# Physics Opportunity at future colliders


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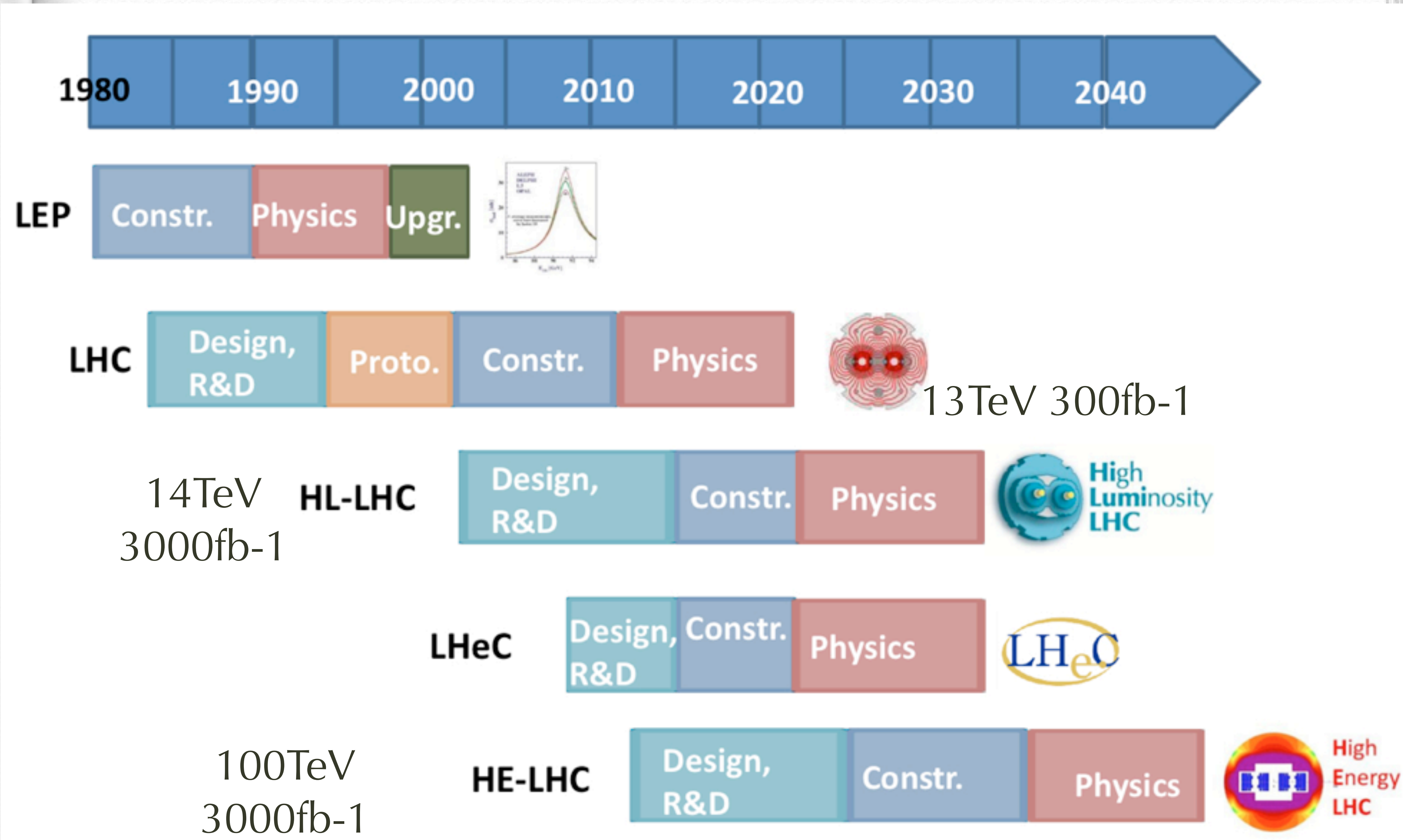
KEK & IPMU

# CERN Bulletin March 19, 2012



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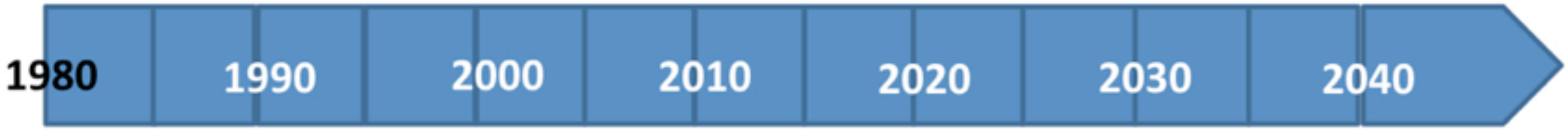
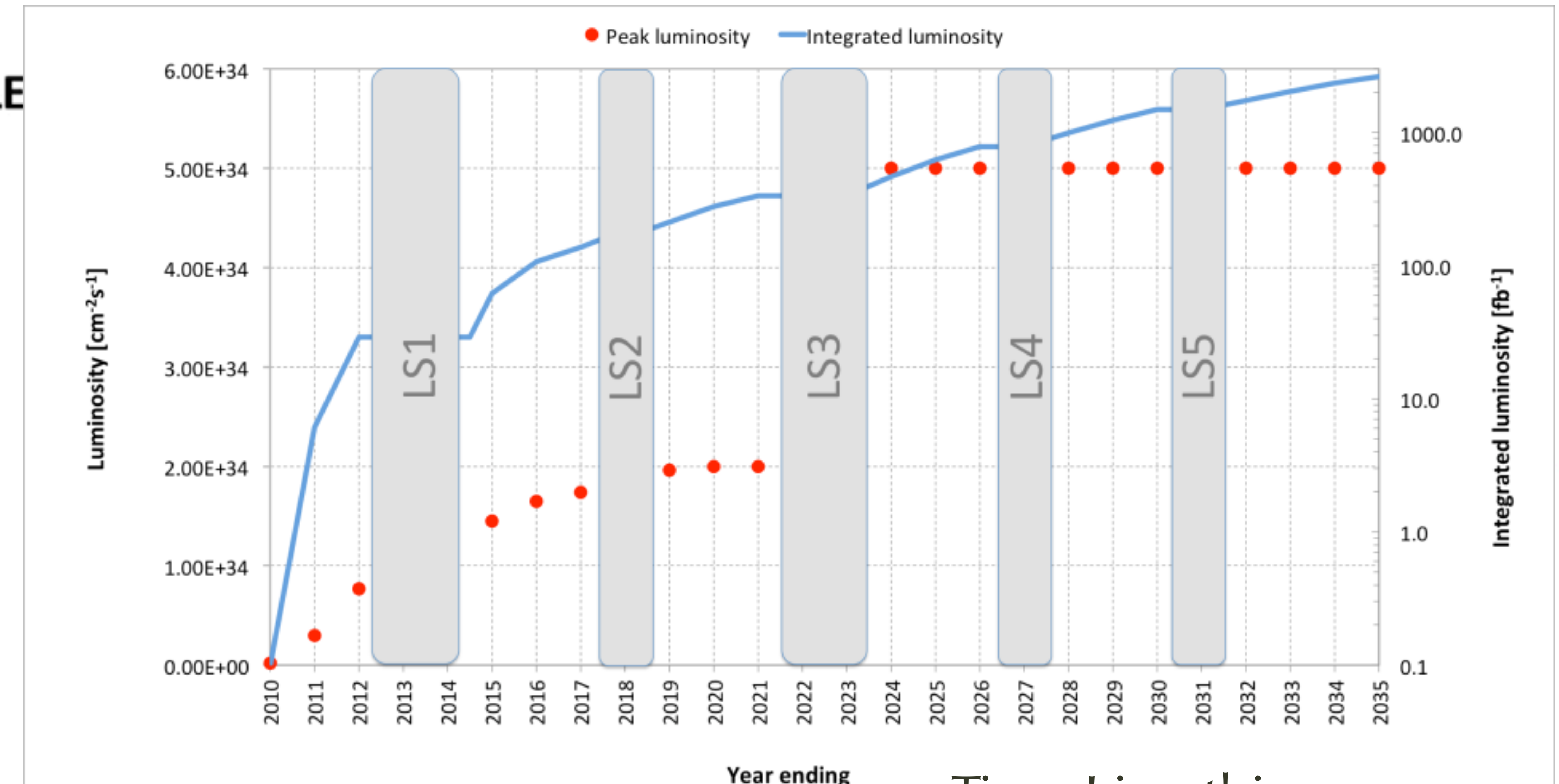



LE

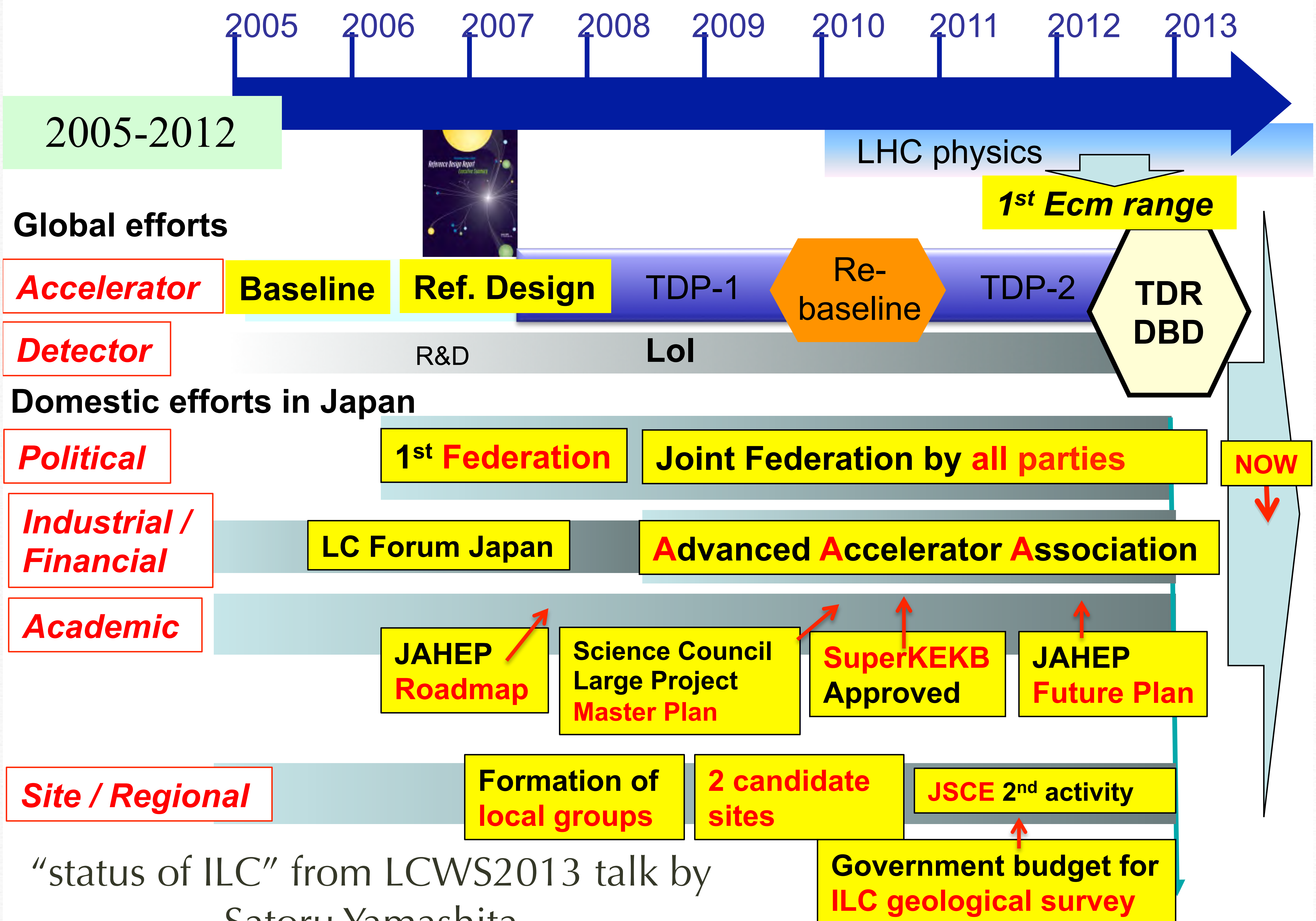



Time Line this summer

3000fb-1

R&D

High Energy LHC




“status of ILC” from LCWS2013 talk by Satoru Yamashita

# BSM is the target

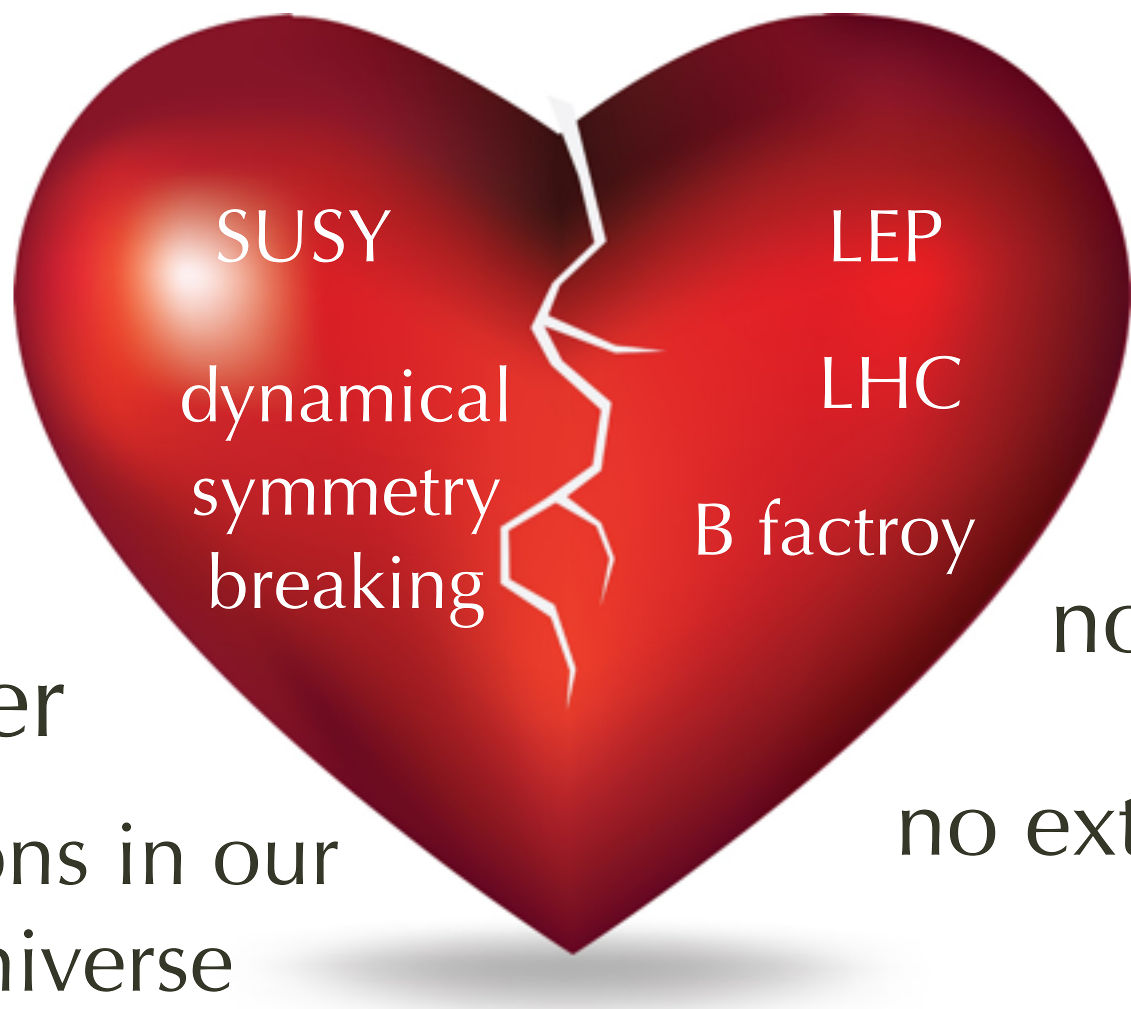
**existing Mystery**

Matter content and gauge interaction

Higgs boson is light

dark matter

baryons in our Universe




**Constraints**

no large EW correction

no extra FCNC

no proton decay

no extra CP violation

# Contents

- SUSY confronts data and future collider
- Jets signatures with "**QCD technologies**"
- "**Composite way**" ; Composite Higgs, top partner, Higgs sector
- Leptons! at future colliders

# 1. Classic Solution:Supersymmetry

- symmetry to exchange boson and fermion.
    - new particle predictions sfermions(0), gaugino(1/2), higgsinos(1/2)

**Higgs vs SUSY**

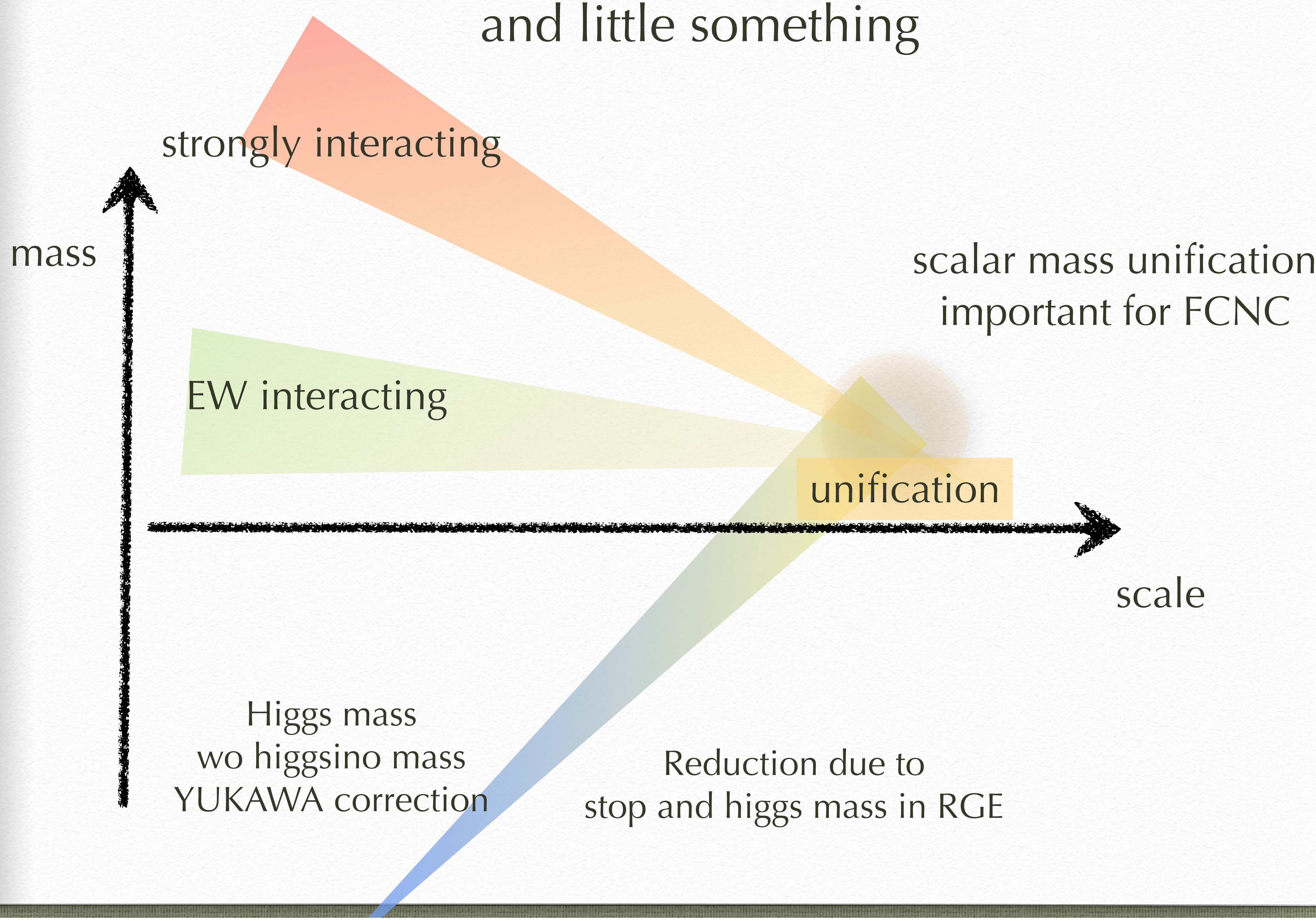
- No new dimensionless coupling and no quadratic divergence
- Higgs 4 point coupling ～gauge coupling. (no negative 4 point coupling)+ radiative correction b

**Answering big question**

- gauge coupling unification
- R parity in MSSM . New stable particle→ DM candidate.

