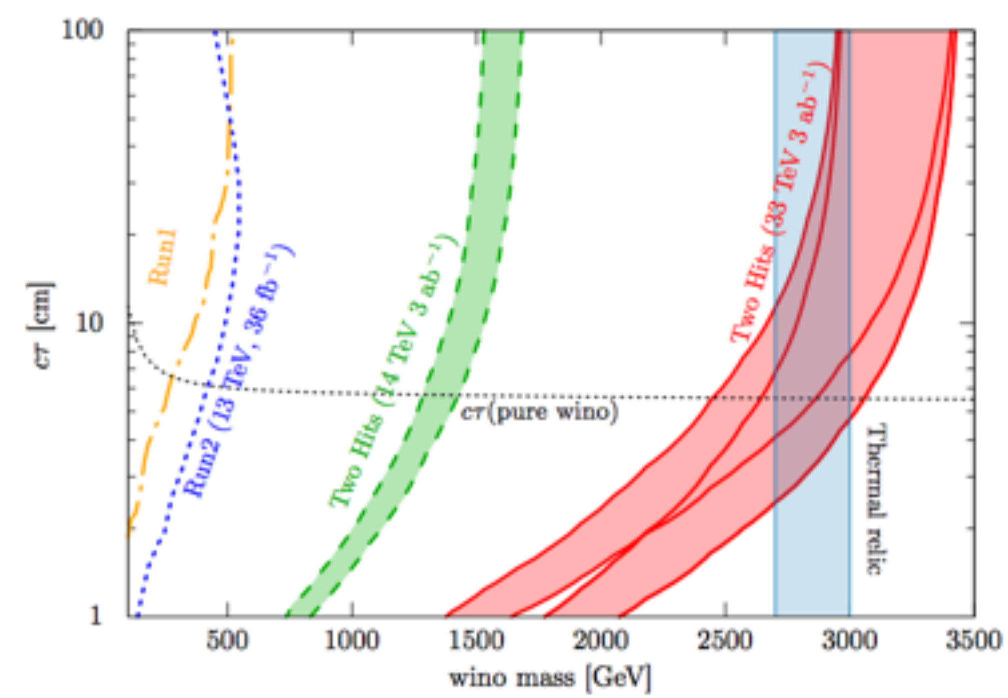
working group report
for prospect of HL-, HE-LHC
arXiv:1812.07831

at 100 TeV,
3 TeV wino detectable
1.1 TeV higgsino marginal

aggressive analysis (using two hit tracks) with tracker upgrade might enable HE-LHC can reach 1.1 TeV pure Higgsino by Disappearing Track searches [H. Fukuda N. Nagata, H. Otono, S. Shirai, arXiv:1703.09675]







appropriate detector design at future colliders is important to cover the pure higgsino

HL-LHCで何ができるか

2027~2038年: HL-LHC　⇒ 粒子が20倍生成される

1. 重い粒子が見つかる可能性
2. **分布の精度が上がる**
3. 稀崩壊の感度が上がる

Higgs Factory

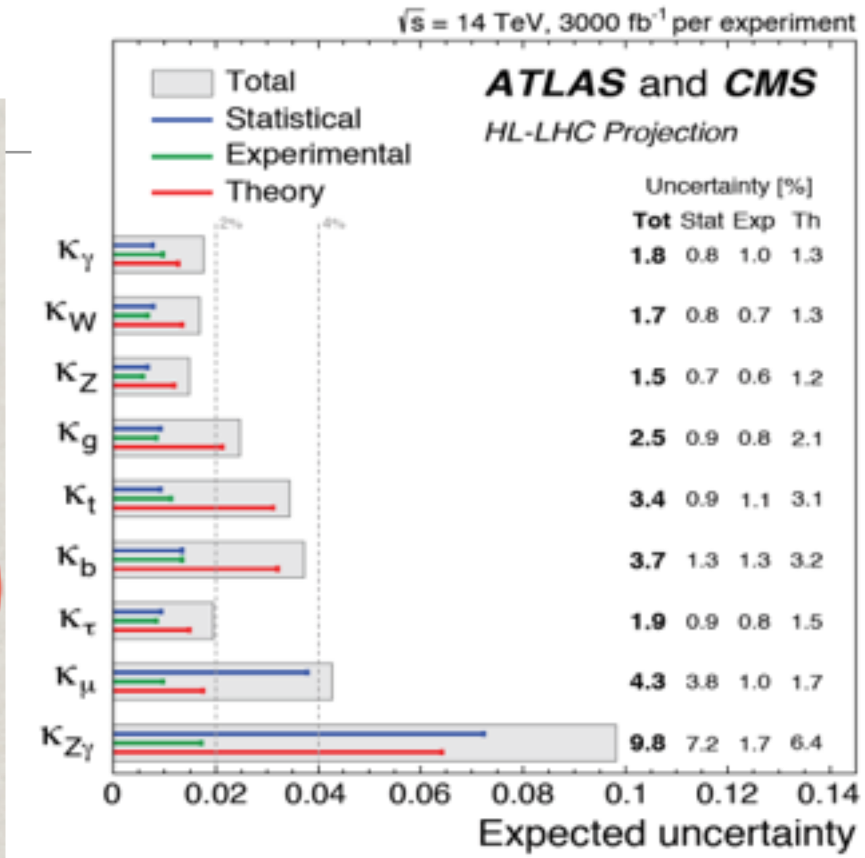
~2-4 % precision expected

~2.5 % BR(invisible) (13% at 139fb-1)

(A). HL-LHC **will be** a Higgs factory:

$pp \to H + X$ at $\sqrt{s} = 14$ TeV for $m_H = 125$ GeV

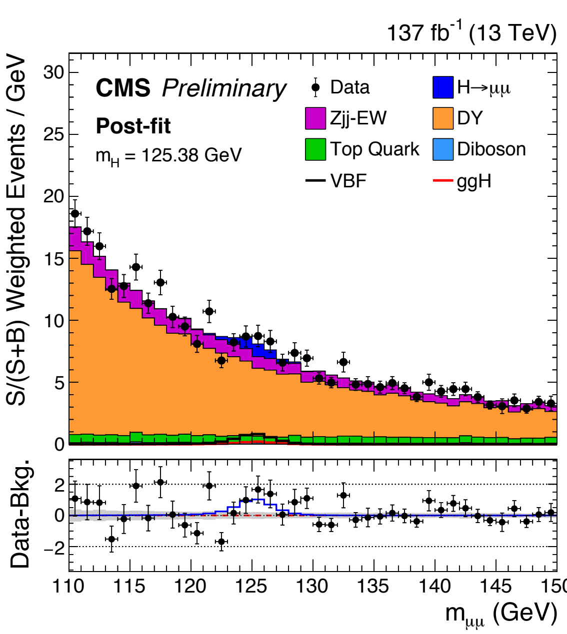
	ggF	VBF	VH	$t\bar{t}H$	Total
Cross section (pb)	49.9	4.18	2.38	0.611	57.1
Numbers of events in 3000 fb^{-1}					
$H \to \gamma\gamma$	344,310	28,842	16,422	4,216	393,790
$H \to ZZ^* \to 4\ell$	17,847	1,495	851	219	20,412
$H \to WW^* \to \ell\nu\ell\nu$	1,501,647	125,789	71,622	18,387	1,717,445
$H \to \tau\tau$	9,461,040	792,528	451,248	115,846	10,820,662
$H \to b\bar{b}$	86,376,900	7,235,580	4,119,780	1,057,641	98,789,901
$H \to \mu\mu$	32,934	2,759	1,570	403	37,667
$H \to Z\gamma \to \ell\ell\gamma$	15,090	1,264	720	185	17,258
$H \to$ all	149,700,000	12,540,000	7,140,000	1,833,000	171,213,000

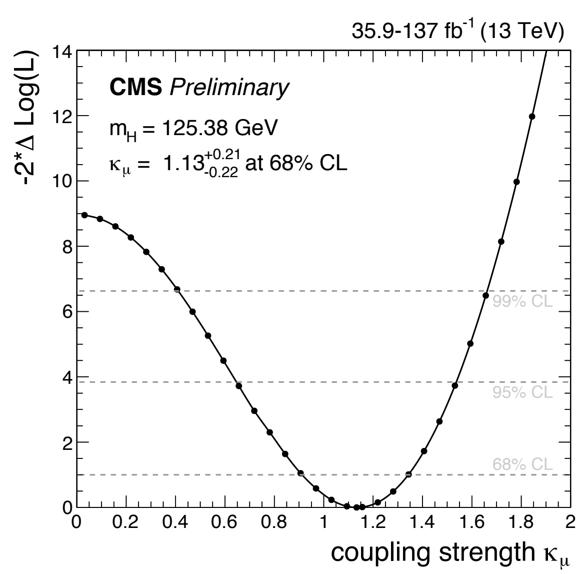


Projected uncertainties on κ_i, combining ATLAS and CMS: total (grey box), statistical (blue), experimental (green) and theory (red).

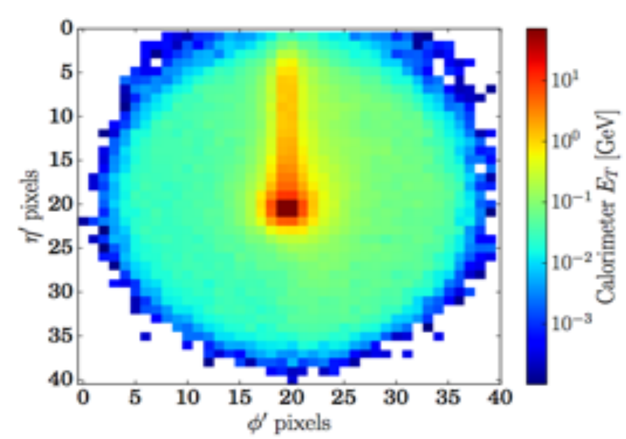
CMS-PAS-HIG-19-006

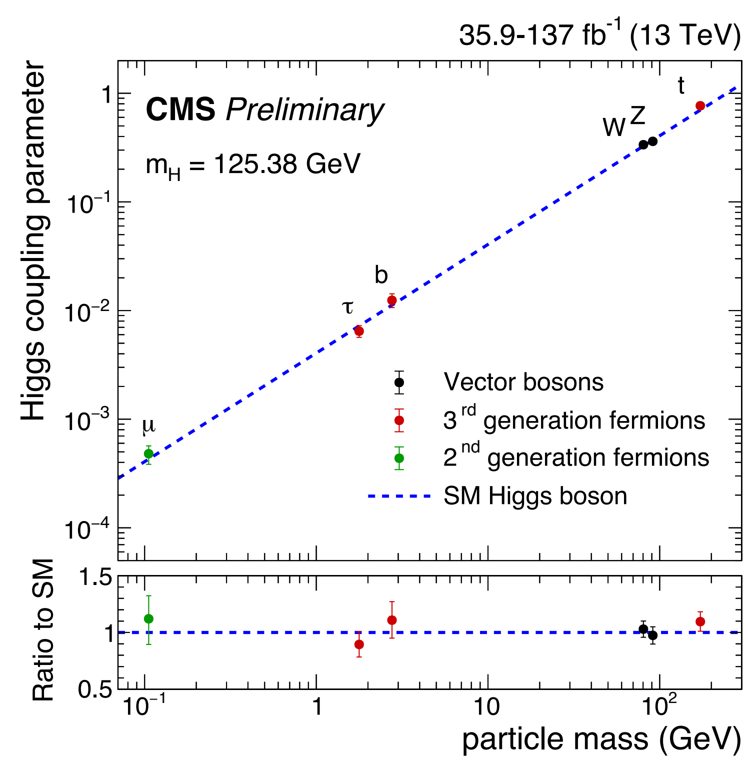
muon yukawa evidence has been achieved !