**but flavor and CP problem -> SUSY breaking models**

# gauge coupling/soft parameter unification
# mass spectrum (mSUGRA/CMSSM)
# and little something



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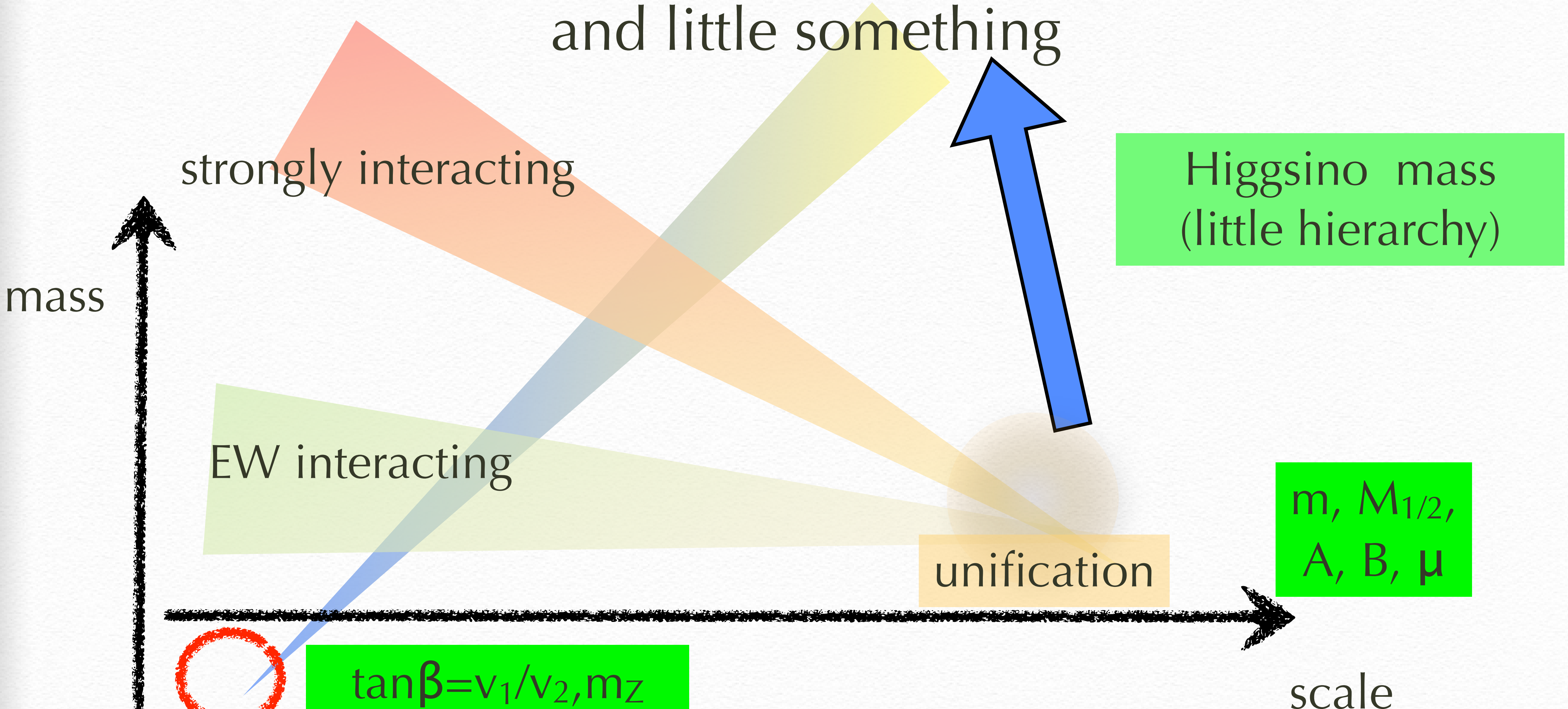



solving constraint of correct symmetry breaking

mSUGRA/CMSSMparameters are

$m$, $M_{1/2}$, $A$, $\tan\beta$

# What is natural,anyway?

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

only wave function renormalization
relatively stable prediction

fine tuning is the **response of Z mass** to the **fundamental parameters "a"**

$$\left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2(a_i; y_t)}{\partial a_i} \right| < \Delta$$

Now what is the "a" ? This idea has been **criticized since it was proposed** in '88

GUT scale based ( Barbieri et al →)

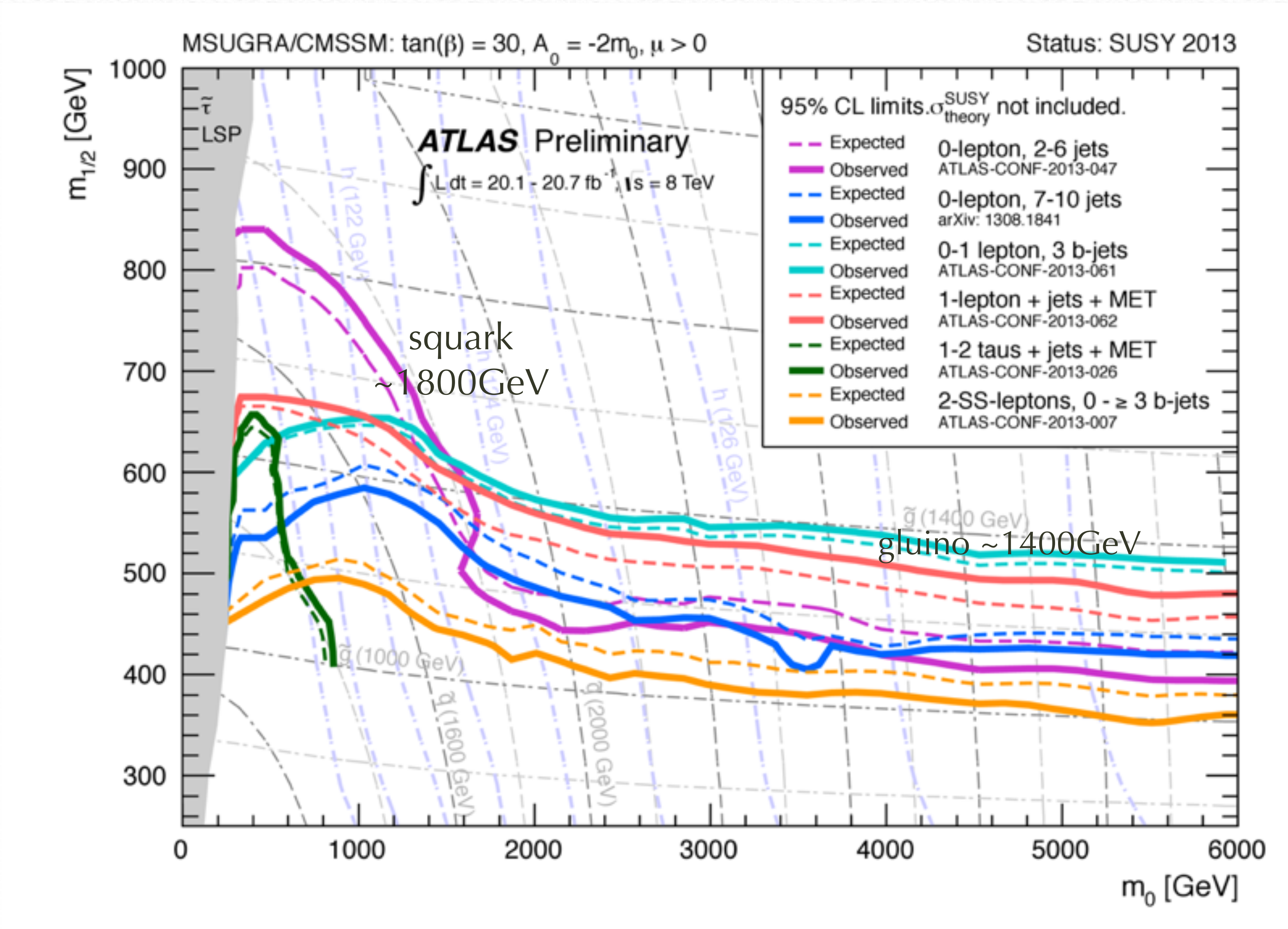
use GUT scale parameters: m, $M_{1/2}$, Δ is more than 100
The level of tuning also changes #parameters at GUT scale

Weak scale based (Baer et al)

use parameter at weak scale: typically 1/10 less fine tuned compared with GUT based analysis

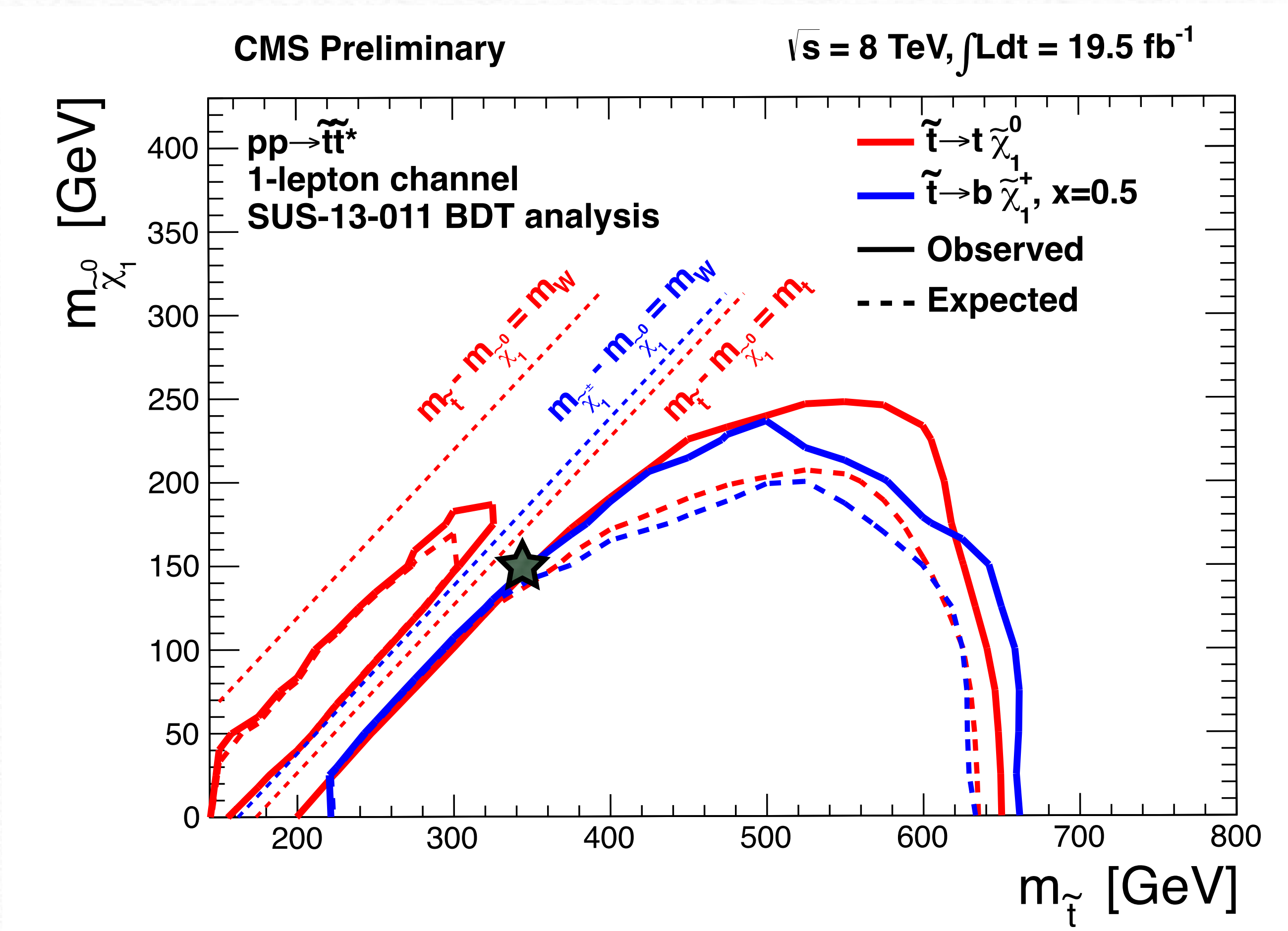
.... Why should we mind?

# SUSY confronts LHC

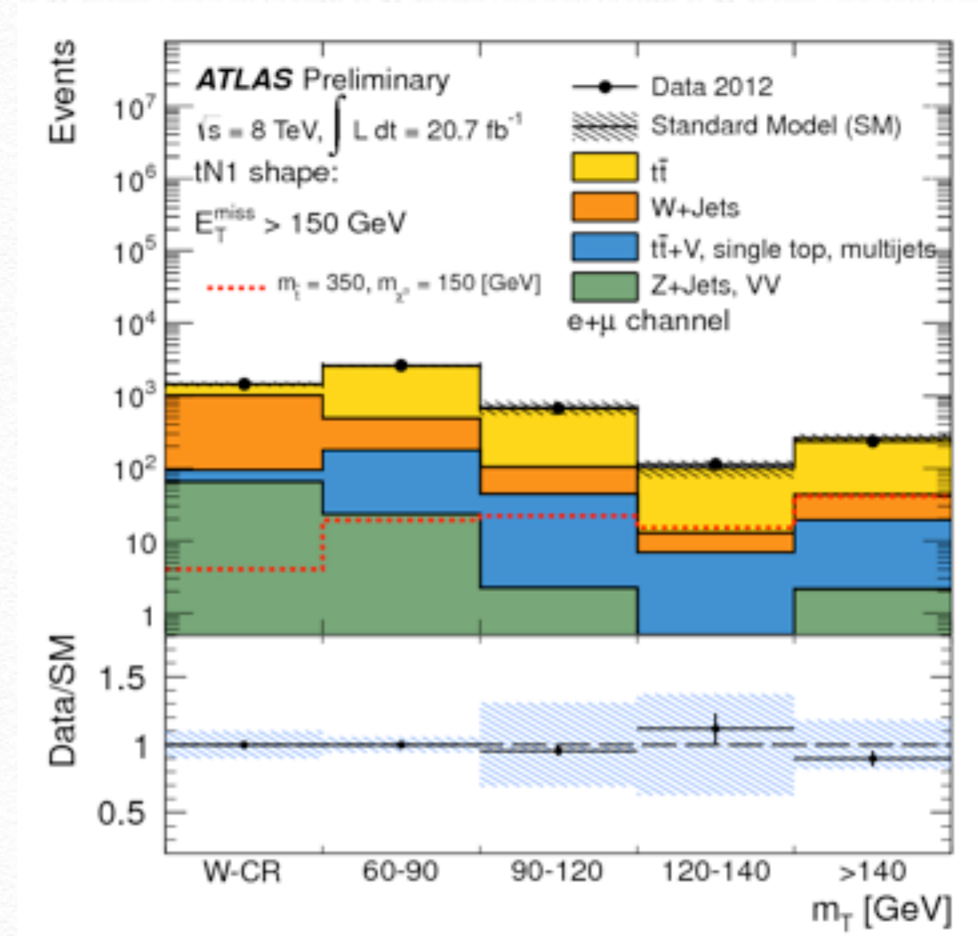


# Light SUSY confronts real data
# M(SUSY ) > 1.5TeV Mstop~ 650GeV GeV

The bound is model independent




exclude up to the region
where mstop~mLSP+mt +30GeV

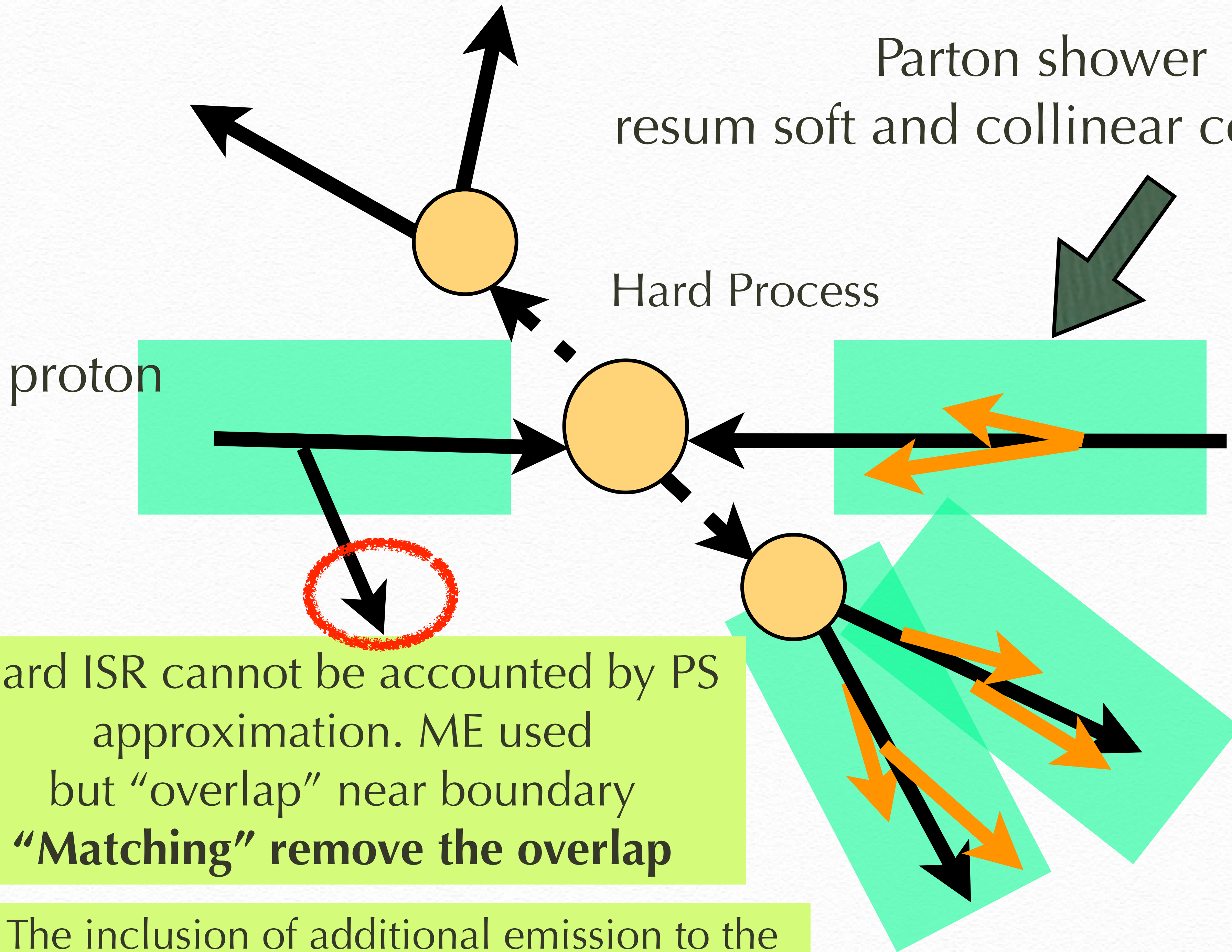



stop 350GeV and LSP 150GeV
There are no region with
S/N>0.1 in this plot!

The limit relys on understanding of background

I am not sure I take this limit but it is still nice to see such efforts

# background estimation powered by "Matching"



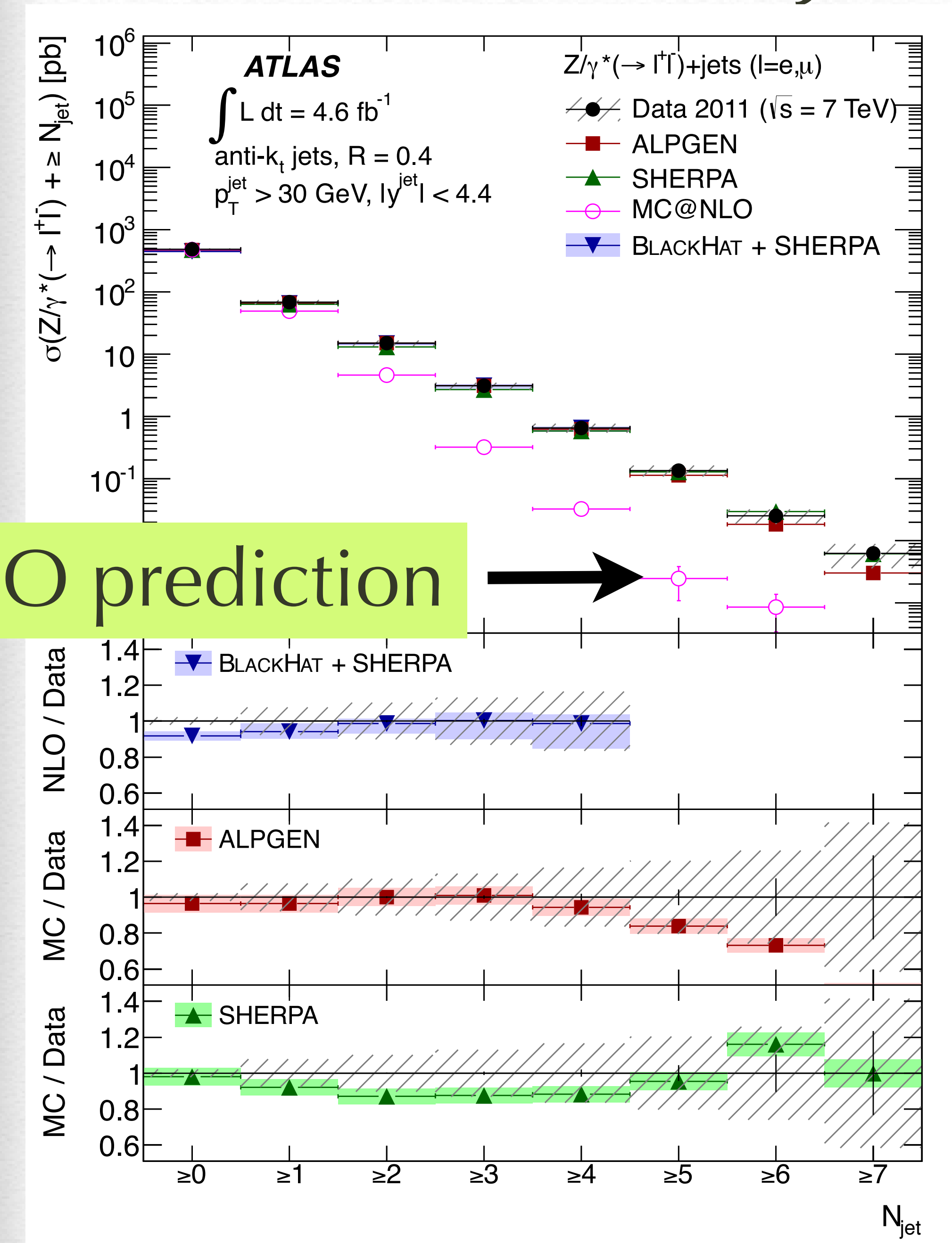

Hard ISR cannot be accounted by PS approximation. ME used but "overlap" near boundary
**"Matching" remove the overlap**

The inclusion of additional emission to the SM process is important when we rely on the cut on $P_{T3}$, $P_{T4}$ and inclusive quantity like $H_T$, Meff...