arXiv:2007.07830





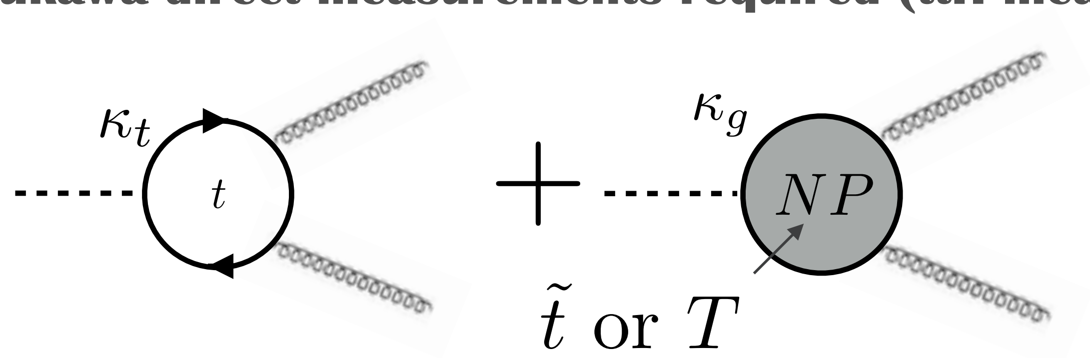
top partner indirect searches

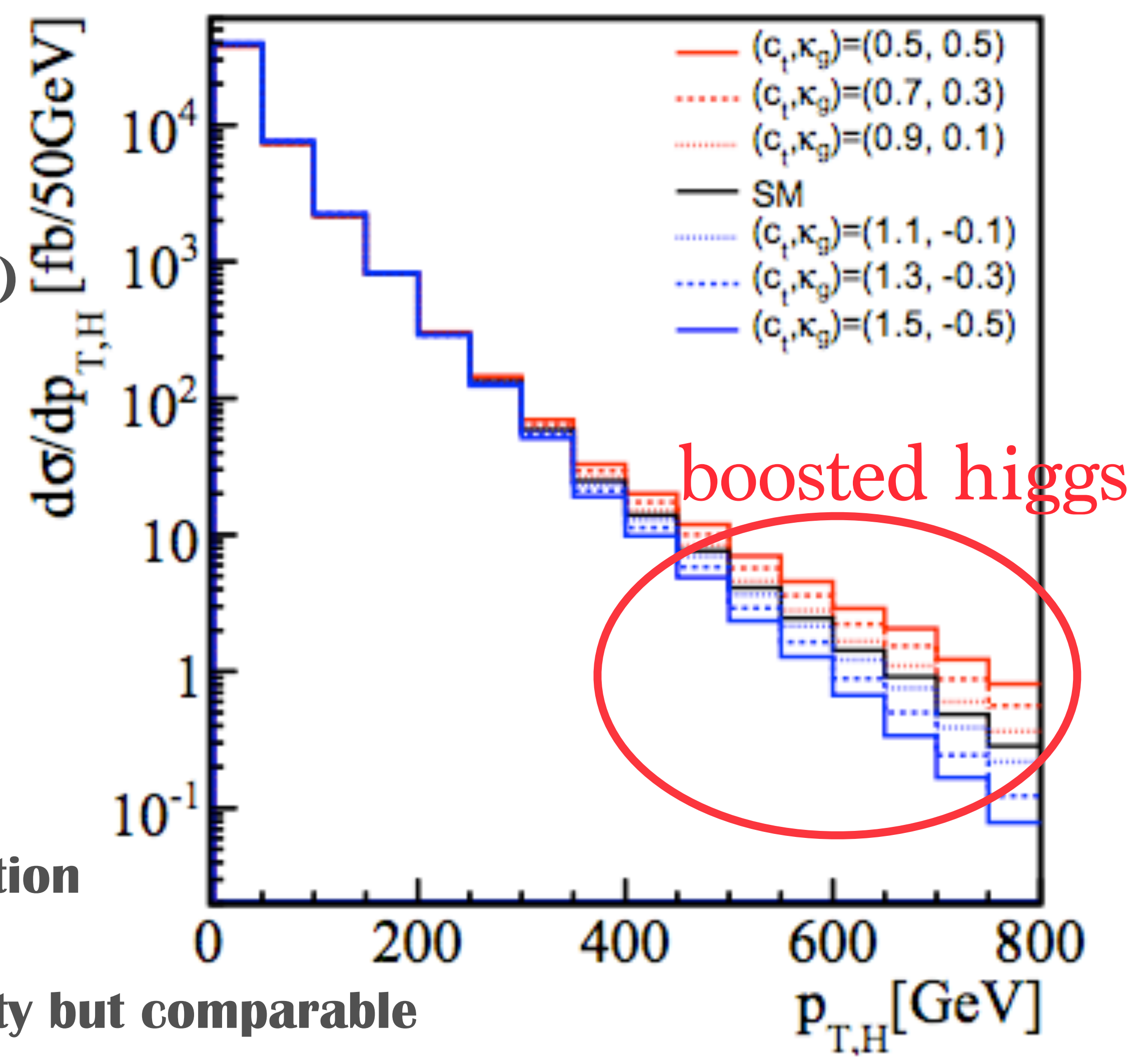
ggH coupling: most important for Higgs production, by top-loop
higgs cross section $\Rightarrow$ top yukawa indirect measurement

Eur.Phys.J. C74 (2014) no.10, 3120
[M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant]

However, if top-partner exists, we cannot distinguish top-partner loop effects from top-loop effects

to solve the degeneracy,
top yukawa direct measurements required (ttH measurements)





different momentum dependence
$\Rightarrow$ we can solve the degeneracy using Higgs pT distribution
we estimated the sensitivity at LHC
complimentary to ttH measurement, weaker sensitivity but comparable

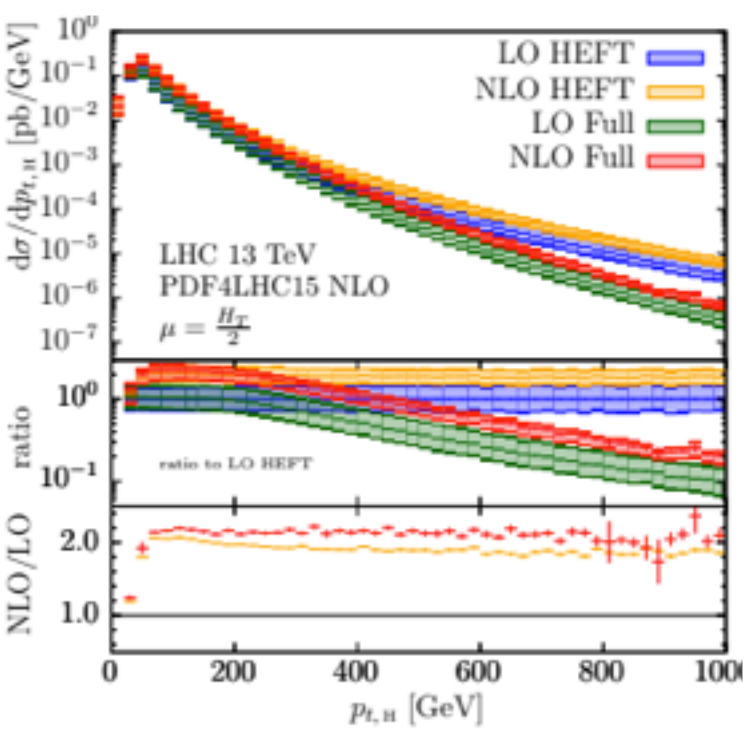
Higgs： $50\ \text{pb} \times 3 \cdot 10^3 \text{fb}^{-1} \sim 10^8$

one of good examples of precision physics, which the overwhelming high statistics at LHC makes possible

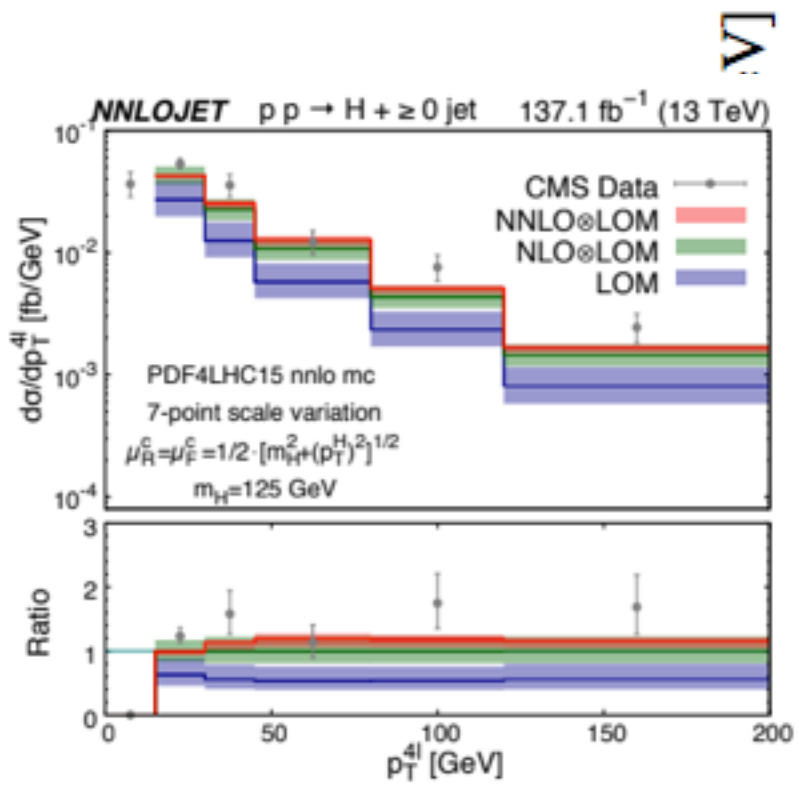
top partner indirect searches

Eur.Phys.J. C74 (2014) no.10, 3120
[M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant]