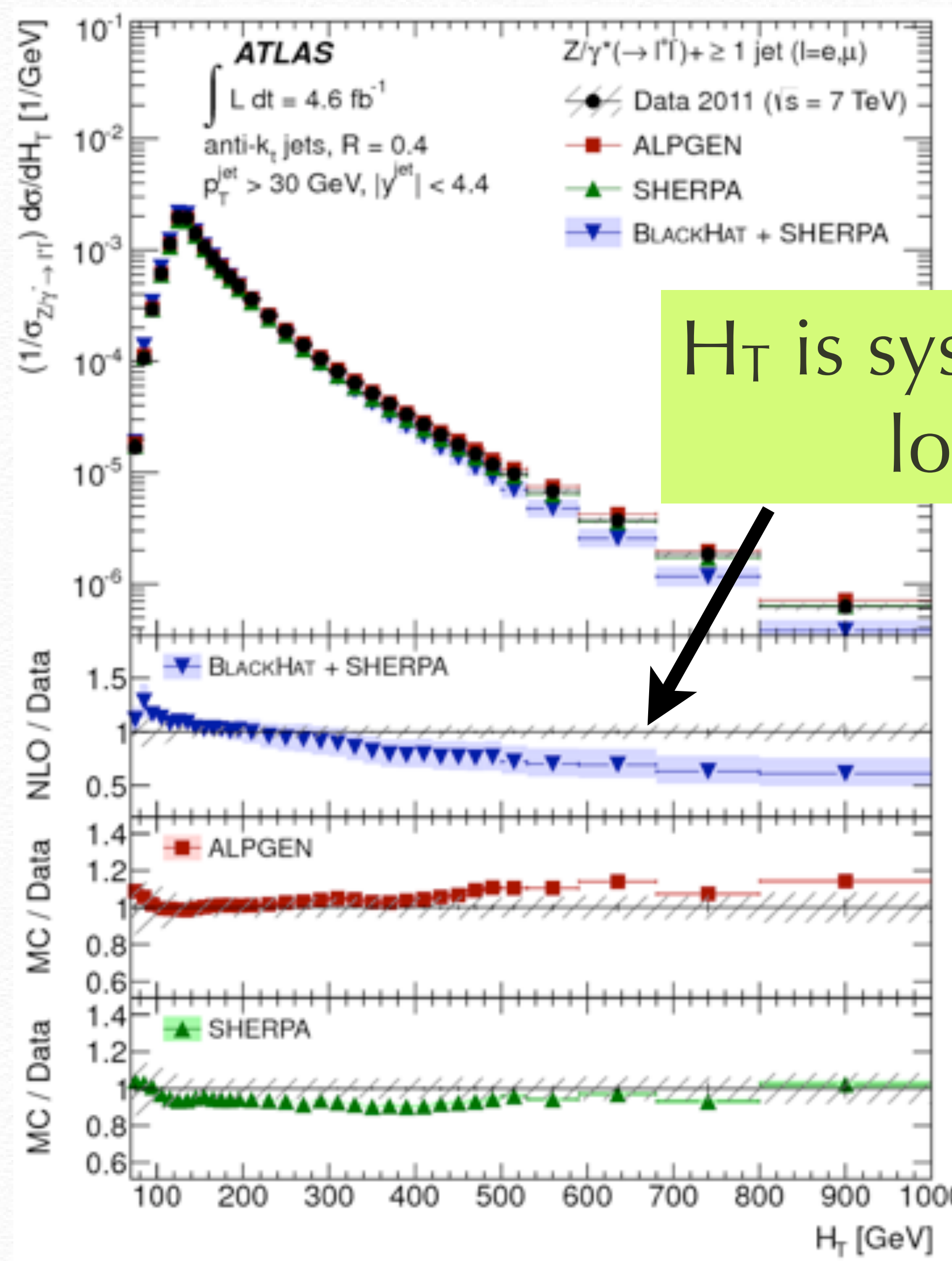
MLM

CKKW 2001

# theory reproducing multijet distribution




NLO prediction




$H_T$ is systematically low yet

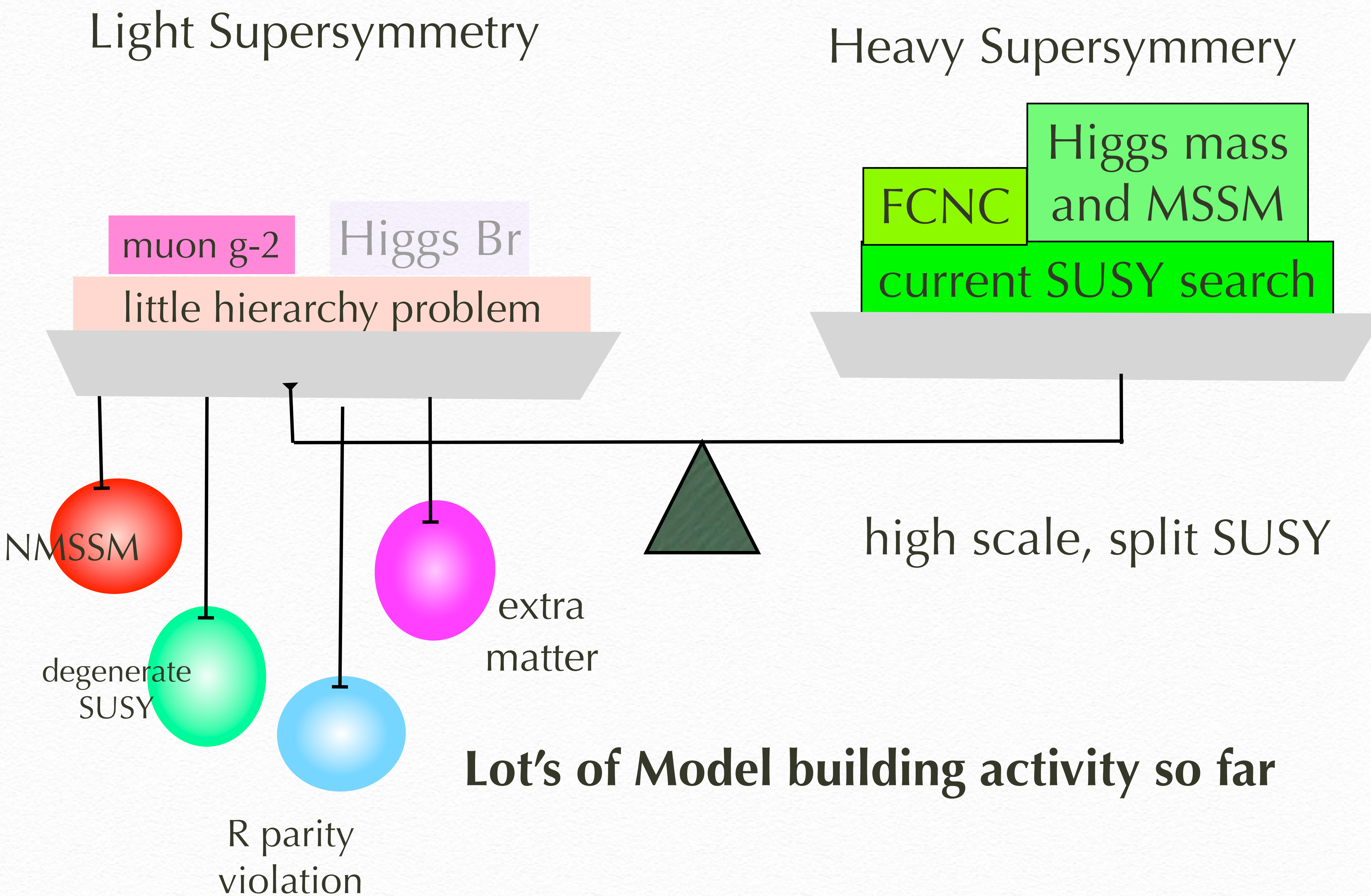
NLO

Tree

Tree

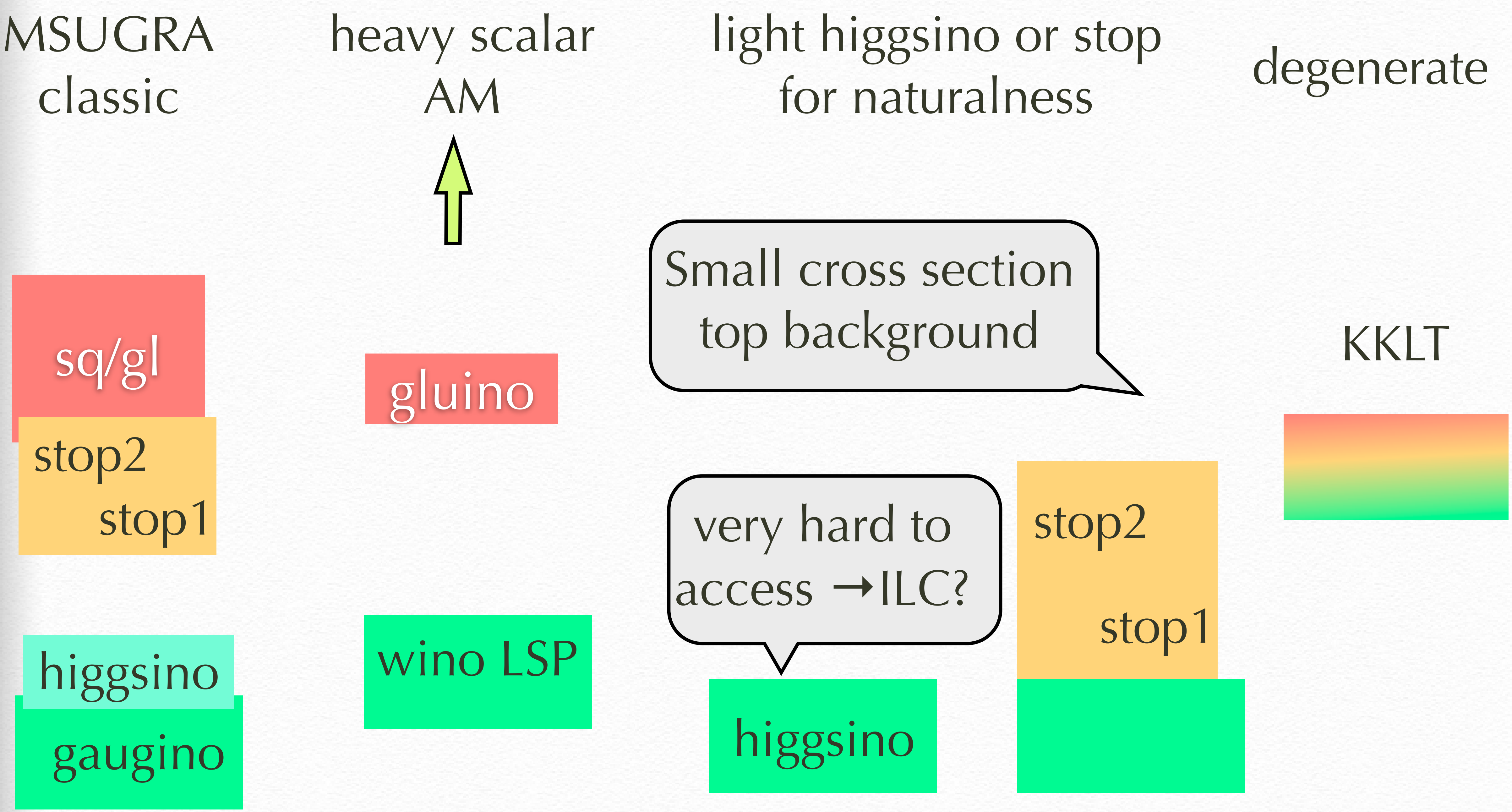
ATLAS 1304.7098

# Mind of SUSY theorists

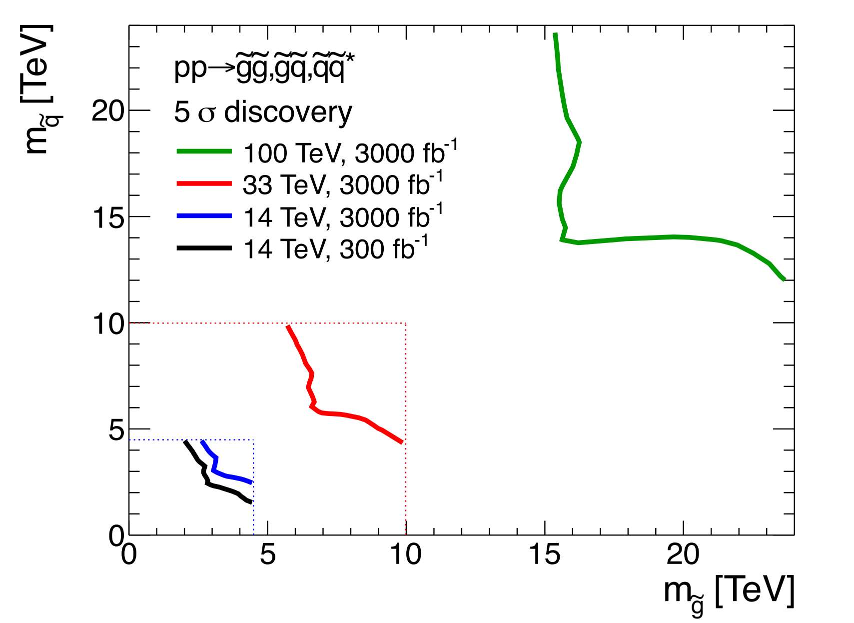



**Lot's of Model building activity so far**

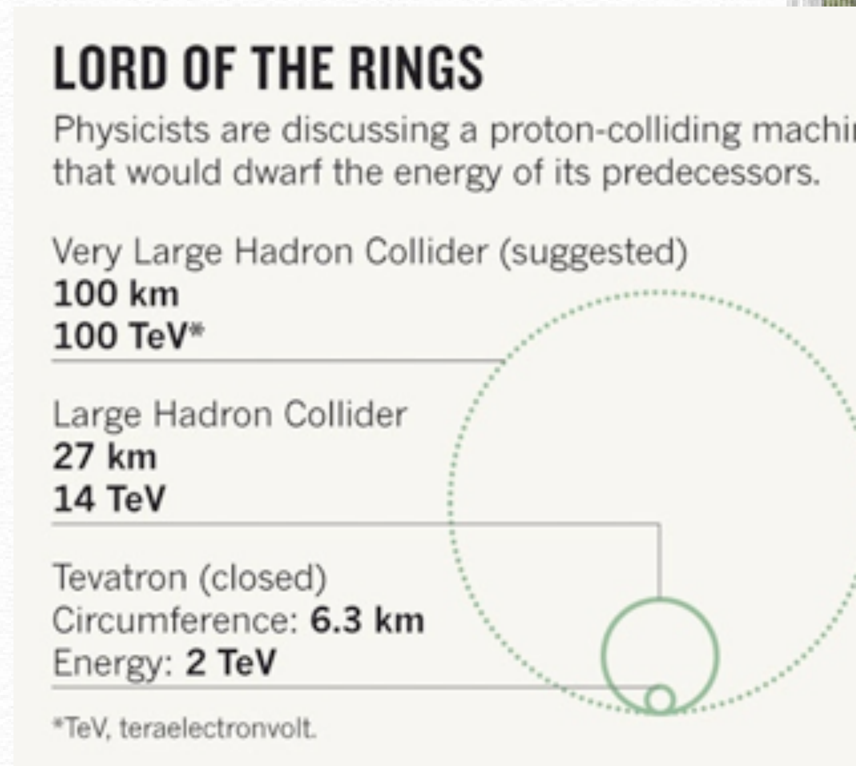
# SUSY spectrum on market

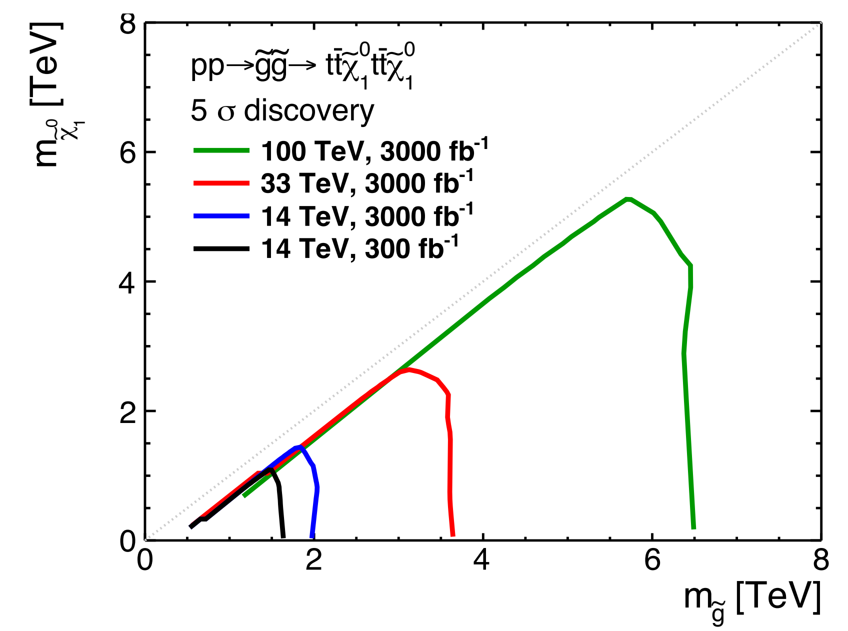


# for light gluino or stop case 5σ discovery does not exceed 10TeV even for 100TeV LHC..




"general SUSY" discovery around 15TeV

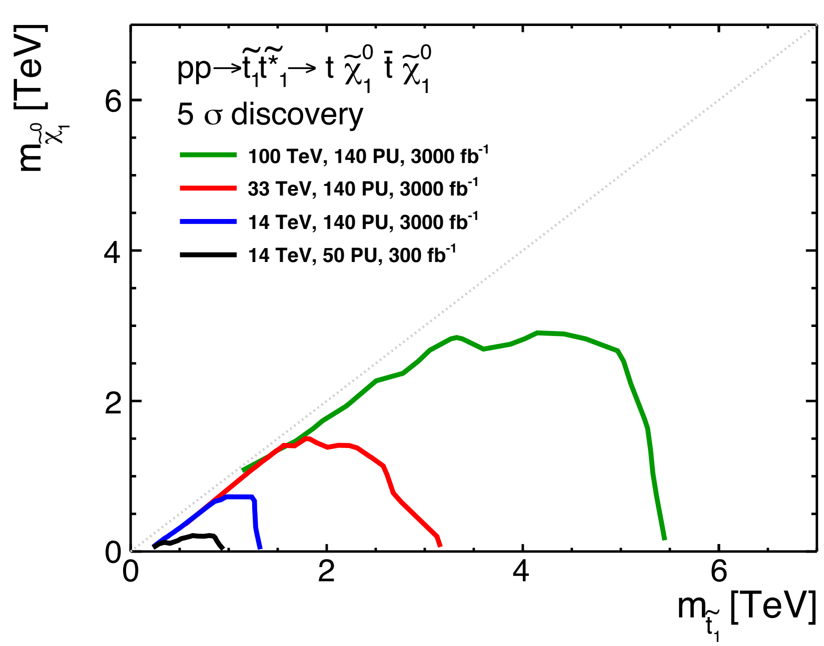



light gluino discovery up to 6.5TeV

Nature News
12 Nov 2013

from 1310.0077
Cohen et al



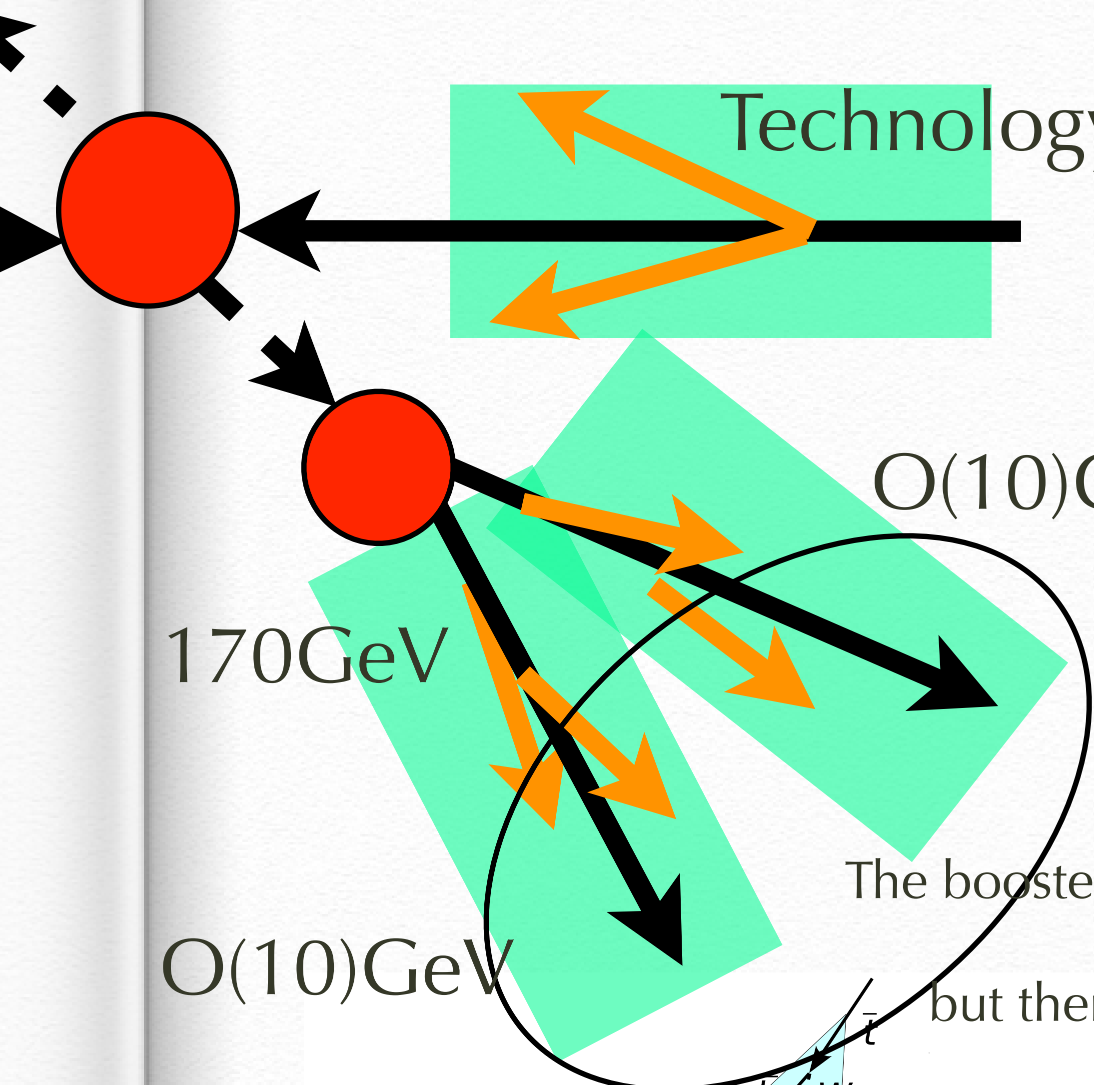

stop up to 5.5TeV

# 2. jets with "QCD tech"

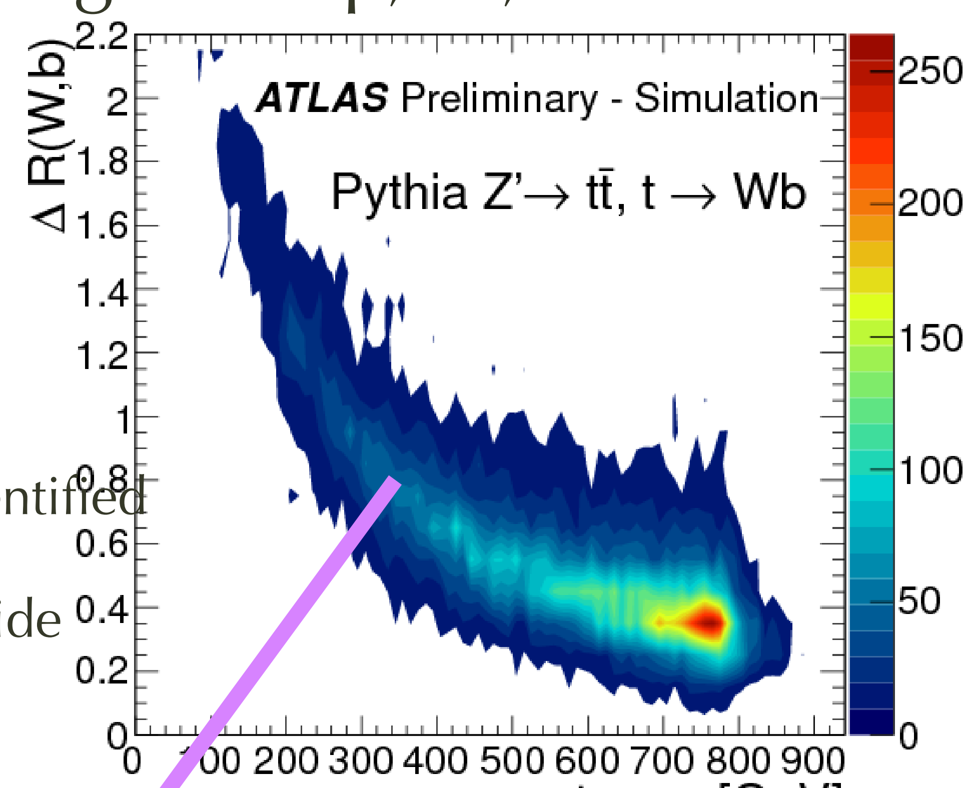
# Jet substructure

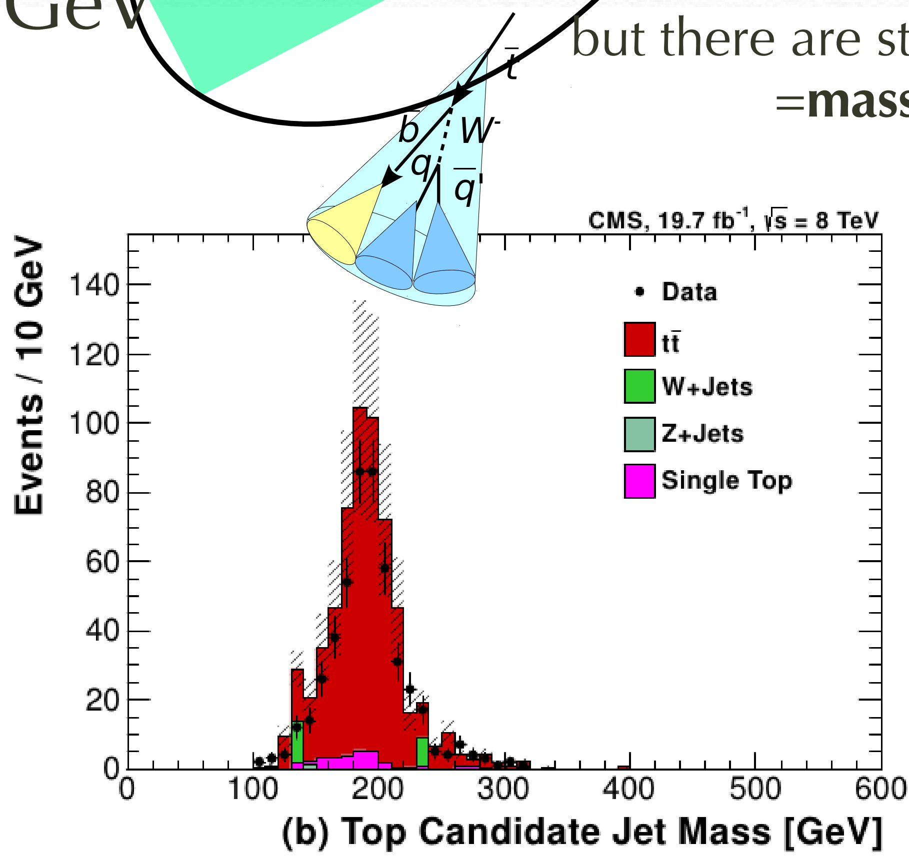
Technology to find boosted heavy object in a jet

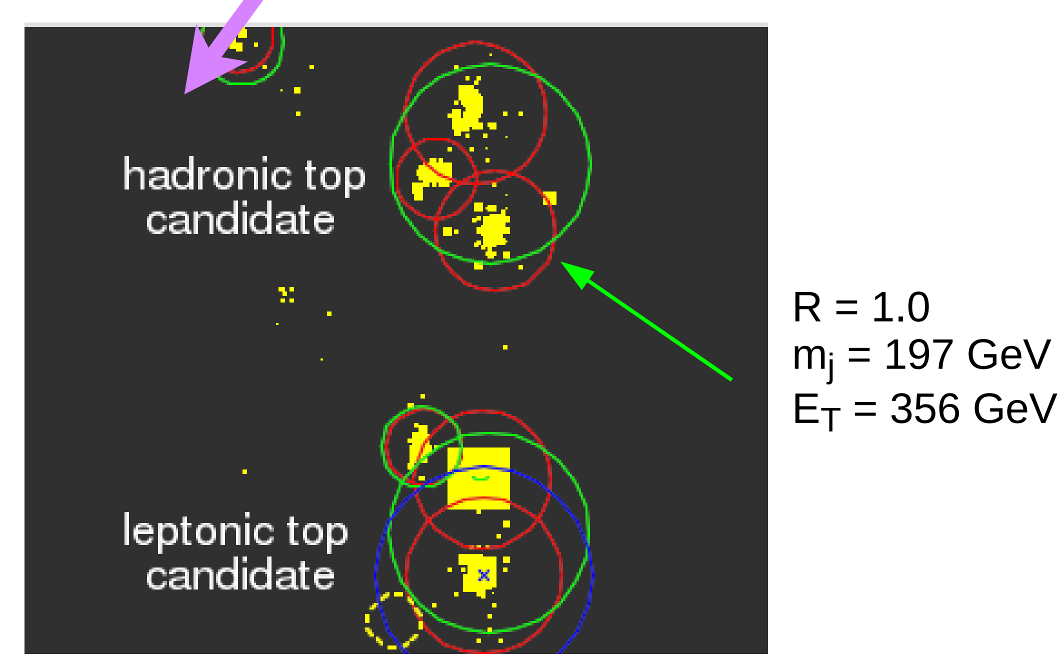
For heavier particle search we expect high $P_T$ top, W, Z