[Jones, Kerner, Luisoni]
arXiv:1802.00349

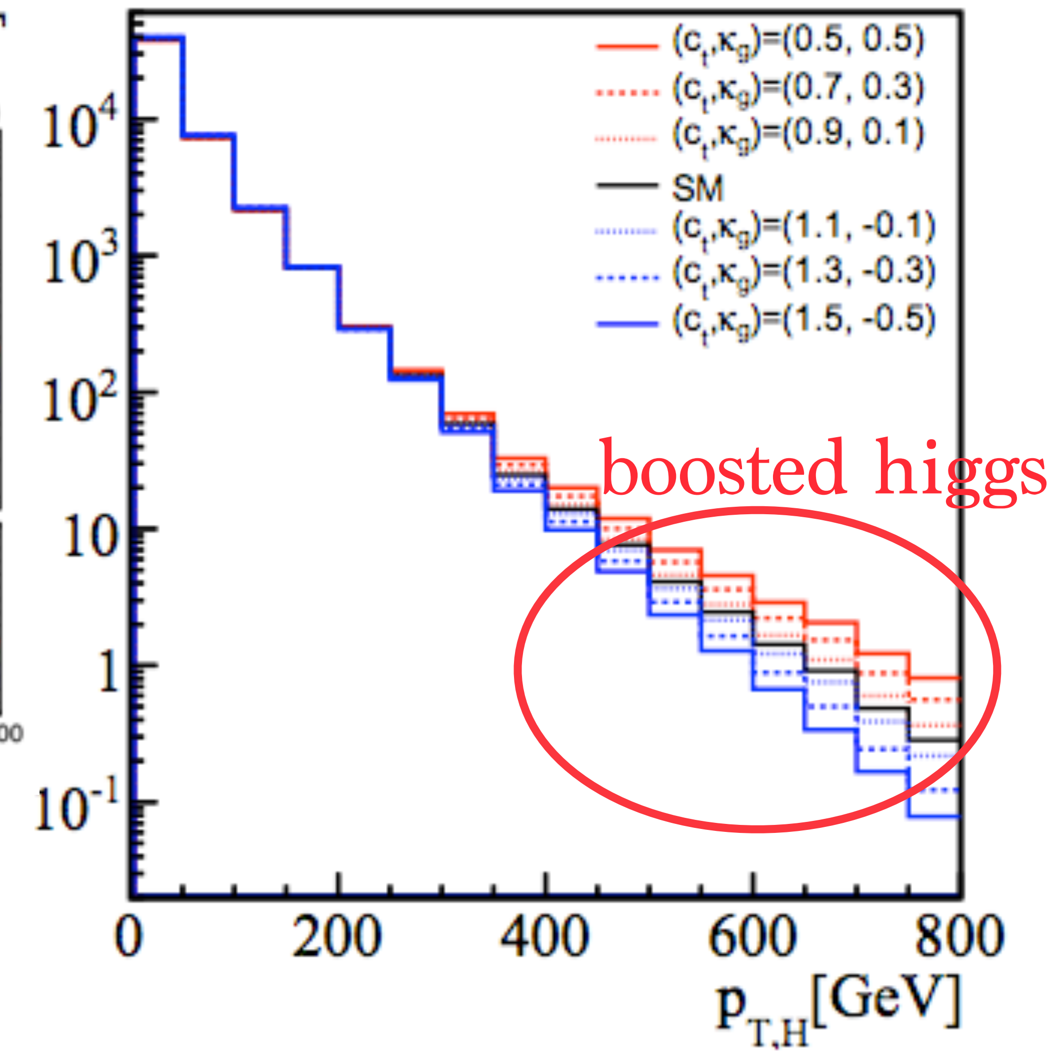


finite mt effects
important also in NLO



NNLO QCD for 2 to 2 process
[Chen, Gehrmann, Glover, Huss]

arXiv:1905.13738

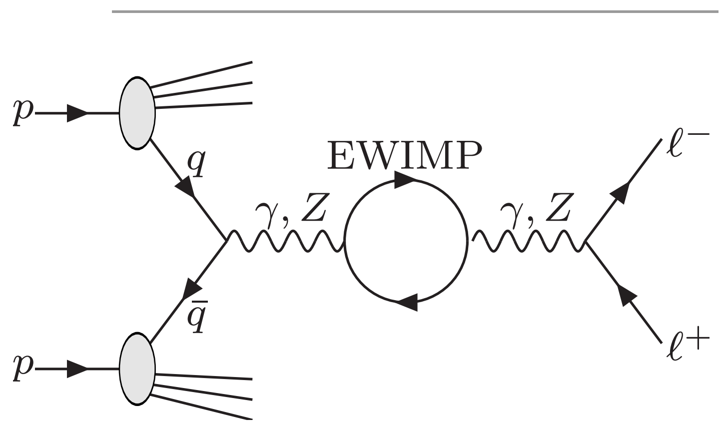


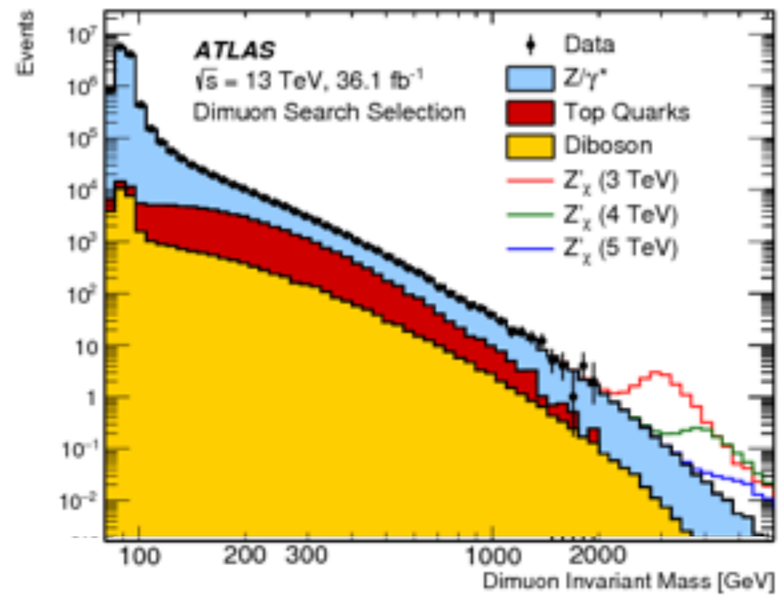
Higgs： $50\ \mathrm{pb} \times 3 \cdot 10^3 \mathrm{fb}^{-1} \sim 10^8$

one of good examples of precision physics, which the overwhelming high statistics at LHC makes possible

EWkino search via loop at HL-LHC and future colliders

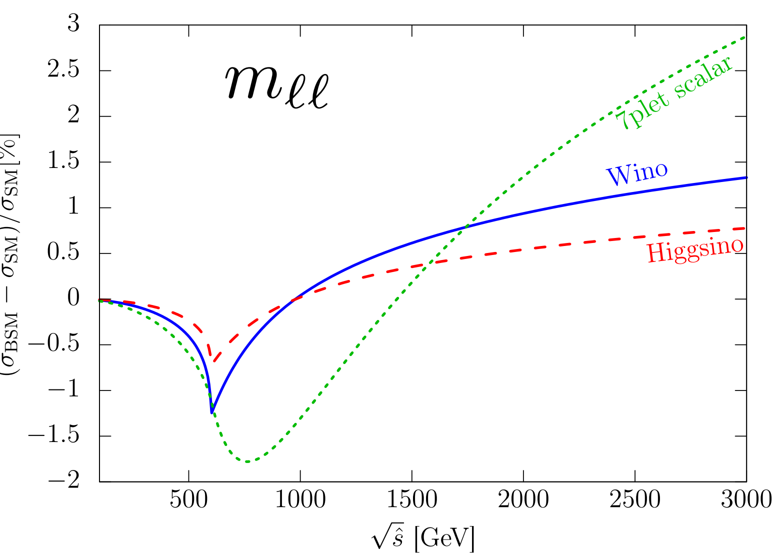
[S. Matsumoto, S. Shirai, MT] JHEP 1806 (2018) 049
[S. Matsumoto, S. Shirai, MT] JHEP 1903 (2019) 076
[L. D. Luzio, R. Gröber, G. Panico] JHEP 1901 (2019) 011

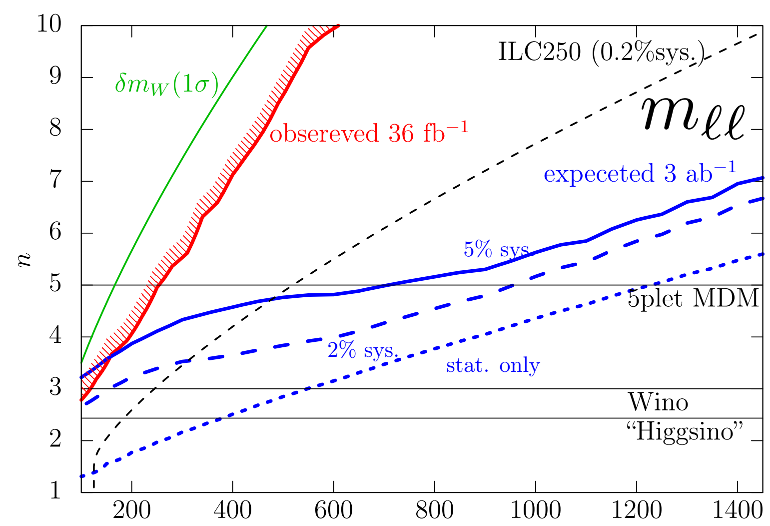




di-lepton/mT distribution via DY production
very large statistics available

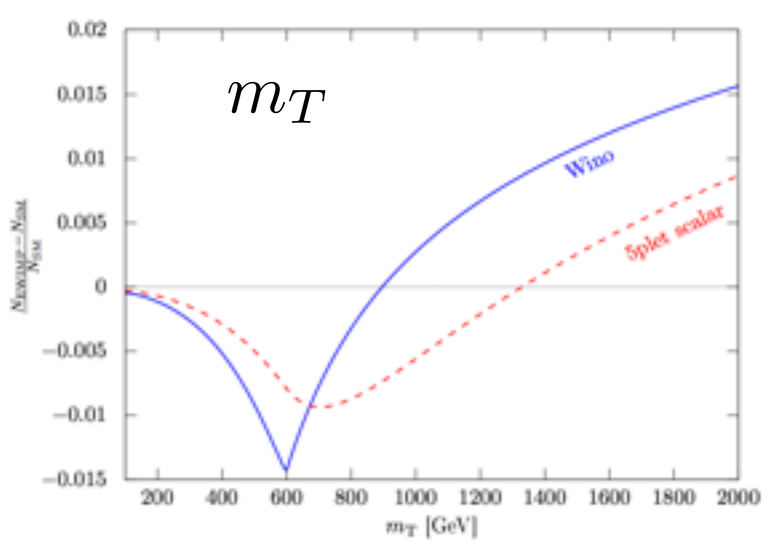
Due to signal-BG interference,
O(1%) dip-peak structure expected at 2m