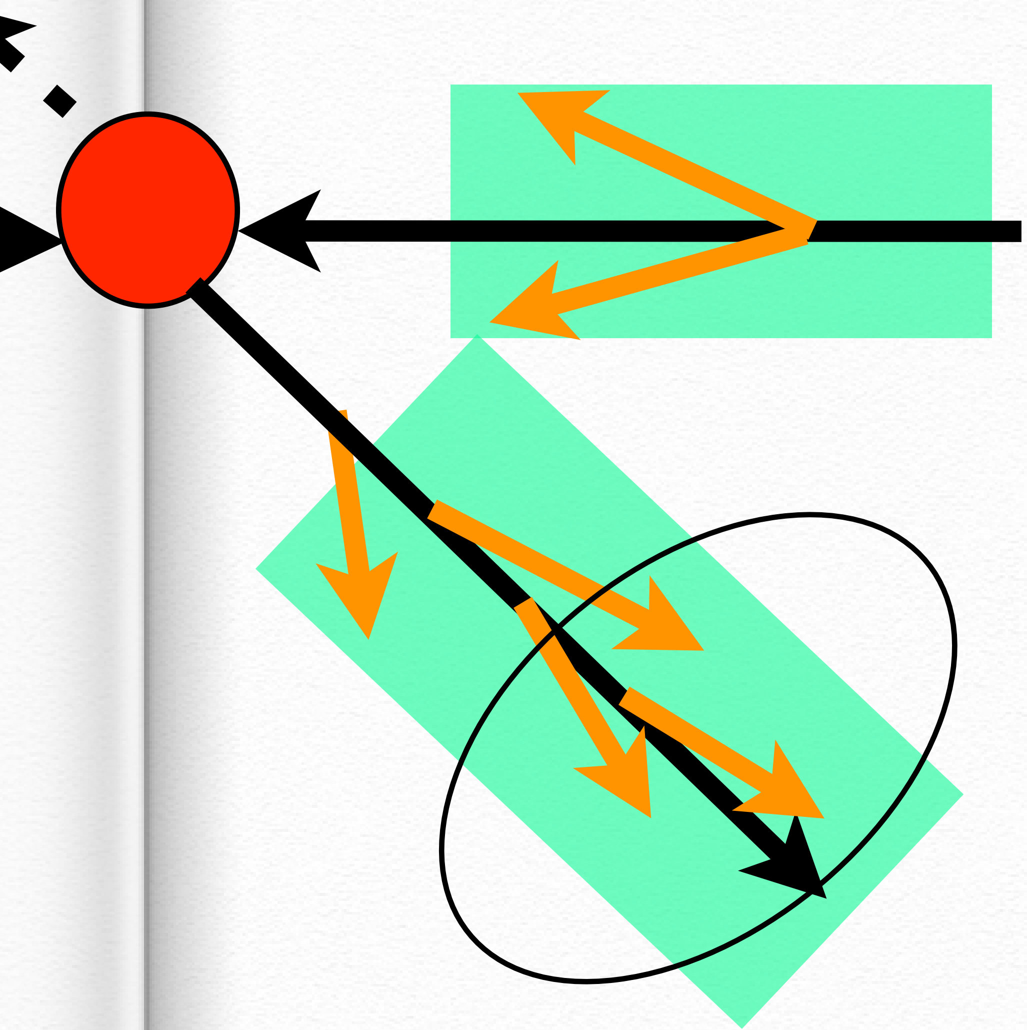



The boosted t, W, Z maybe identified as a single jet
as a single jet
but there are structures inside
=**mass drop**



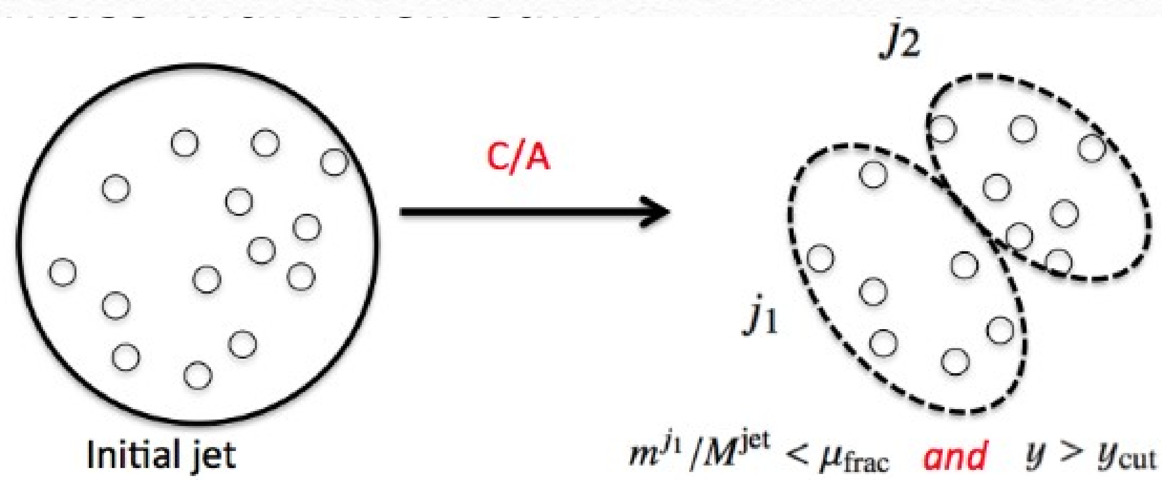


# Jet substructure reduce QCD background

single parton would not create sub-substructure

→Mass Drop(identify hard object)

→Trimming(ignore soft activities)




$$\frac{\min[(p_T^{j_1})^2, (p_T^{j_2})^2]}{(M^{\text{jet}})^2} \times \Delta R^2_{j_1,j_2} > y_{\text{cut}}$$

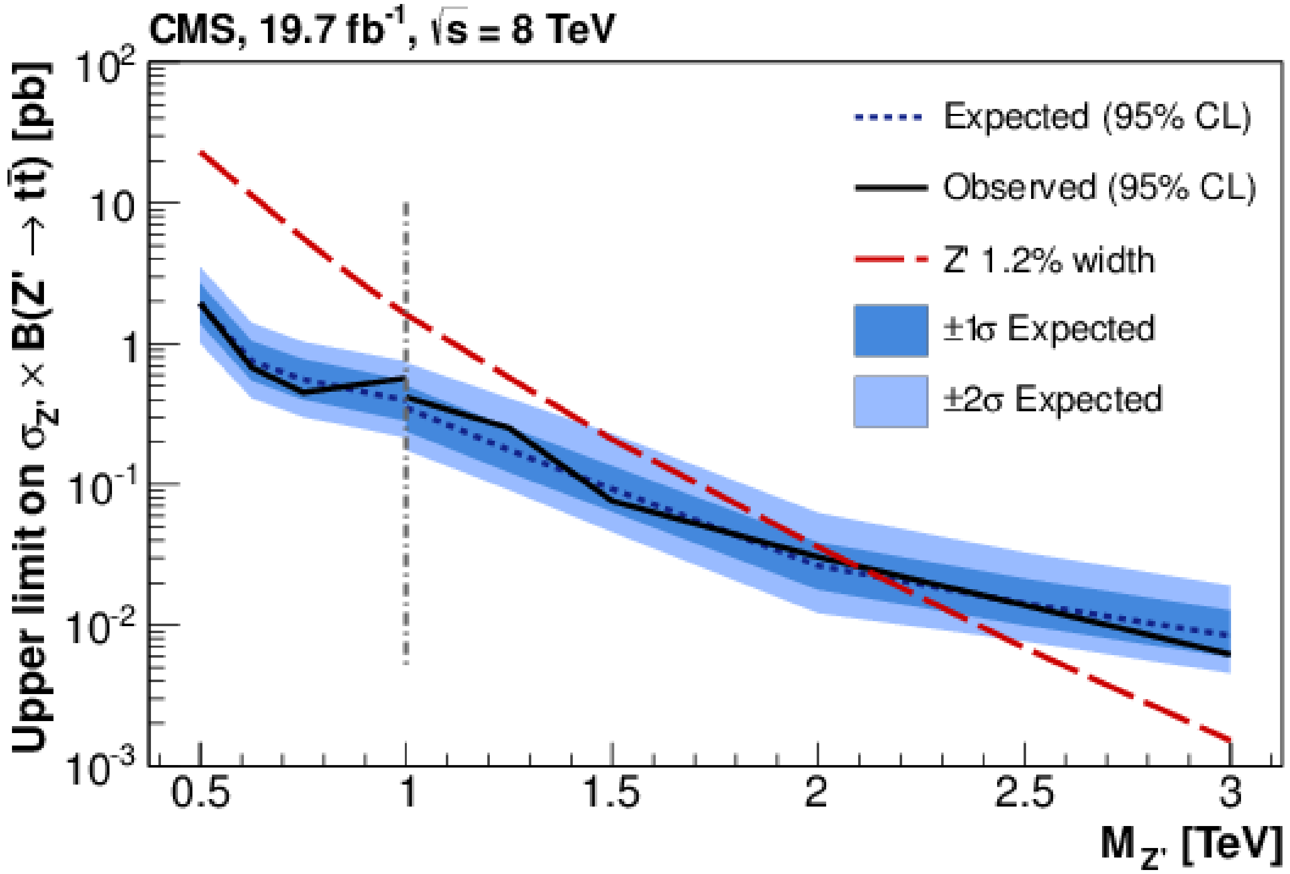
# Combined Limits

**Low mass analysis:**

- Limits from pdf fit

**High mass region:**

- Template fit to $m_{t\bar{t}}$ distribution
- Combine l+jets and hadronic channels




**Limits:**

- Narrow Topcolor Z': m>2.1 (2.1 expected) TeV
- Topcolor Z' with 10% width: m>2.7 (2.6) TeV
- RS Kaluza-Klein gluon: m>2.5 (2.4) TeV
- S=σ(SM+BSM)/σ(SM) <1.2 at 95% CL for $m_{t\bar{t}}$>1 TeV

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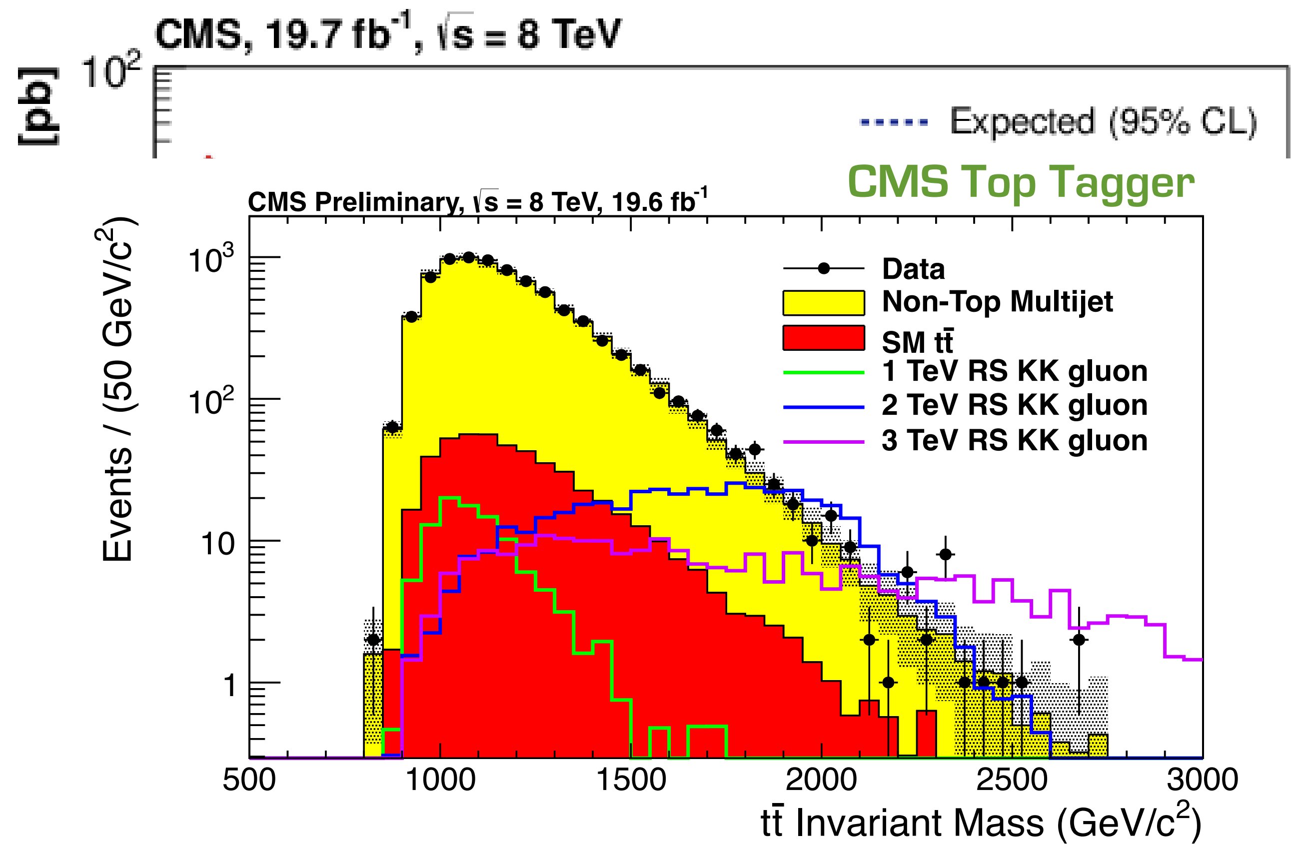


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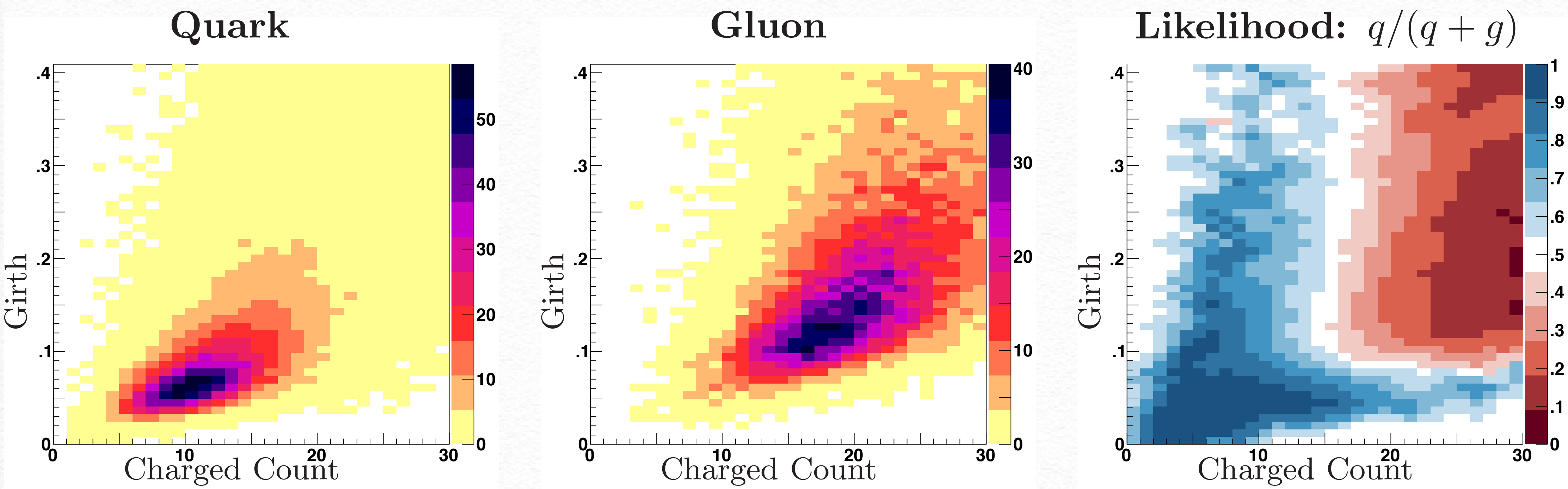
# quark and gluon jet substructure

"gluon jet" : more charged tracks and broader than "quark jet"




Girth : $$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} r_i \ .$$

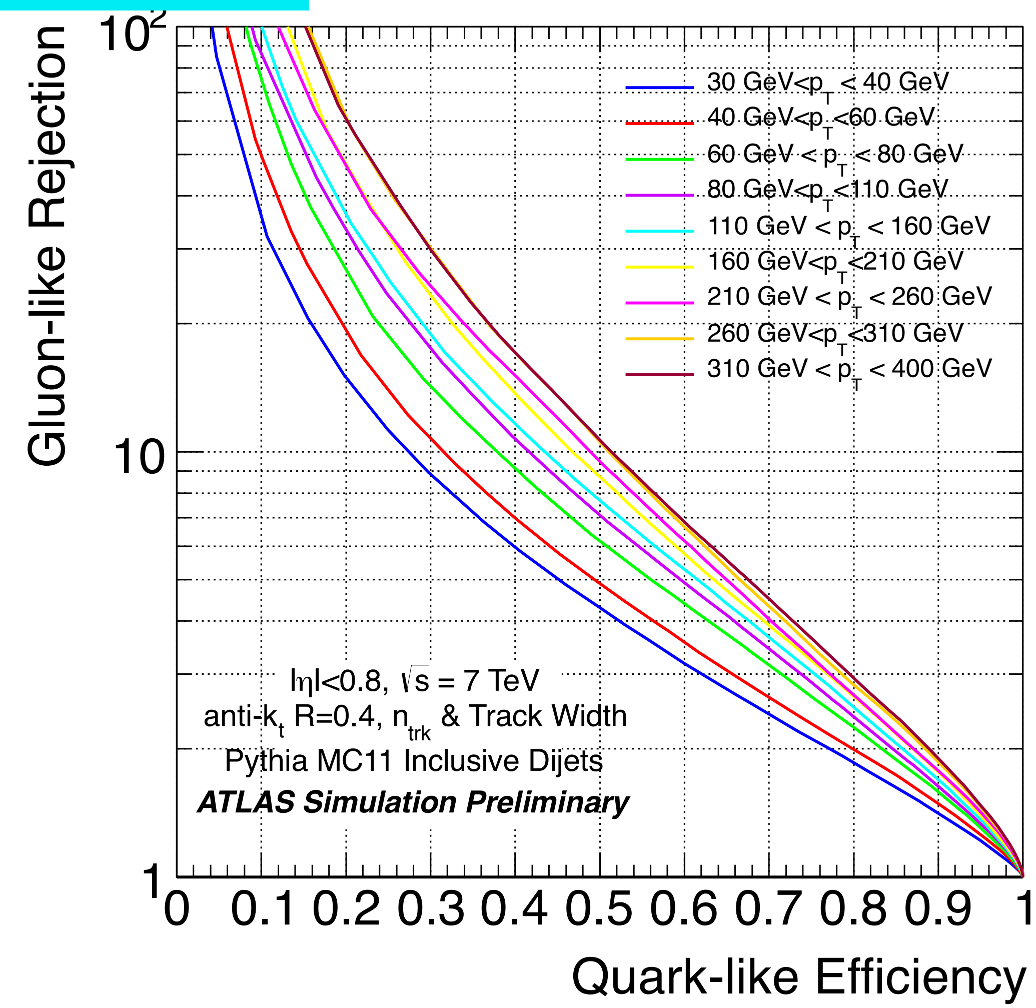
arXive 1211.7038 Gallicchio and Schwartz

# quark and gluon comparisons

ATLAS-CONF-2012-138

Nhan Tran (FNAL) for Lepton Photon

- Quark- and gluon-initiated jets have different properties
- Many search applications for distinguishing quarks and gluon jets
  - Hadronically decaying vector bosons
  - monojet, dijet searches
  - SUSY searches with high quark jet multiplicity
- **Jet width and number of charged tracks** provide good discrimination




Example: for 50% quark jet efficiency, we can reject 90% gluon jets

More discriminant at higher pTs

need careful validation of the data



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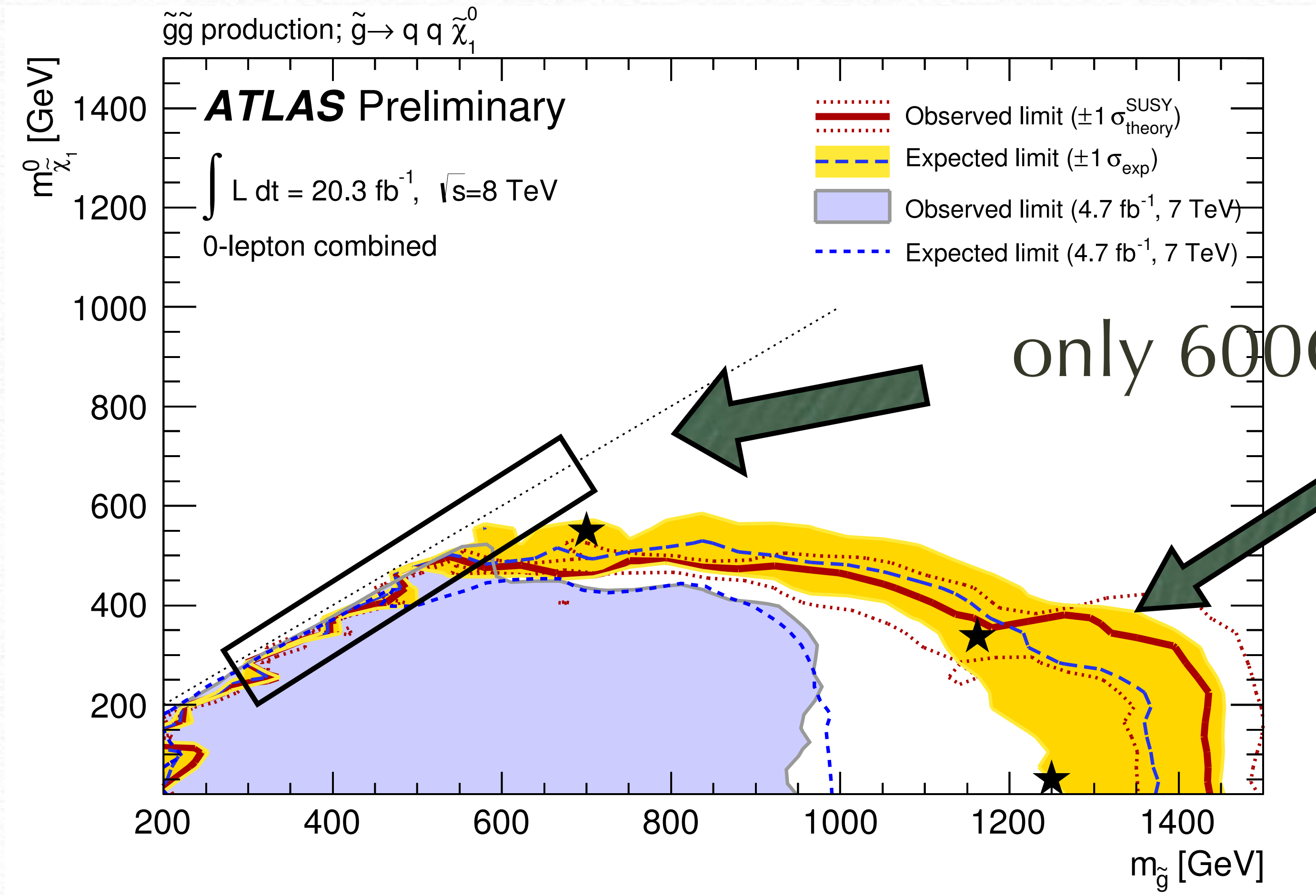
# Where to apply? a thought on "degenerate SUSYcase "




only 600GeV for degenerate

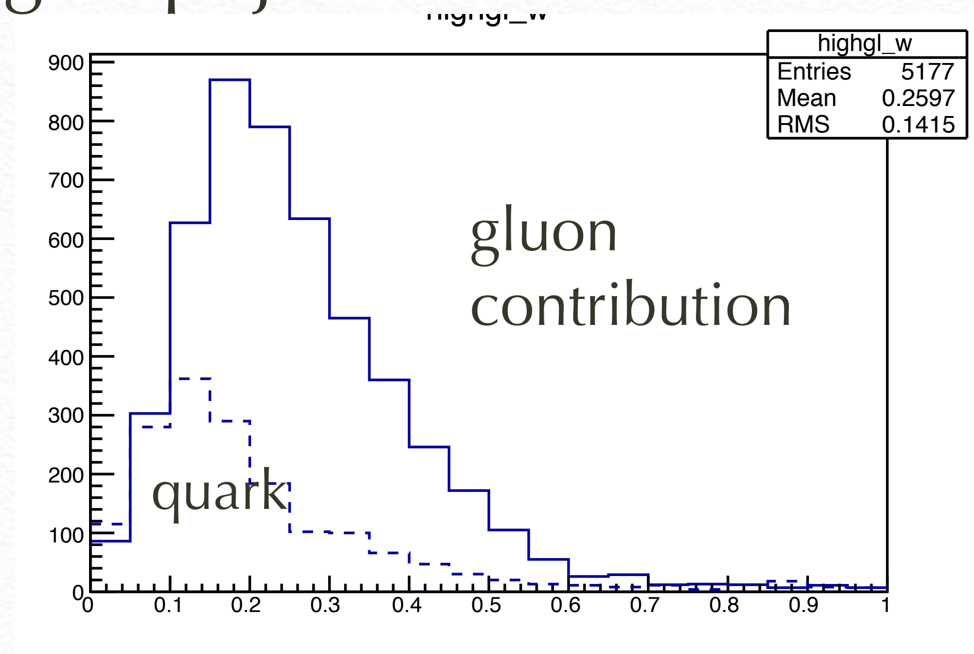
limit for large mass difference→1400 GeV

**Related with the question "how light the SUSY particle could be"**

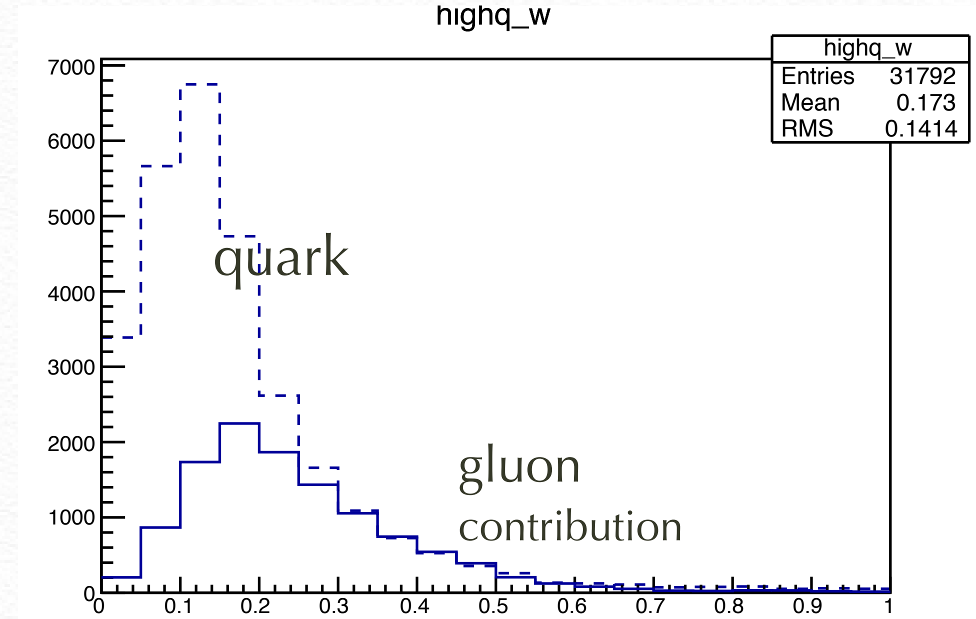
- for degenerate region, searches are based on ISR jets. Main background is Z+multijet.

# ISR difference

highst pt jet "width"    for pT between 75GeV ~125GeV




2gluino + up to 3jets

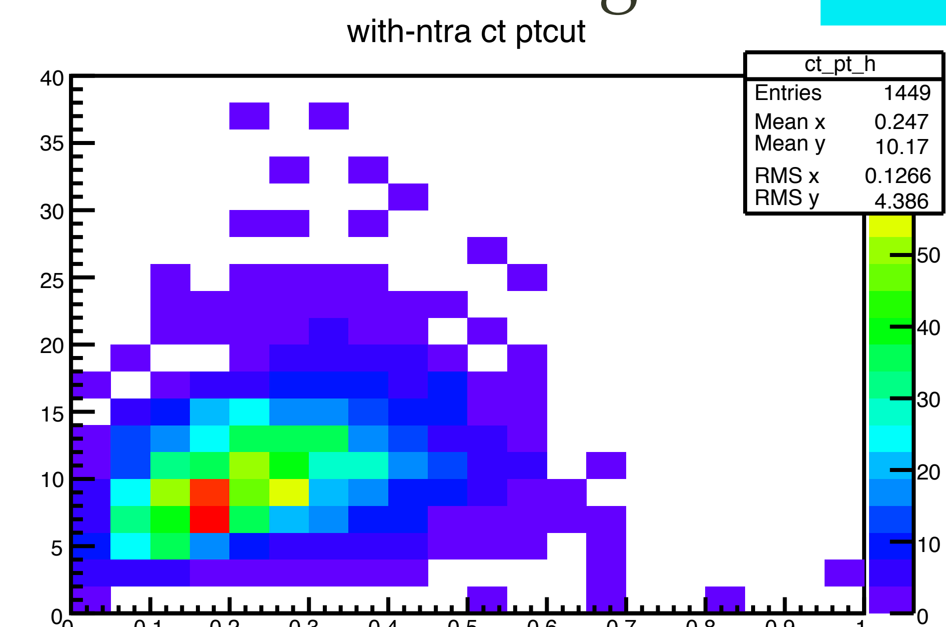



z+up to 3j

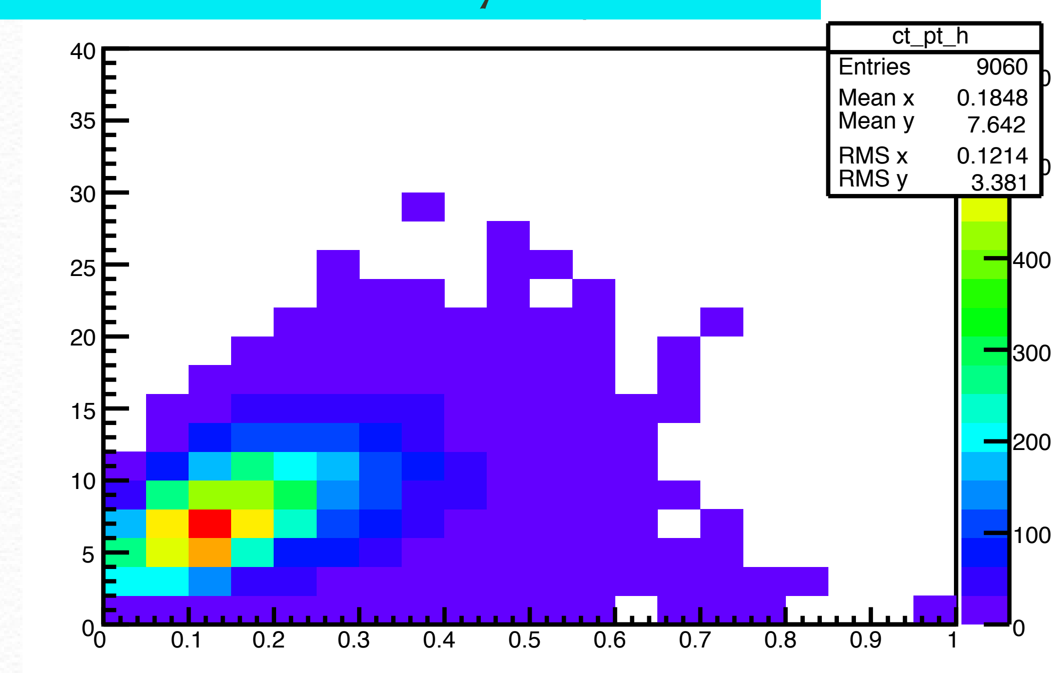
in the central region

Enhancement of S/N by factor 2

number of track




jet width

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# 3.. Composite Models

- Technicolor model... Scale up of chiral symmetry breaking in QCD. Higgs as pion（bound state of some strong interaction)　conflicts with EW precision data

- The Little Higgs model→Composite Higgs model
  - Higgs as the pNGB of some global symmetry breaking. Typically SO(5)/SO(4), either elementary or composite
  - The theory still needs **"top partners"**, because top must be in a representation of the global symmetry
  - UV completion ⇄ RS model　　Holography

# Physics

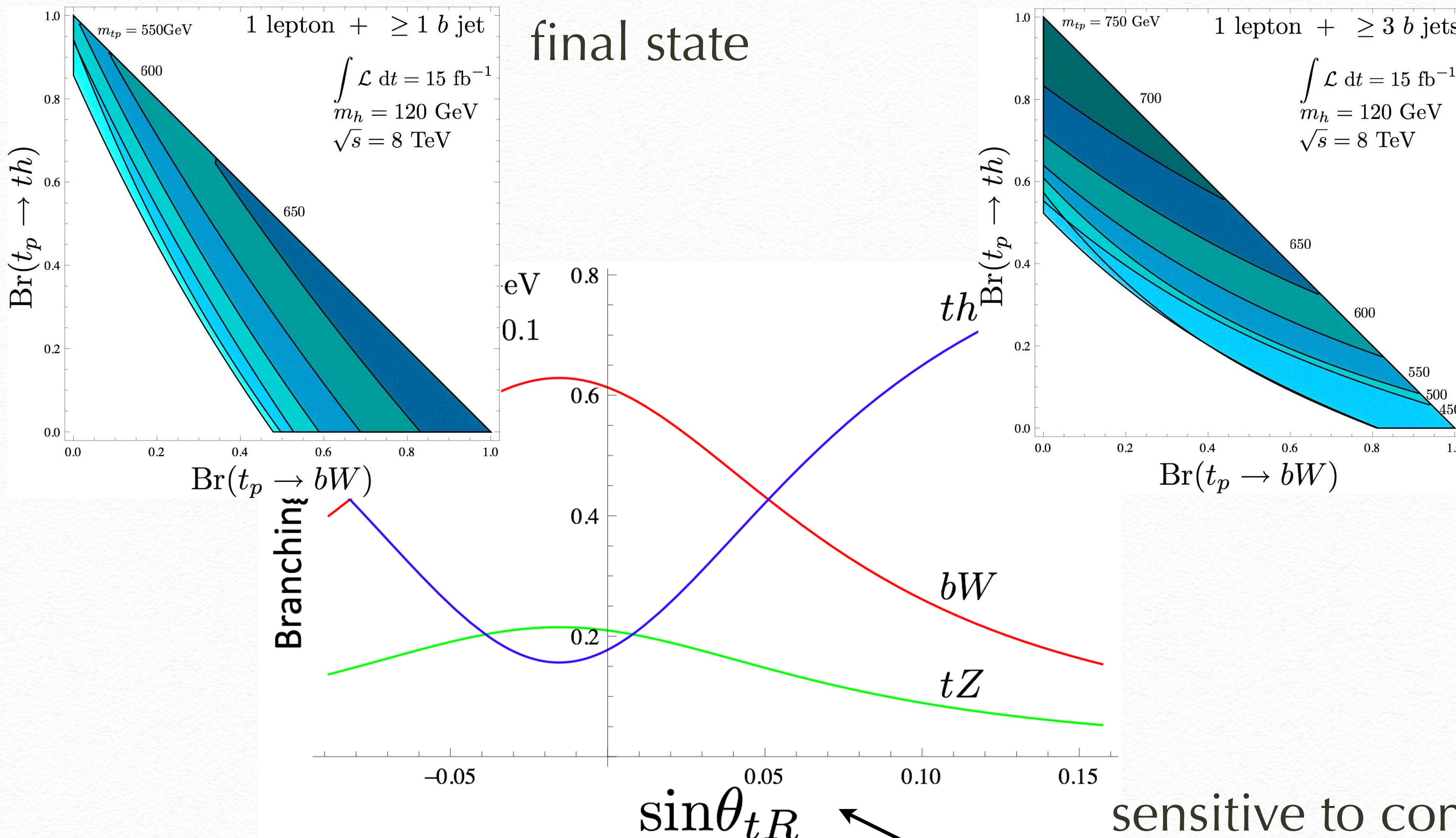
- Top partners from $SU(2)_L$x $SU(2)_R$ symmetry
  - $T_L$ $T_R$ mixed with $t_L$ $t_R$ in standard model sector then decay into bW, tZ, tH.
  - q(Q=5/3), q(2/3), q(-1/3)    Agashe, Contino Pomarol
- RS model --gluon KK (production: coupling to the 1st generation quark, dominantly decays into ttbar)
- Radiative correction to Higgs decay
- Being now constrained by LHC