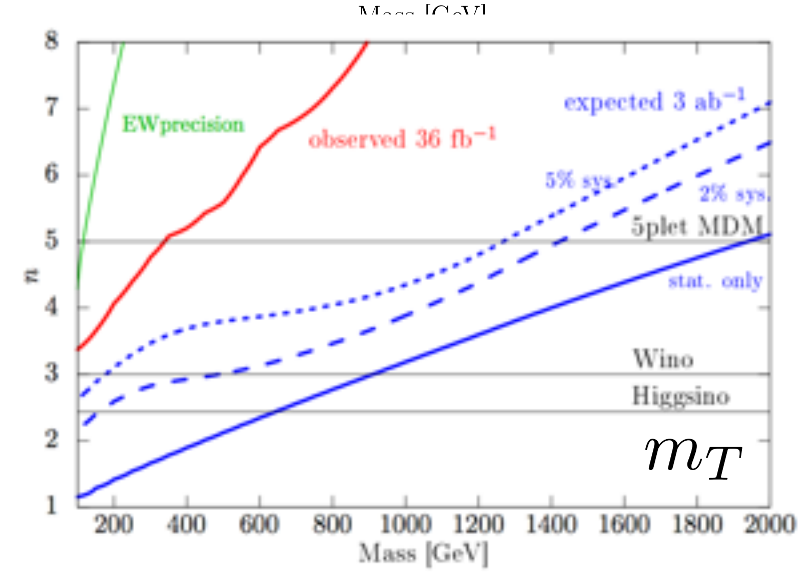


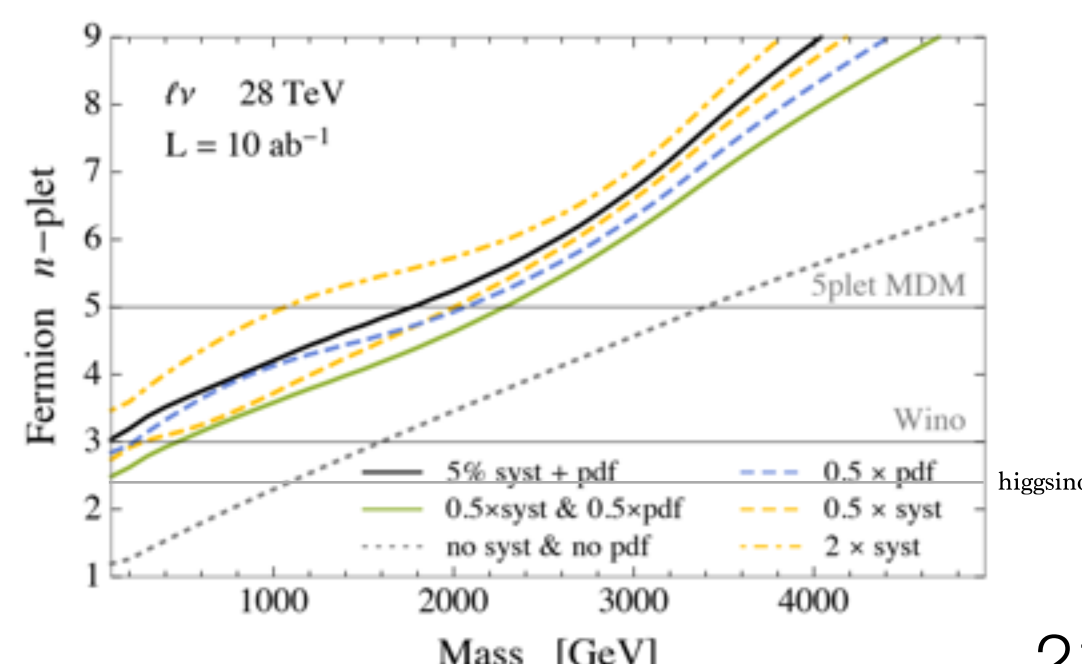


At HL-LHC, it might be sensitive
to a light Higgsino for optimistic cases

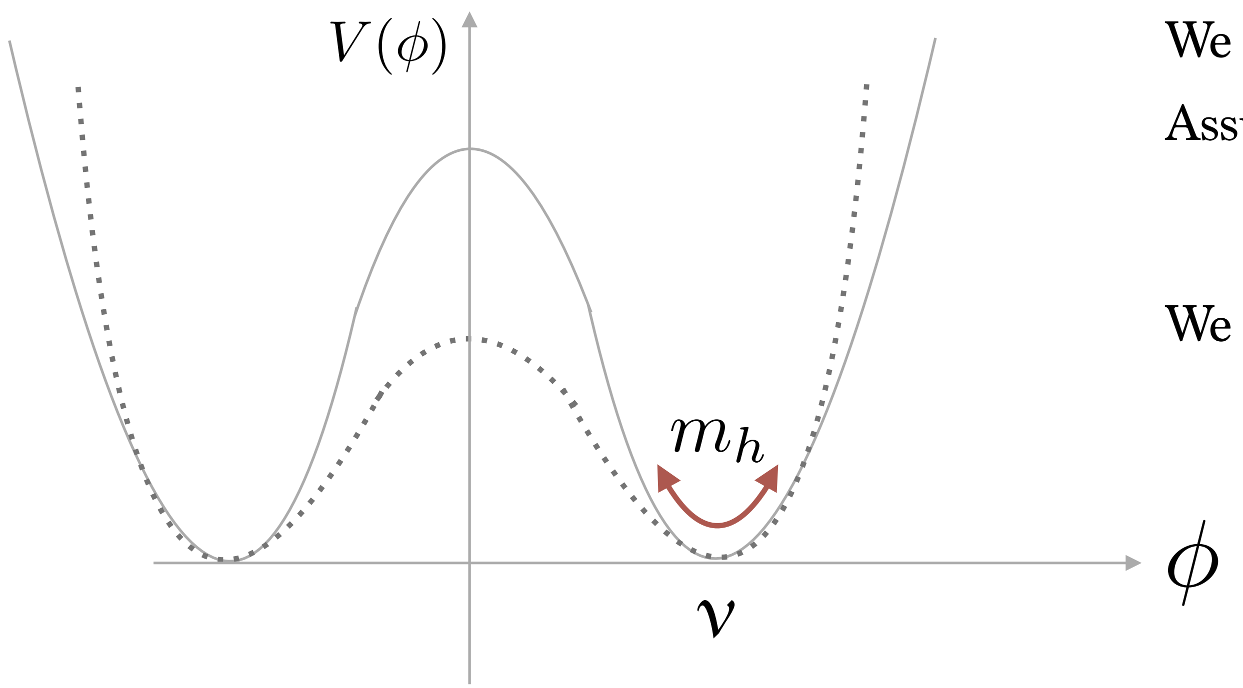
At HE-LHC, 1TeV Higgsino accesible
with no sys. uncertainty







Higgs potential shape



We know the local structure around the VEV (v and mh)

Assuming the simple potential V(Φ)= $\lambda\phi^4 + \mu\phi^2$

$$V(h) = \frac{\lambda}{4}h^4 + \lambda v h^3 + \cdots = \frac{\lambda_4}{4!}h^4 + \frac{\lambda_3}{3!}h^3 +$$

We should have the relation

$$\lambda_4 = 6\lambda$$

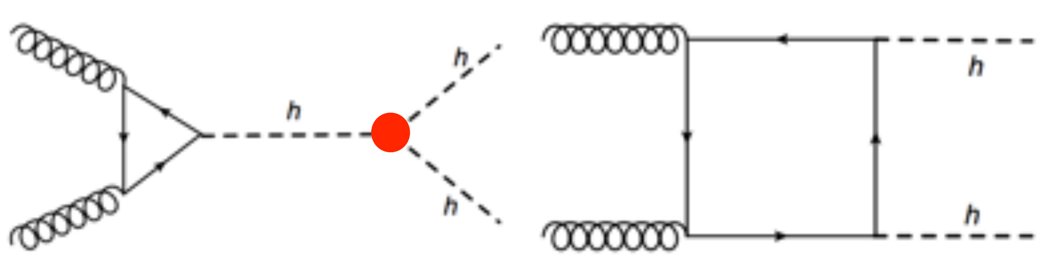
$$\lambda_3 = 6\lambda v = \frac{3m_h^2}{v} \qquad \lambda_{\rm SM} \approx 1/8.$$

EW Baryogenesis : strong 1st phase transition required
⇒ 50-70% deviation in Higgs triple coupling

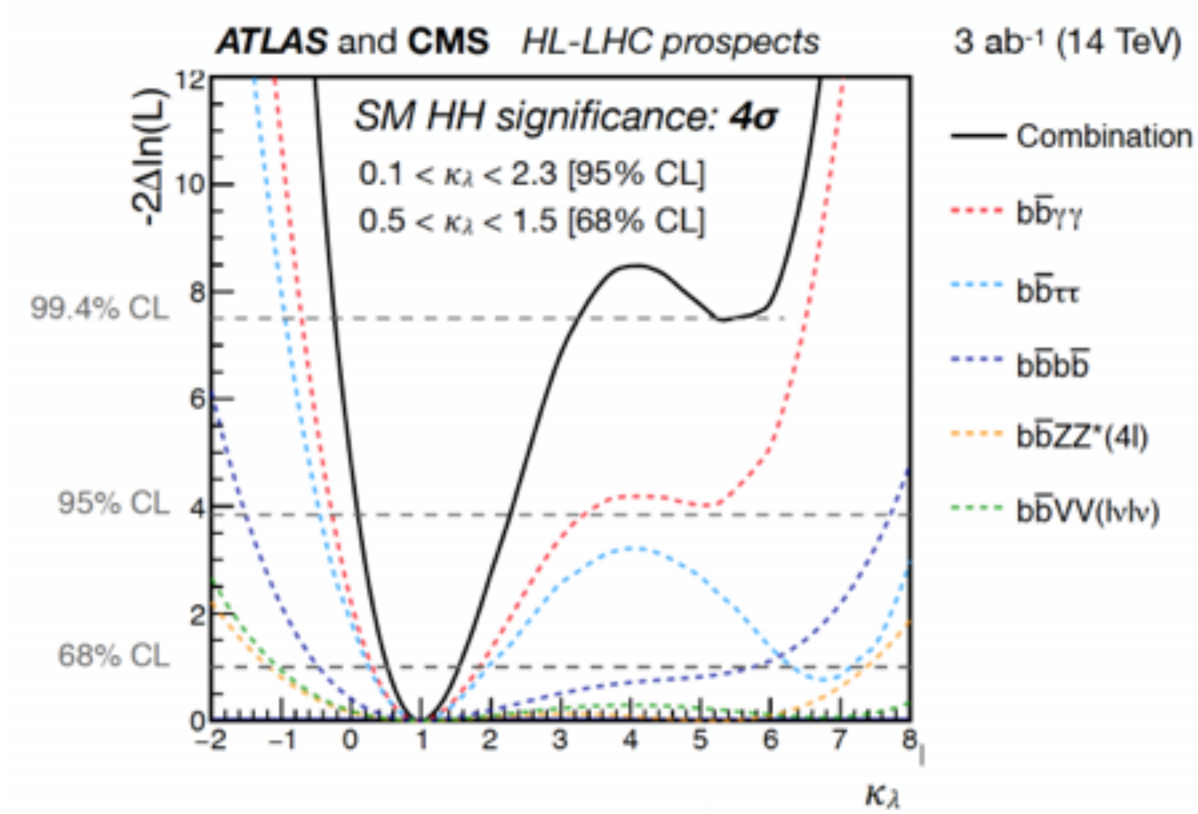
$$\lambda_3 = \frac{3m_h^2}{v} + \frac{6v^3}{\Lambda^2} \gtrsim 1.7\lambda_{3,\rm SM}$$

[C. Grojean, G. Servant, J. Wells]

HH pair production



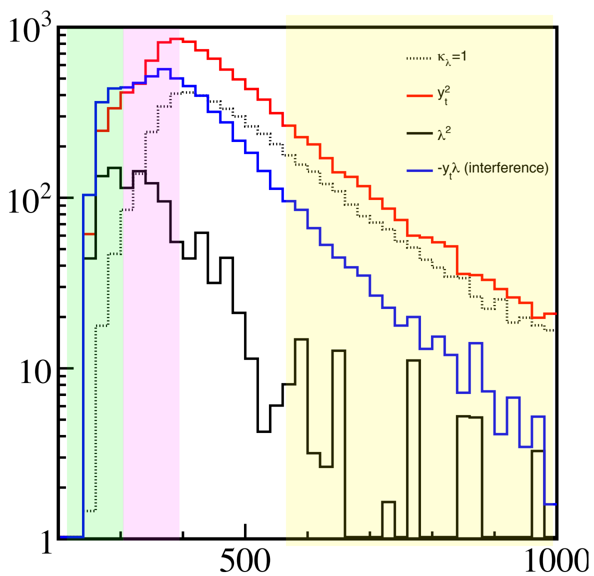
bbγγ mode is best channel

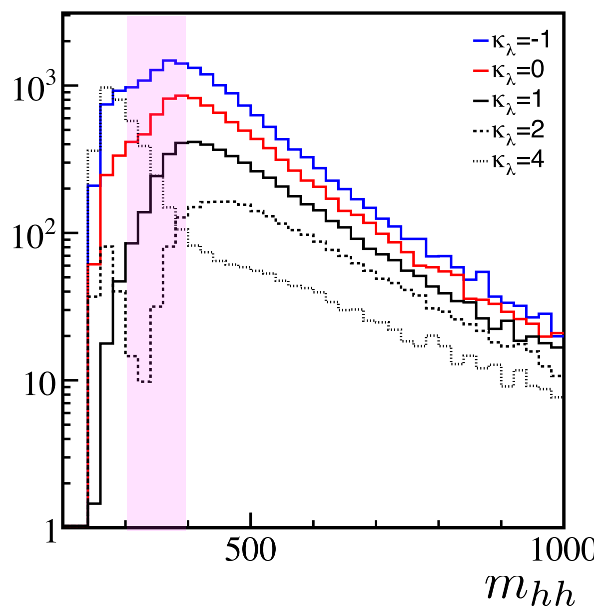


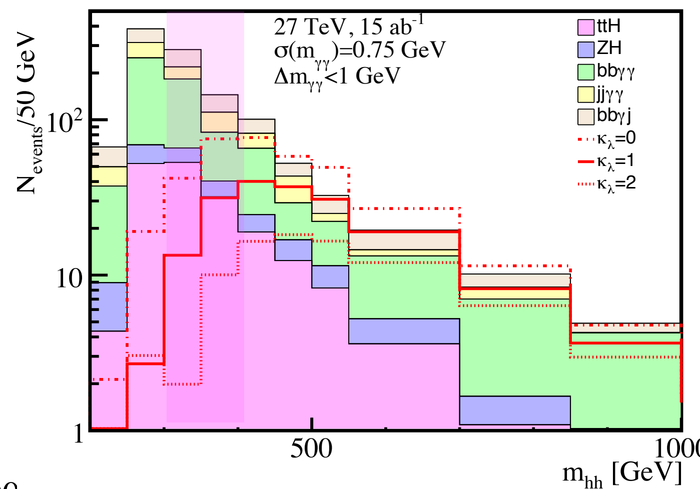
50% measurement is not enough to judge EWBG

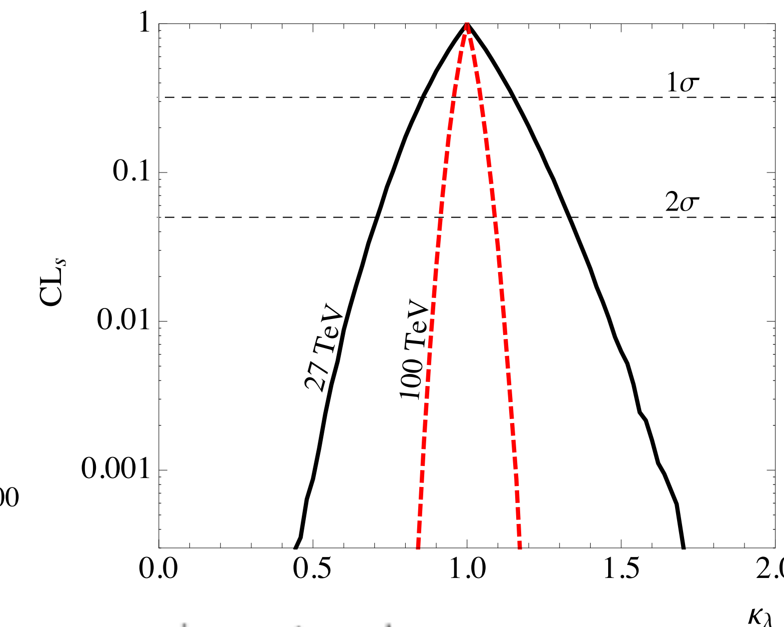
study for future colliders

D. Goncalves, T. Han, F. Kling, T. Plehn, MT
[Phys. Rev. D 97, 113004 (arXiv:1802.04319)]







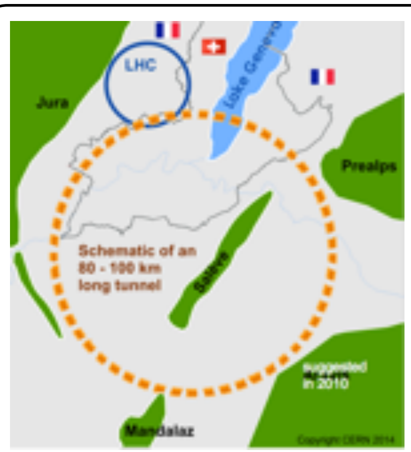


in event numbers

14 TeV $\xrightarrow{\times 20}$ 27 TeV $\xrightarrow{\times 20}$ 100 TeV

HL–LHC sensitivity 50% ⇔ HE-LHC (27TeV) 15% (100TeV: 5%)

We first in the world estimate the sensitivity at 27TeV (including ISR-jet effects) :
important input for the future decision making



CERN/China future colliders

HE-LHC: 27 TeV 2040〜

FCC : 100TeV 2043〜

(late 2017, energy of HE option is determined as 27TeV)

at some point we have to decide either way,
study needed for the decision making important

EW Baryogenesis : strong 1st phase transition required
⇒ 50-70% deviation in Higgs triple coupling

whether we can exclude ? (question to answer yes-no)
We have shown 27TeV would be enough to answer it

HL-LHCで何ができるか

2027~2038年: HL-LHC　⇒ 粒子が20倍生成される

1. 重い粒子が見つかる可能性
2. 分布の精度が上がる
3. **稀崩壊の感度が上がる**

top factory

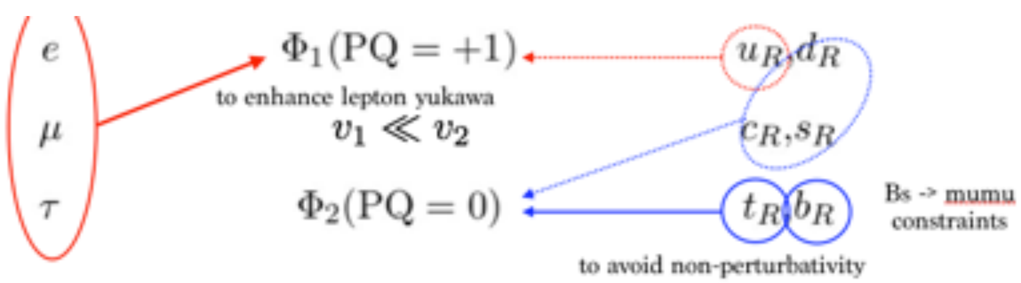
Top pair copiously produced : 1nb x 3ab^{-1}= 3 x 10^{9} pairs

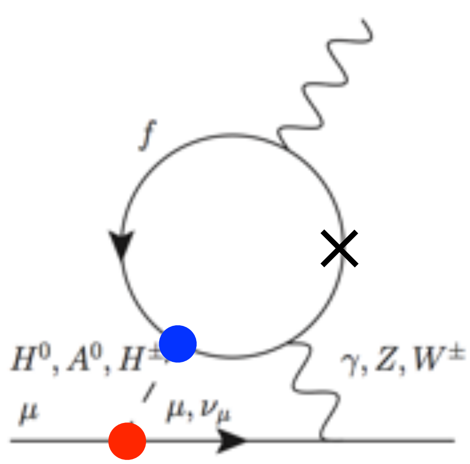
Top FCNC 95%C. L. reach at 3ab^{-1}

$t \to gu$	$t \to gc$	$t \to qZ$	$t \to \gamma u$	$t \to \gamma c$	$t \to Hq$
3.8×10^{-6}	3.2×10^{-5}	$2.4 - 5.8 \times 10^{-5}$	8.6×10^{-6}	7.4×10^{-5}	10^{-4}

We consider very light pseudo-scalar A in a variant axion model to explain muon g-2. (u-type lepton-specific 2HDM)

[arxiv:1807.00593, C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]

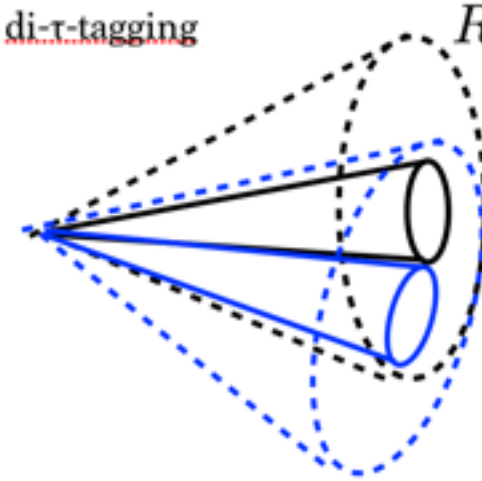




$\propto m_\mu m_f^2/m_H^2$

boosted A → ττ from top decays

di-τ-tagging

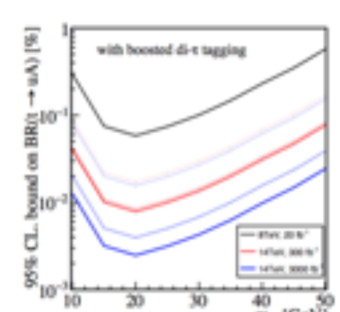


mutual isolation

[A. Katz, M. Son, B. Tweedie, PRD 83, 114033(2011).]

if core 1 is removed, the rest is τ-tagged

if core 2 is removed, the rest is also τ-tagged



For mA=15GeV

$BR(t \to uA)$ < 0.08%

(10% by CMS study)