# top partner study at LHC

Harigaya , Matsumoto, Nojiri, Tobioka PRD86(2012) 015005

1b for b W final state

3b for th final




sensitive to composit

$$\mathcal{L}_{\rm eff} = -m_U \bar{U}_L U_R - y_3 \bar{Q}_{3L} H^c u_{3R} - y_U \bar{Q}_{3L} H^c U_R - (\lambda/\Lambda)\, \bar{U}_L u_{3R} |H|^2 + h.c.,$$

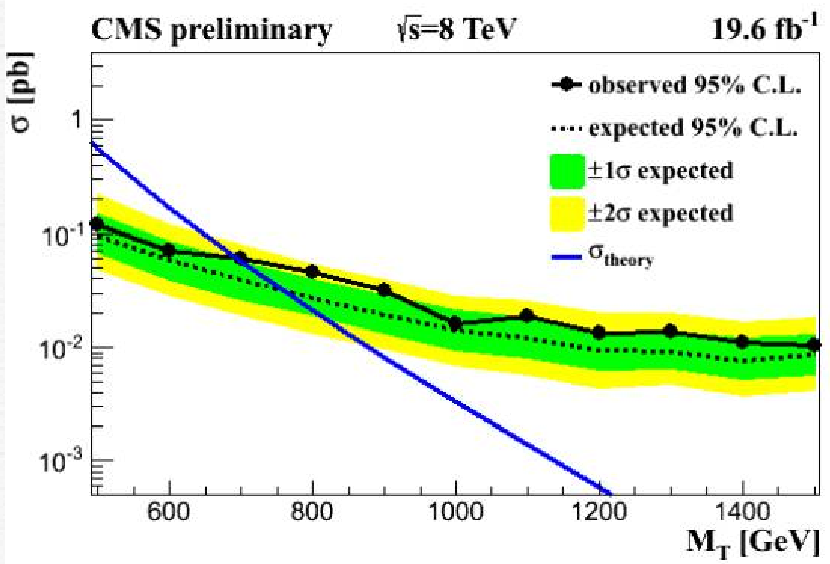
# VLQ $T^{2/3}$ : all channels

The limits are calculated with a likelihood fit

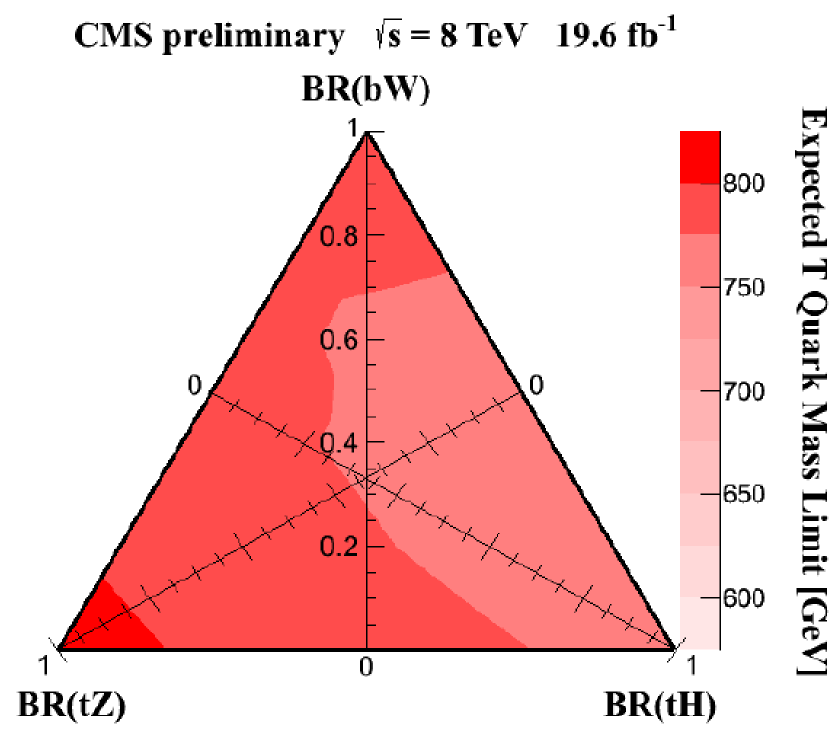
- based on the number expected and observed for the multilepton channels
- based on the BDT discribution for the lepton+jets channels

A scan was done with BR to tW, bZ, bH varying with step of 0.1:

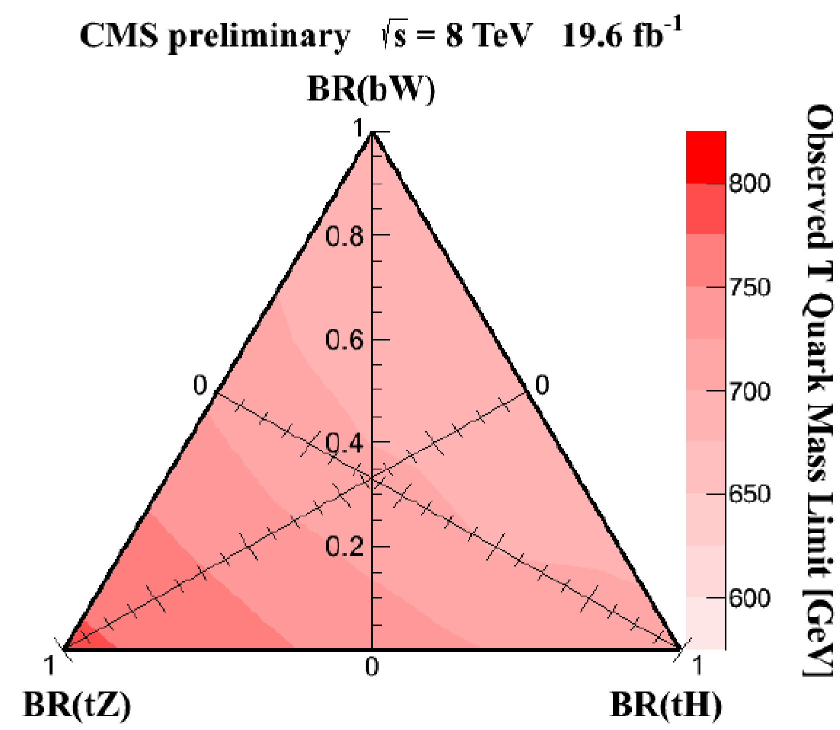
For BR(B→tW)=50%
BR(B→tZ)=25%
BR(B→tH)=25%




**Observed limit**: 696 GeV




Expected limits




Observed limits

Masses below 687-782 GeV are excluded on 95% CL depending on combination of branching fractions.

real data(CMS)
see also ATLAS talk on Nov 24th



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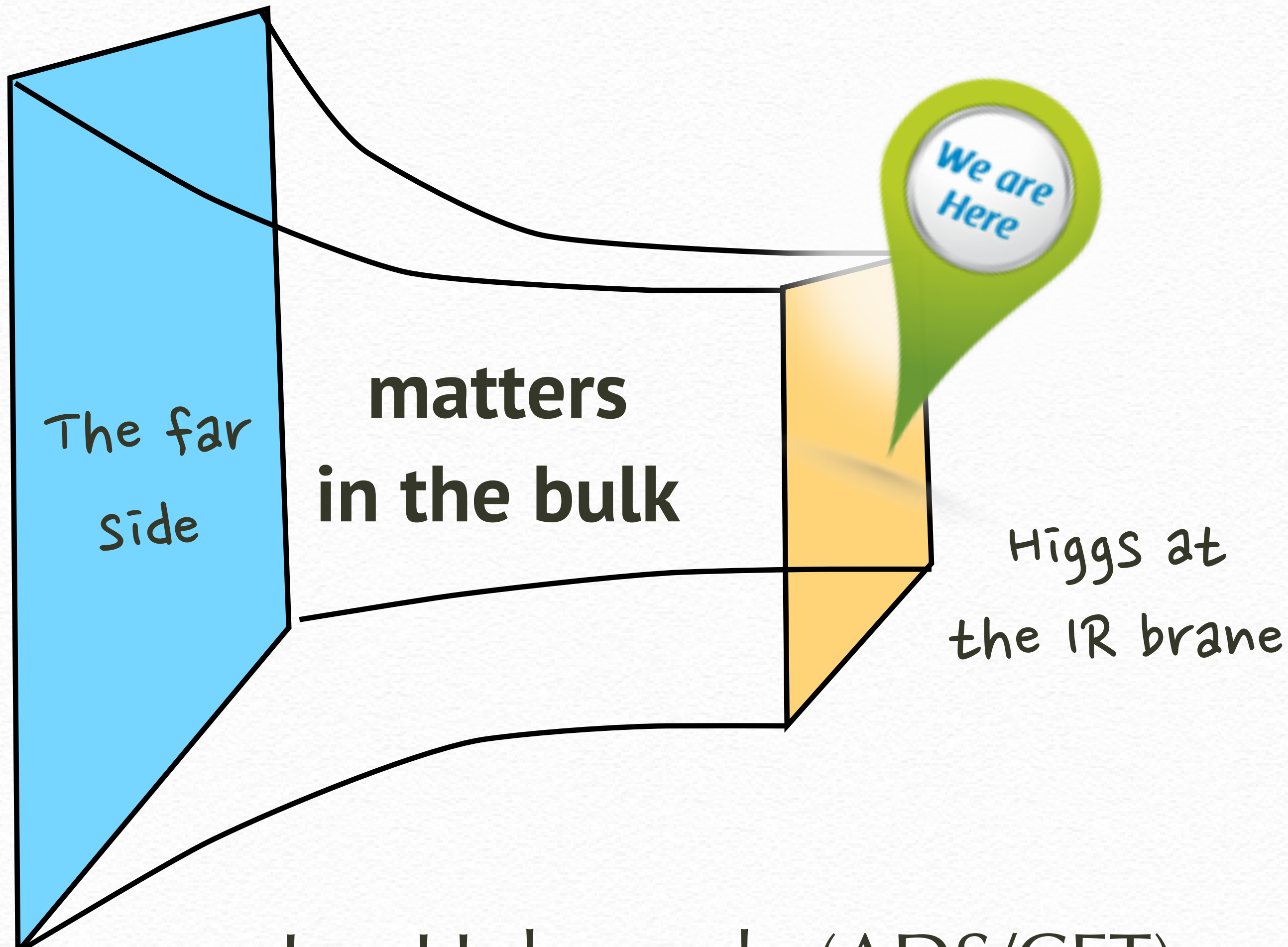
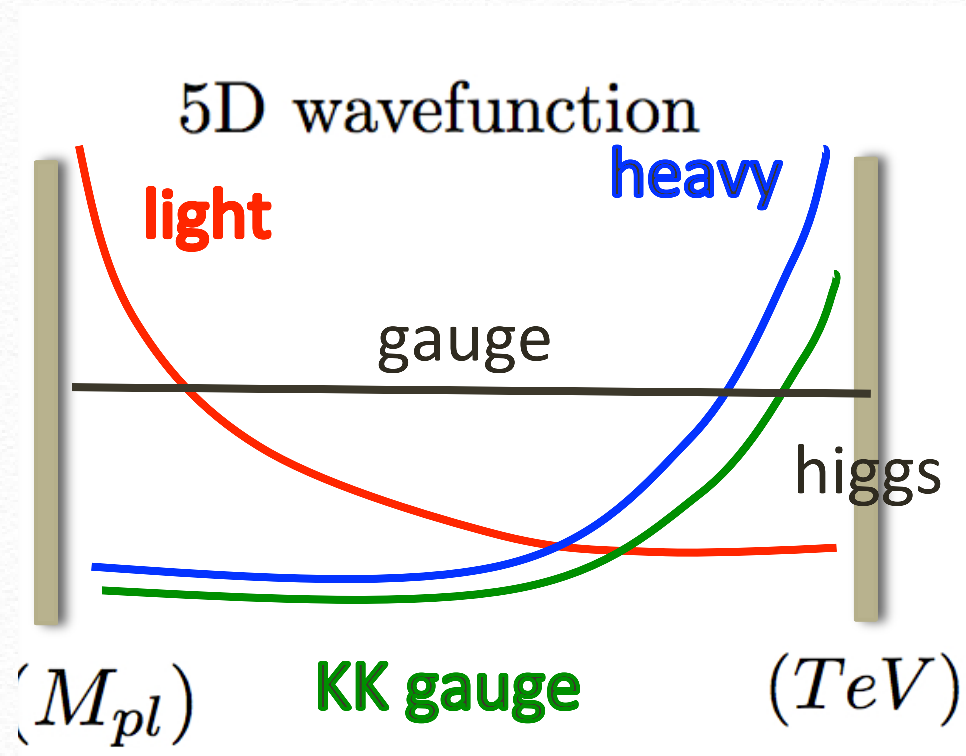
- Randall-Sundrum model (Composite Higgs model)

extra yukawa contribution




In Holography(ADS/CFT) expectation/imagination

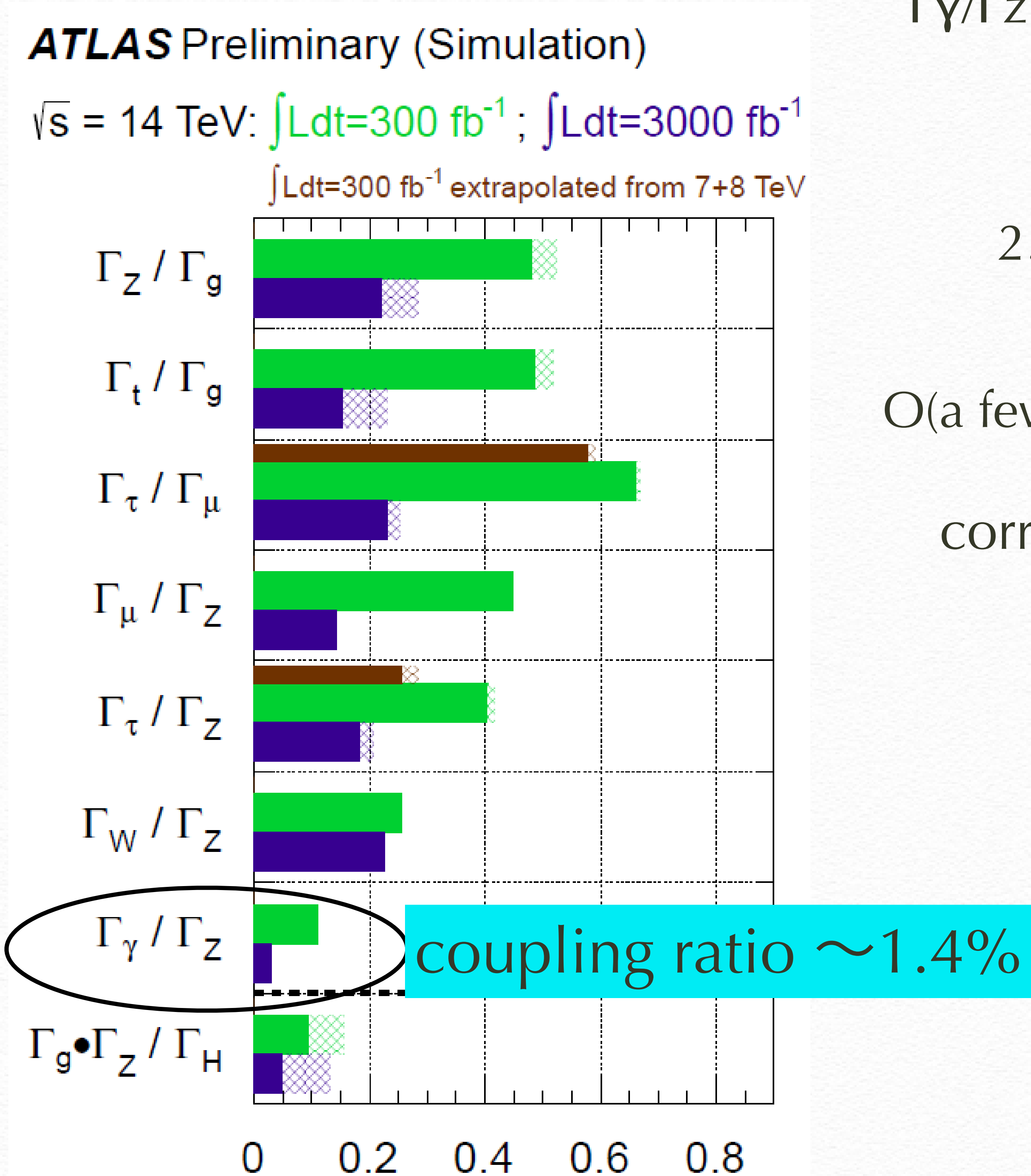
IR brane: breaking of Conformal invariance