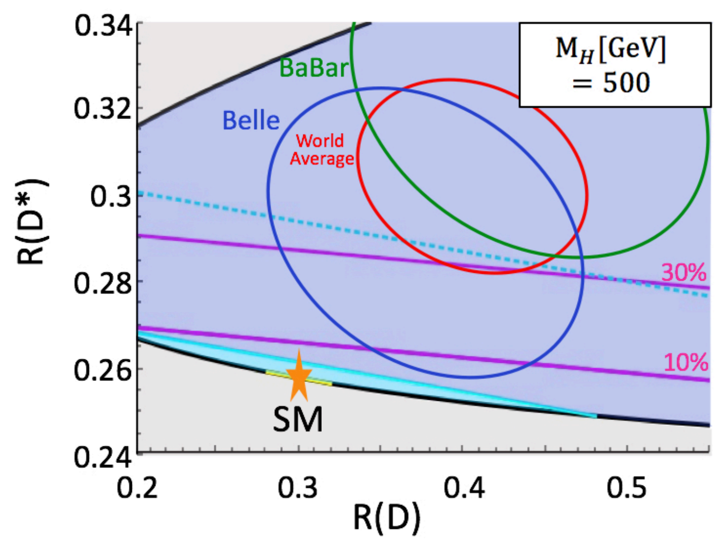
0.003-0.01% in future

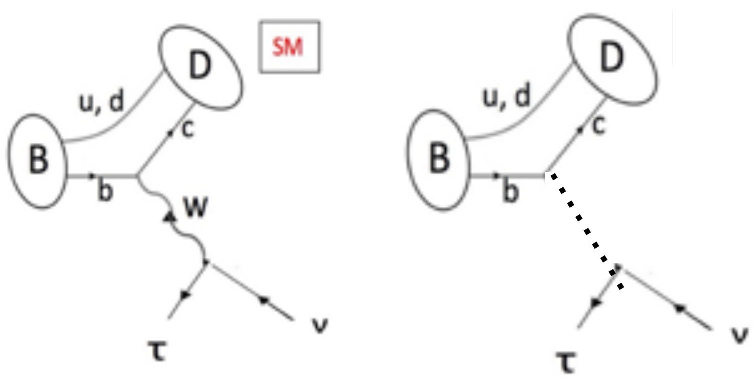
test of flavor anomaly at LHC

Syuhei Iguro (Nagoya U.), Yuji Omura (KMI, Nagoya), MT
arXiv:1810.05843

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

∼3-4σ deviation reported

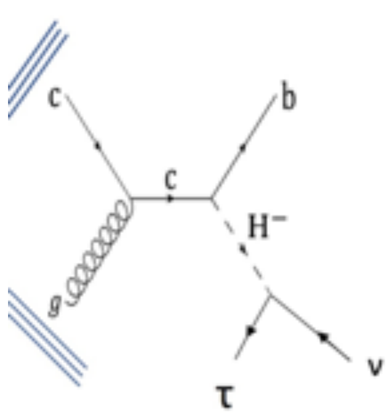


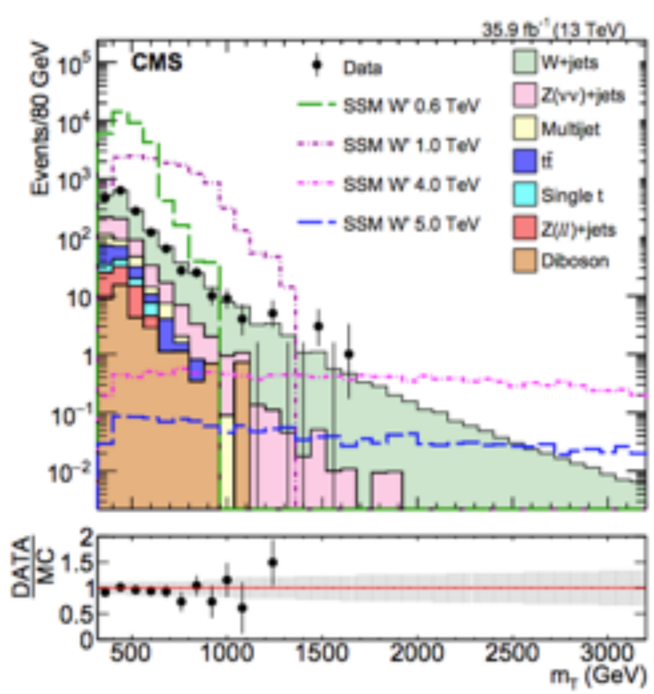


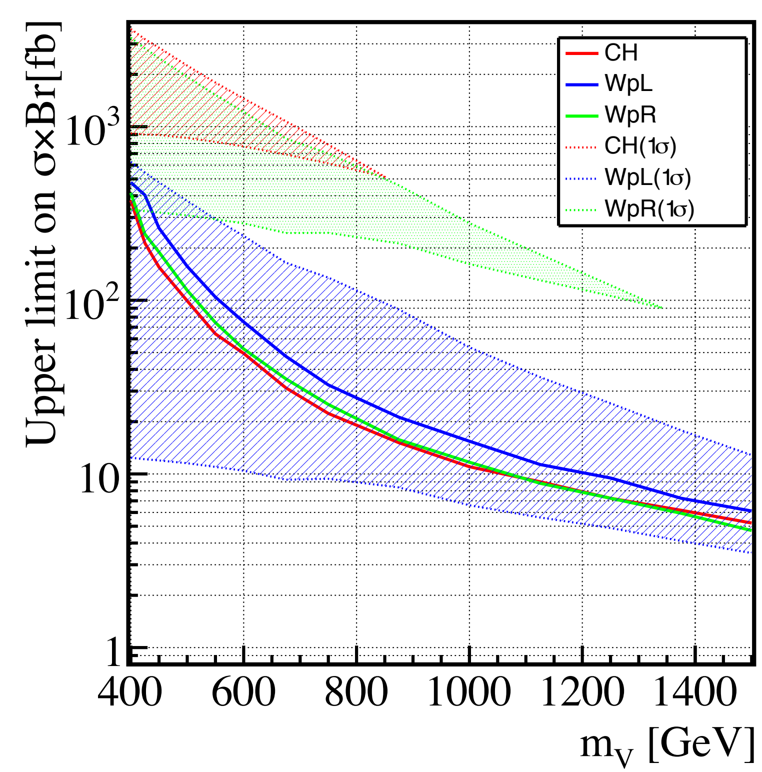
charged higgs can solve it

constrained by $BR(B_c \to \tau\nu)$ but large uncertainty

At LHC τν searches already set stronger bound for such a charged higgs





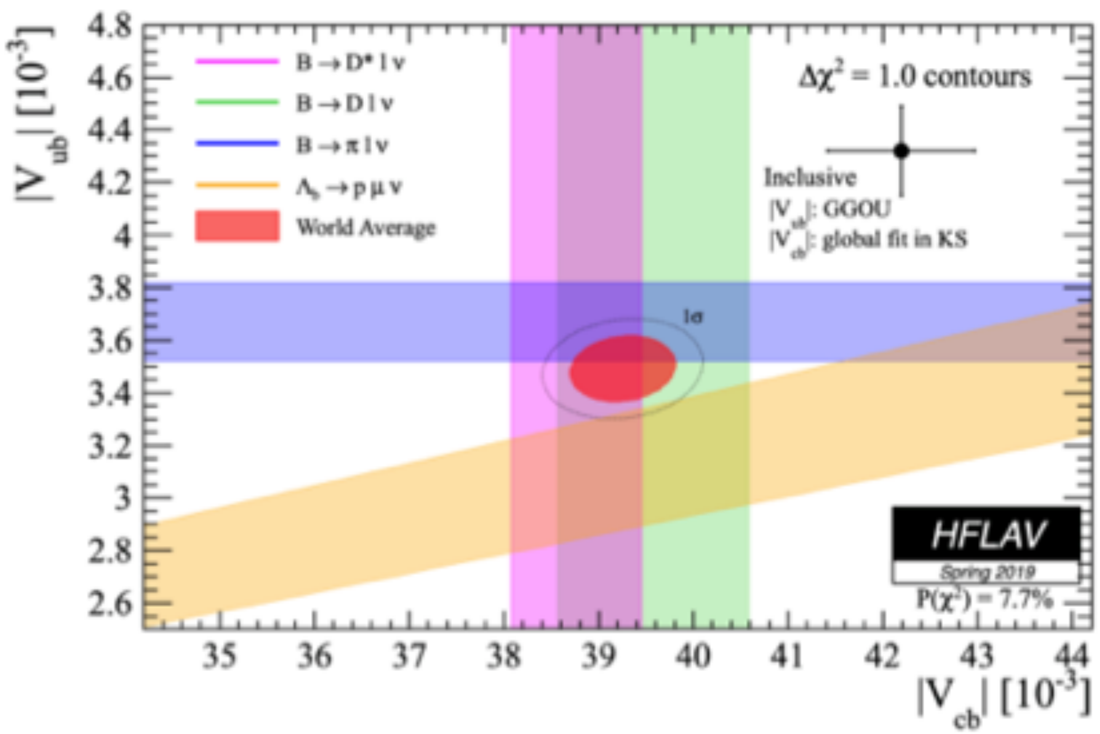


test of flavor anomaly at LHC

S. Iguro, , MT, R. Watanabe [arXiv:20XX.XXXXX to appear]

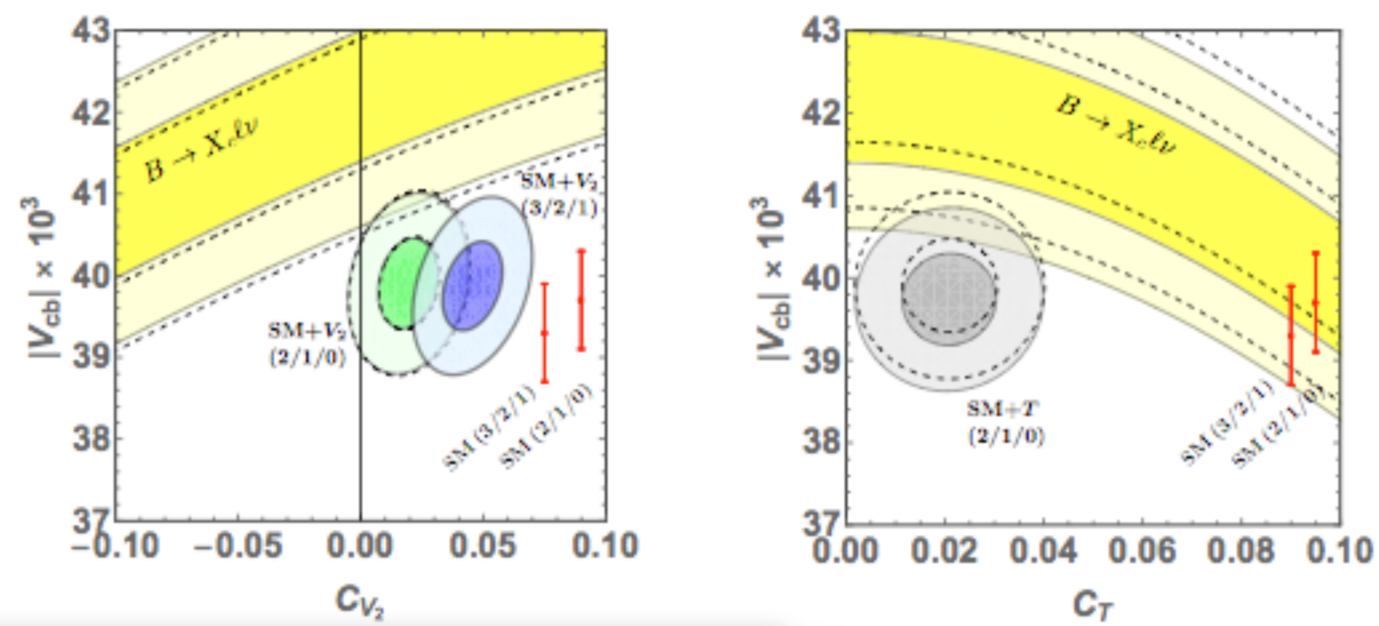
Vub, Vcb determinations from exclusive, inclusive analyses have discrepancy

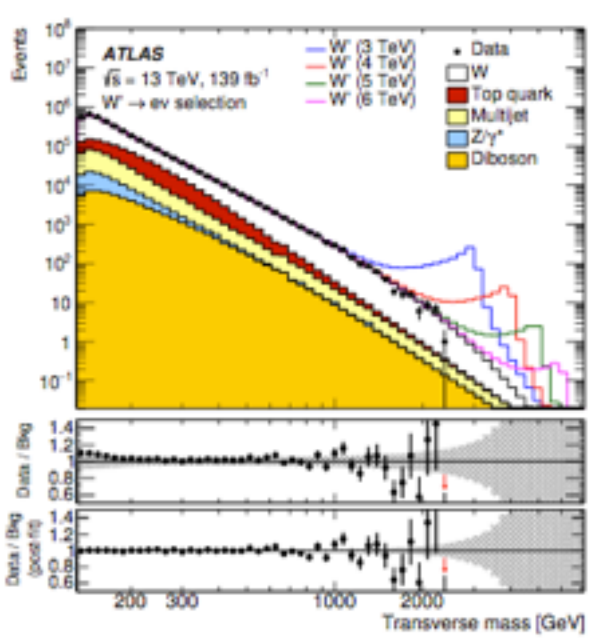
NP contributions might better accommodate the situation

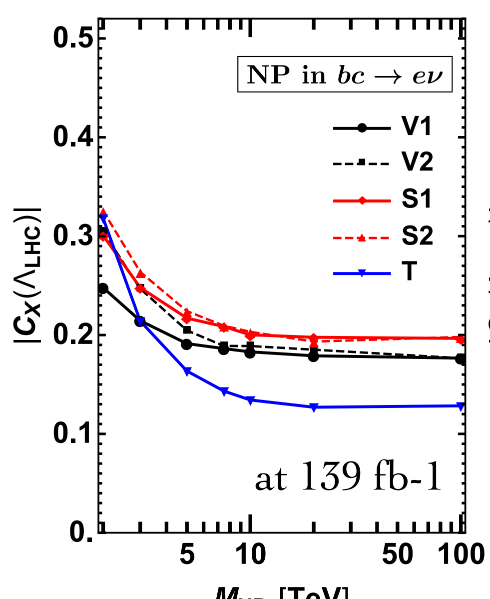


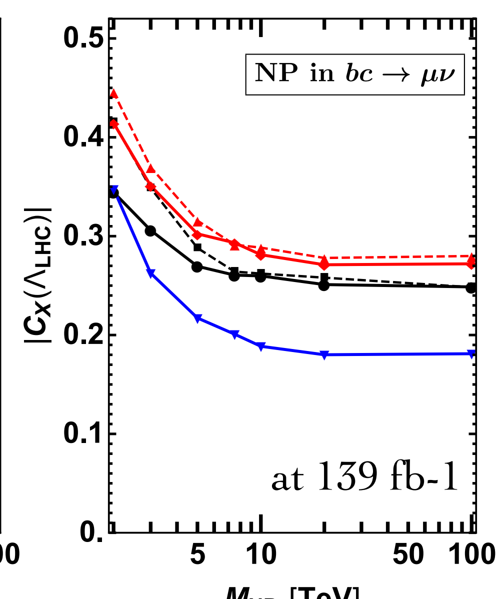
$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb}\left[(\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) + C_{V_2}(\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) + C_T(\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell)\right], \quad (1)$$

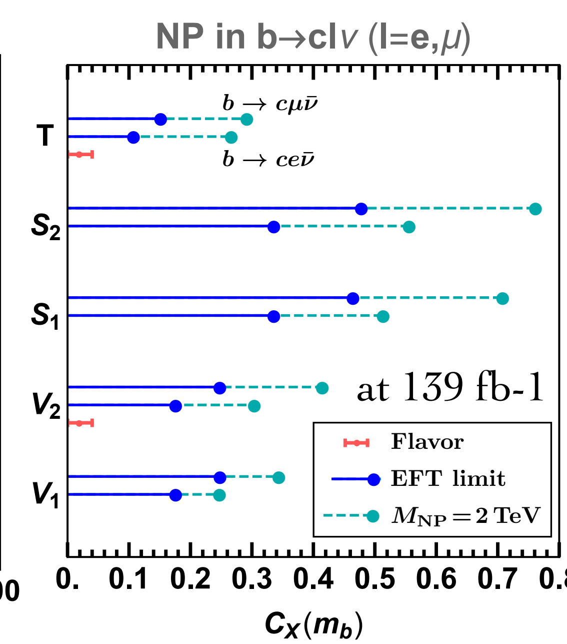
S Iguro, R. Watanabe [arXiv:2004.10208 [hep-ph]].









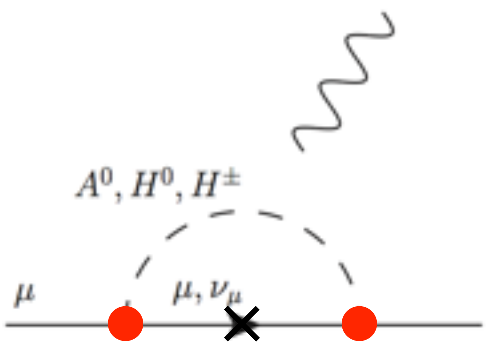


We consider the UV models to generate the op. at LHC

found rather sensitive to M_NP

test of LFV for muon g-2

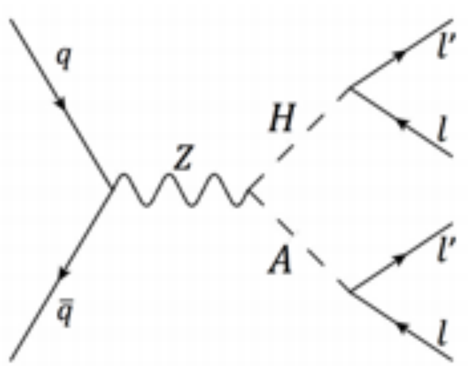
Syuhei Iguro (Nagoya U.), Yuji Omura (KMI, Nagoya), MT
arXiv:1907.09845

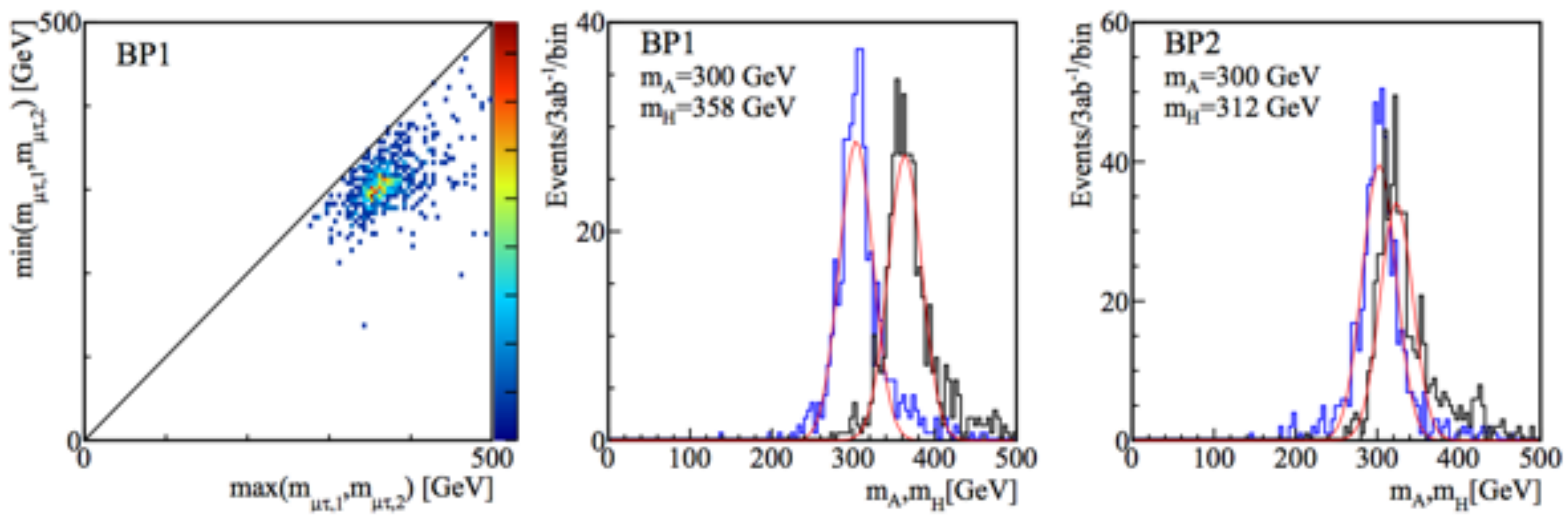


introducing LFV coupling has an advantage   LFV enhance with $m_\tau/m_\mu \sim 17$

consider the case only LFV couplings $\rho^{\mu\tau}, \rho^{\tau\mu}$ introduced for heavy higgses in 2HDM

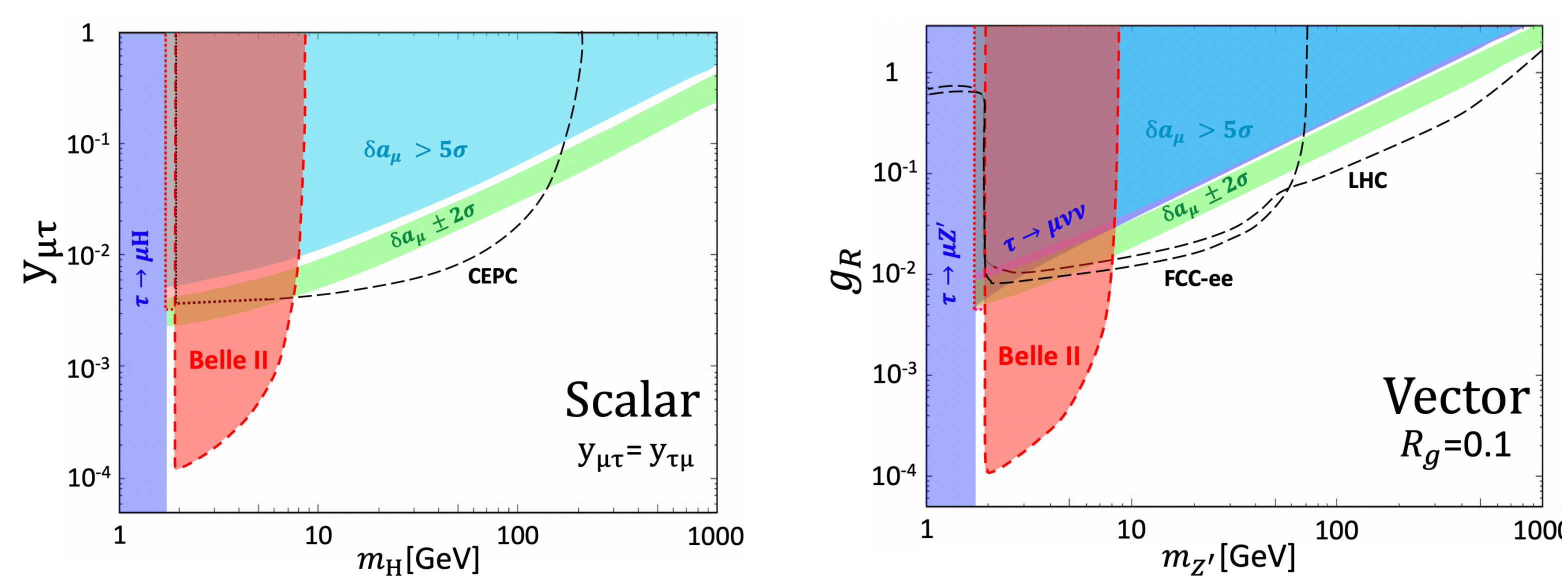
4 leptons from HA production $\mu^\pm\mu^\pm\tau^\mp\tau^\mp$



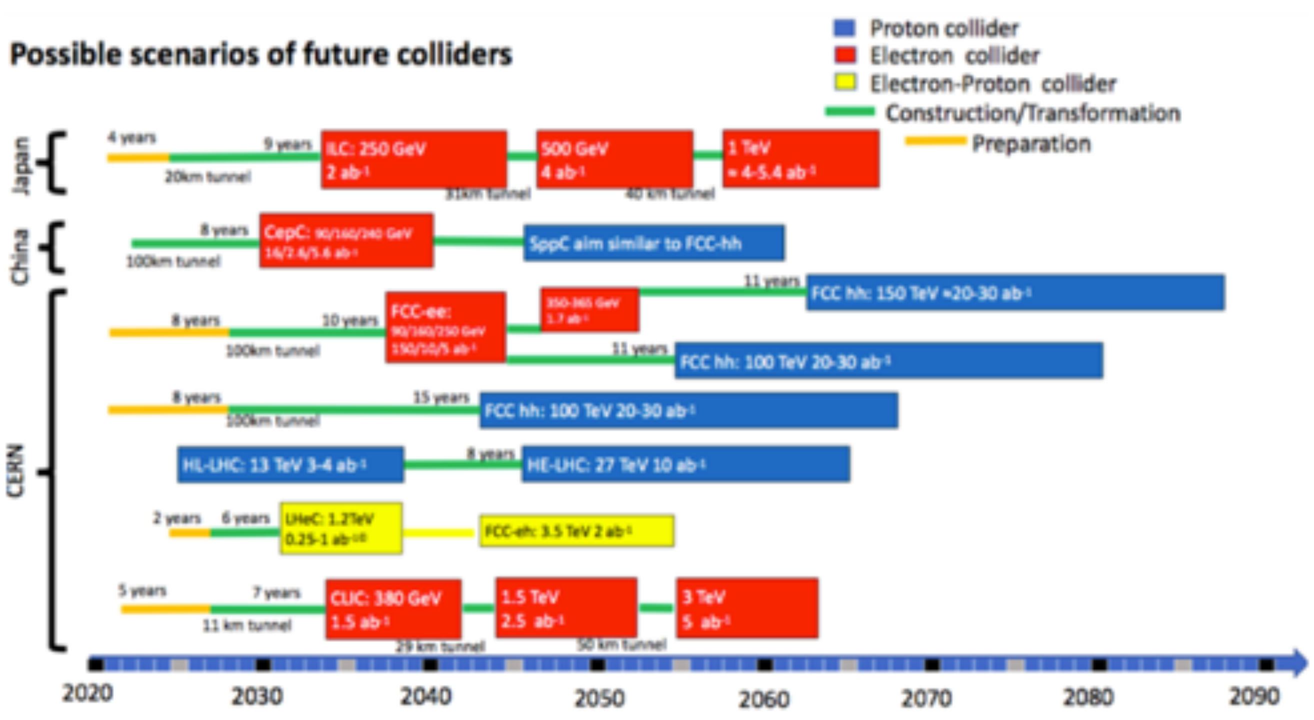


similar singlet extension case also considered, $\mu^\pm\mu^\pm\tau^\mp\tau^\mp$ is again the signature.   [S. Iguro, Y. Omura, MT: arXiv:2002.12728]

remaining parameter region
filled by Belle II



LHeC arXiv: 2007.14491



The timeline for different scenarios for future colliders.

CDR default e-beam : 60GeV $\sqrt{s} = 1.3$ TeV

new default : 50 GeV (initially 30GeV)

$\sqrt{s} = 1.2$ TeV

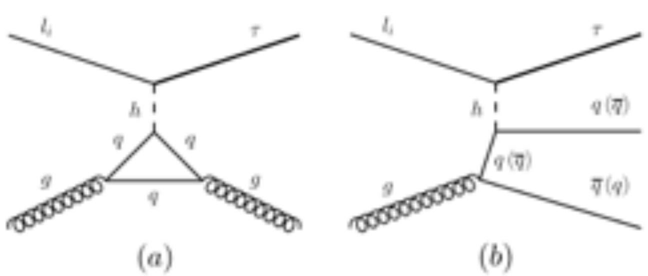
$\mathcal{O}(1)\mathrm{ab}^{-1}/\mathrm{year}$

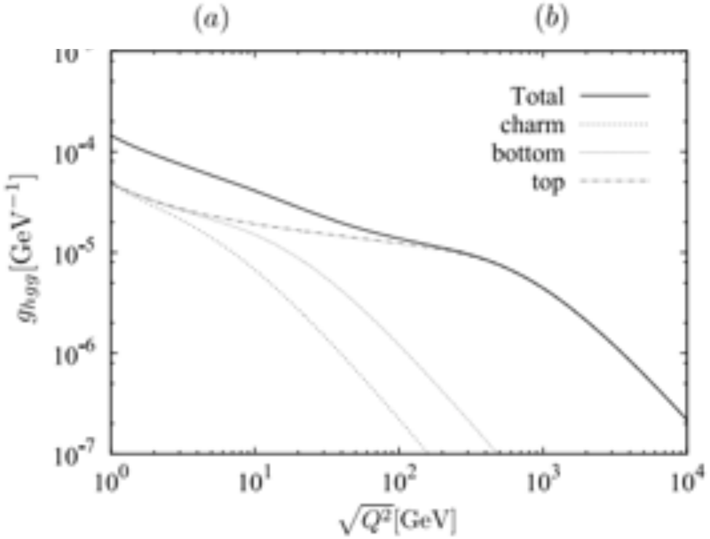
DIS, better determination of PDF

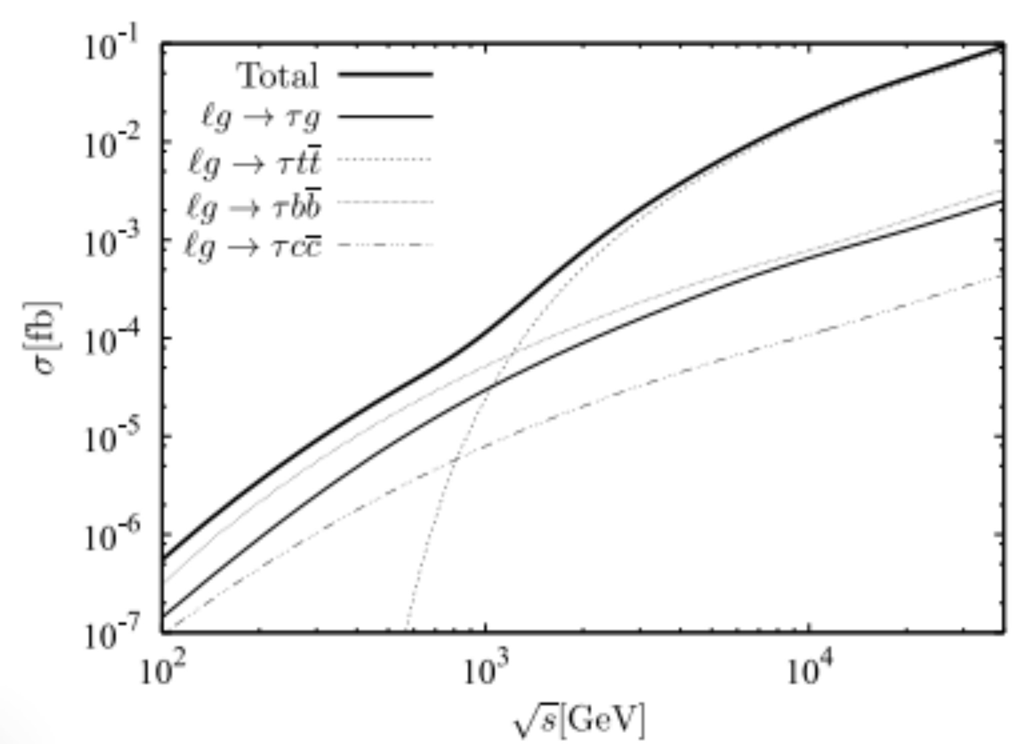
it would reduce the systematic uncertainty of the data obtained at HL-LHC

Higgs mediated CLFV scattering

MT, Y. Uesaka, M. Yamanaka
Phys. Lett. B 772, 279-282 (2017) [arXiv:1705.01059]







For maximally allowed coupling,

$$\sqrt{|\rho_{e\tau}|^2 + |\rho_{\tau e}|^2} = 2.4 \times 10^{-3}$$

$\mathcal{O}(100)$events would be produced

Summary

Naturalness : we probably just enter the natural parameter space finally
lots of opportunities at LHC

targets :

scalar top → boosted technique : extended to Machine Learning/Deep Learning
degenerate region : mono-jet, mono-top for additional information

EWkinos → being thermal relic set upper bound, require co-annihilation partners
degeneracy → soft-leptons, mono-jet, long-lived particles
(disappearing track, displaced vertex)
loop effects possibly detectable at HL-LHC

HL-LHC : Higgs factory / top factory

pT distribution : different pt bin gives independent information

rare decays : sensitive for new physics

flavor anomalies : gradually sensitive at LHC

Future hadron colliders required to cover most of the parameter space with thermal relic neutralino