anomalous dimension to generate Yukawa coupling

5th dimention size -> radion, mix with Higgs boson

precision physics requires Λ~10TeV

# HL-LHC and Higgs Boson




$\Gamma\gamma/\Gamma z$ ~2.9% error from HL-LHC phase2

$\oplus$

ILC error of H width

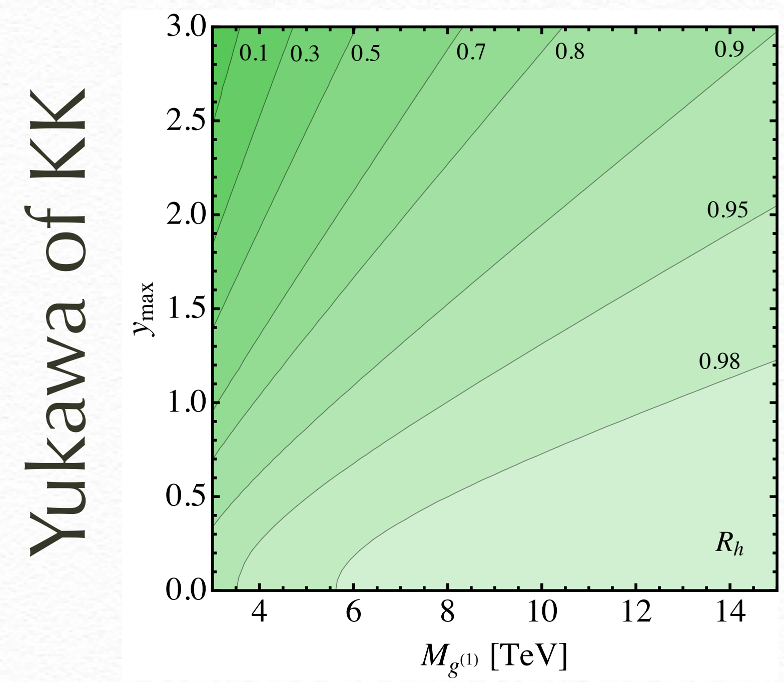
2.7%(Lum up 0.5%) at 500GeV,

$\Downarrow$

O(a few %) Br for γγ, and gg, loop physics

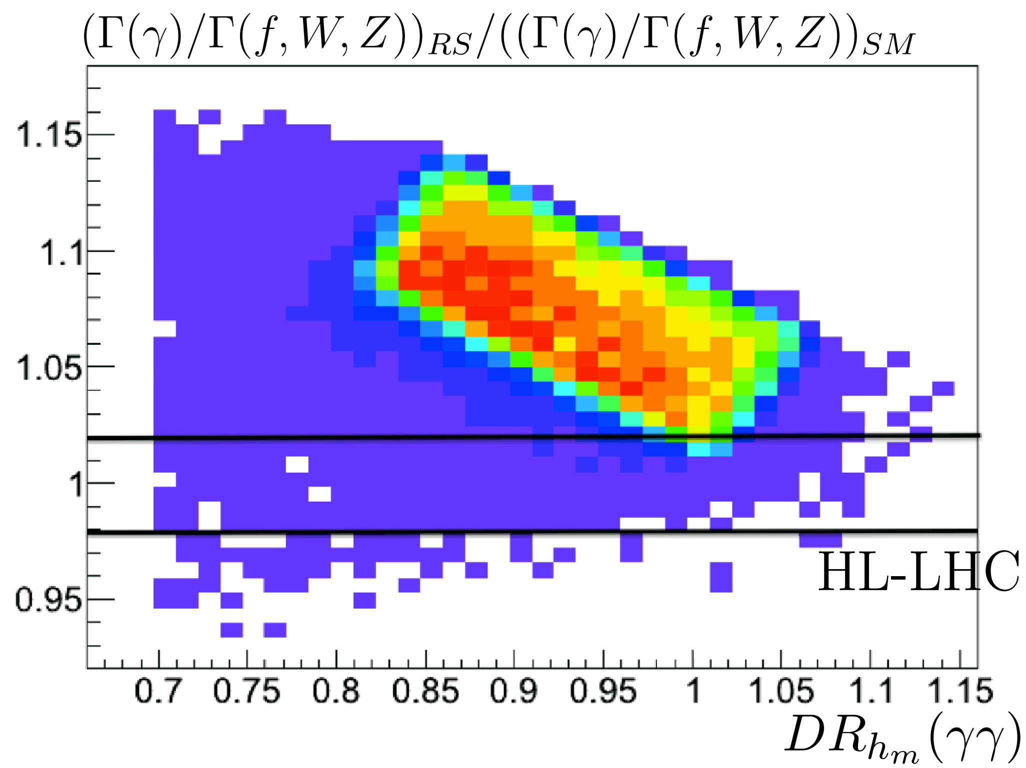
correction to gg→ h production

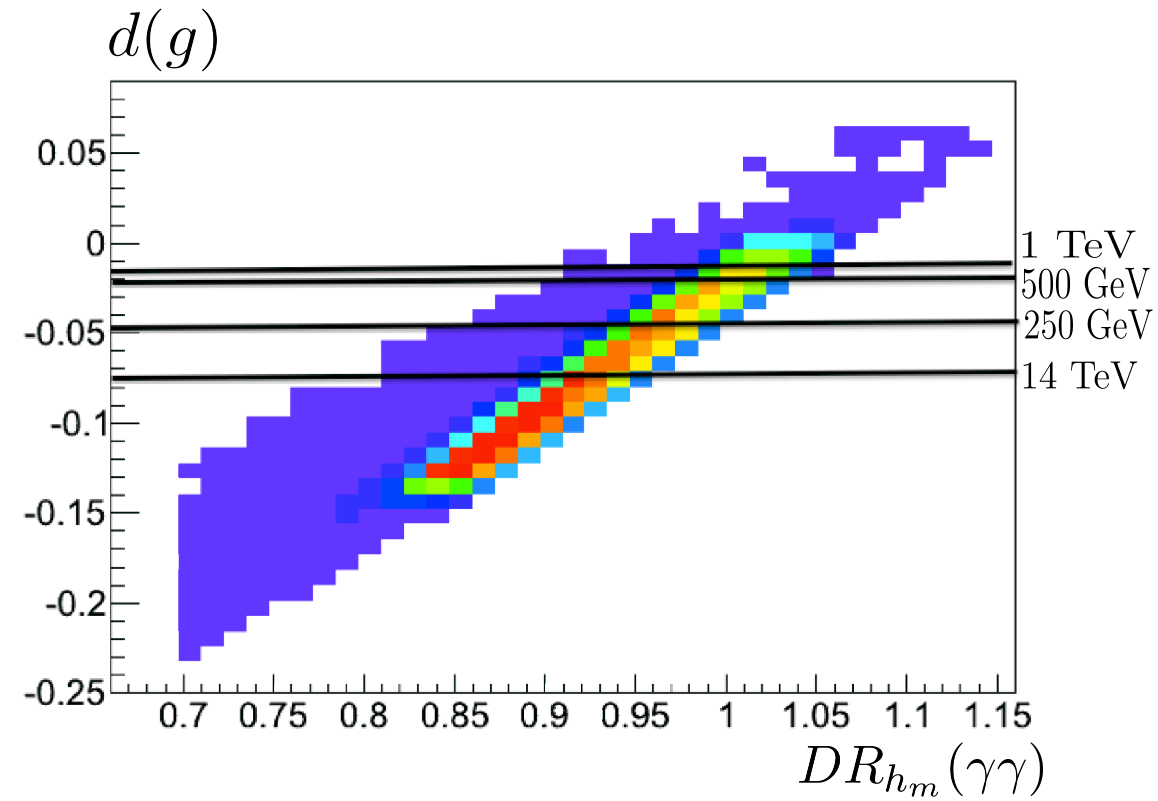
Carena et al JHEP 1208(2012)156

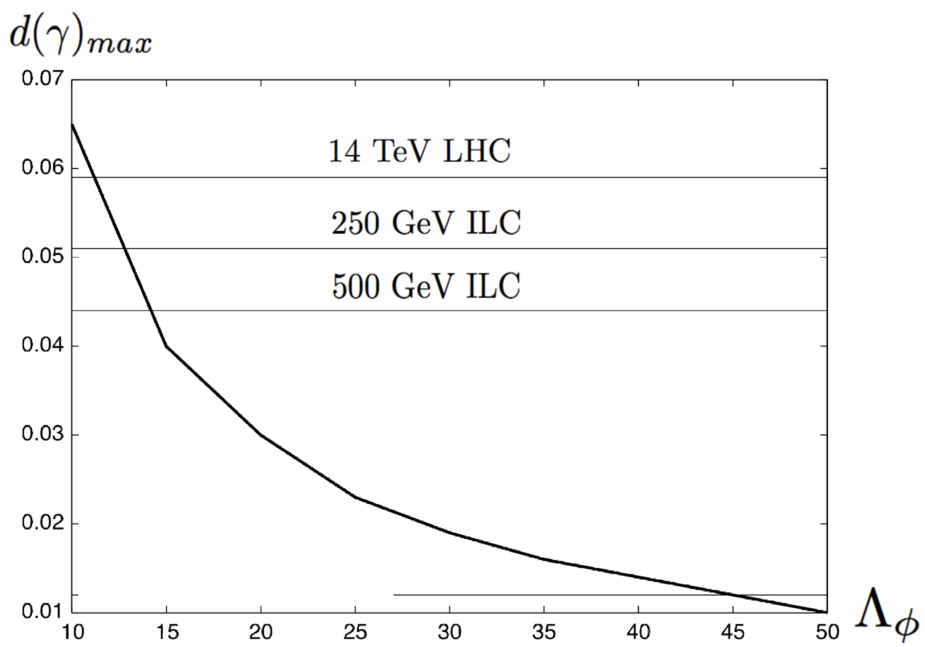



mass of gluon KK

Deviation of higgs couplings in each channels in radion-higgs miixng model and sensitivity in future colliders




$\Lambda_\phi$=10 TeV

separation of effect of measurement of bulk yukawa coupling and radion higgs mixing is also possible

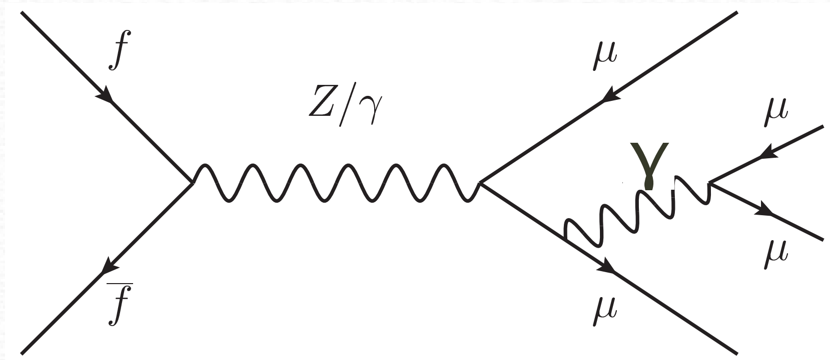
Kubota and Nojiri in progress

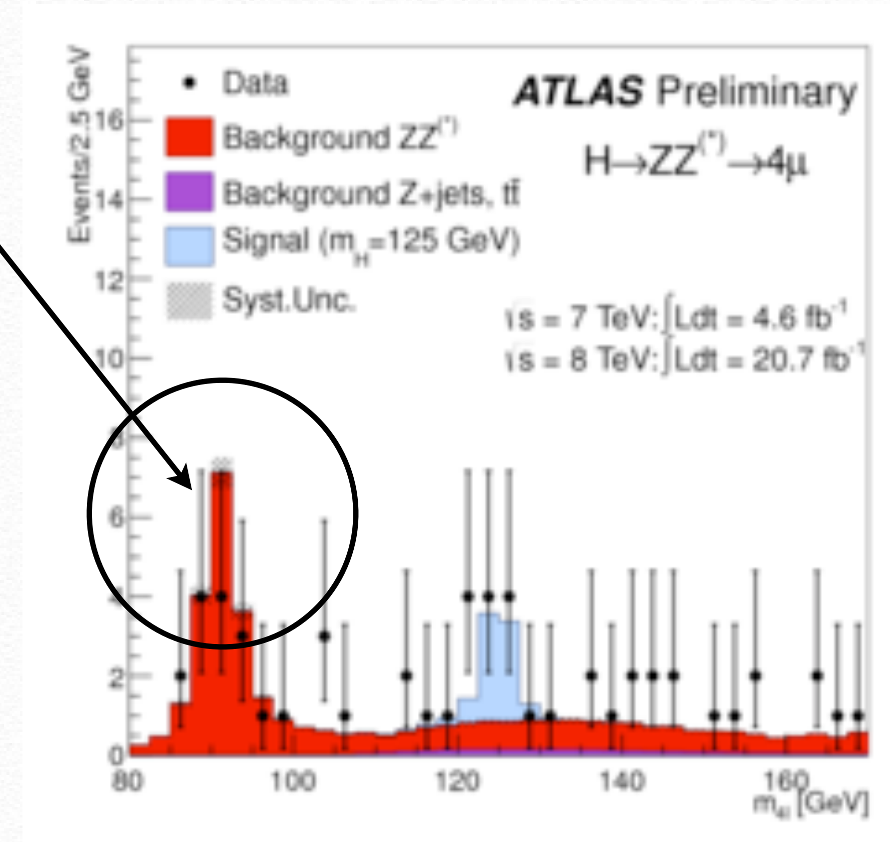
We can observe deviations even strong constraint at the ILC

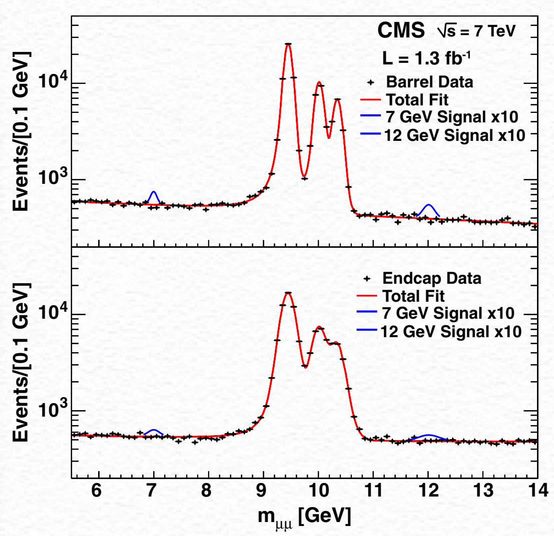
# 4. leptons!
# at future collider

# power of LHC~Luminosity

This is something
we have not seen before

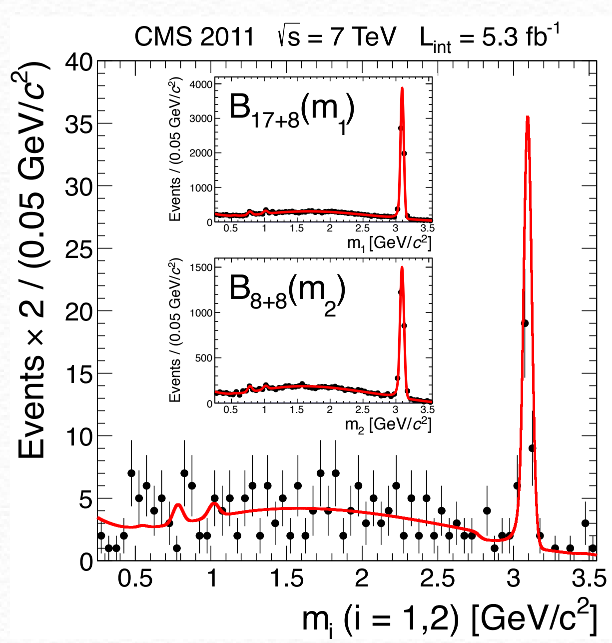


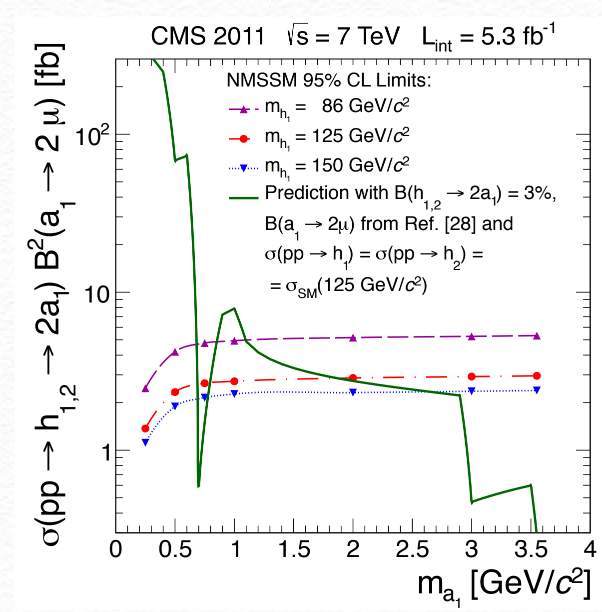

search of light Higgs
decaying into 2μ

PRL 109.121801



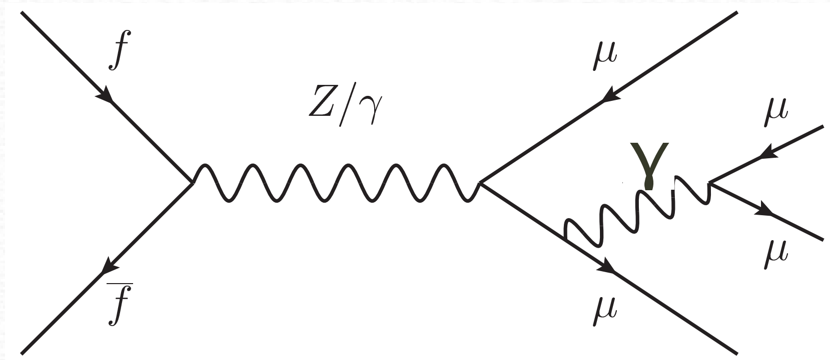

h→ a1 a1 →4μ

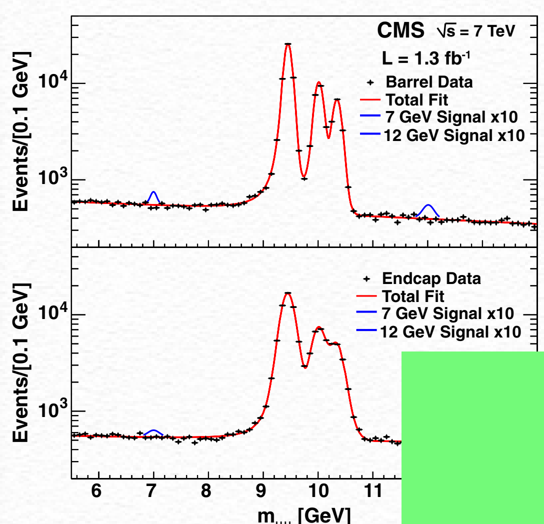
CMS 4μ search
1210.7619



# power of LHC~Luminosity

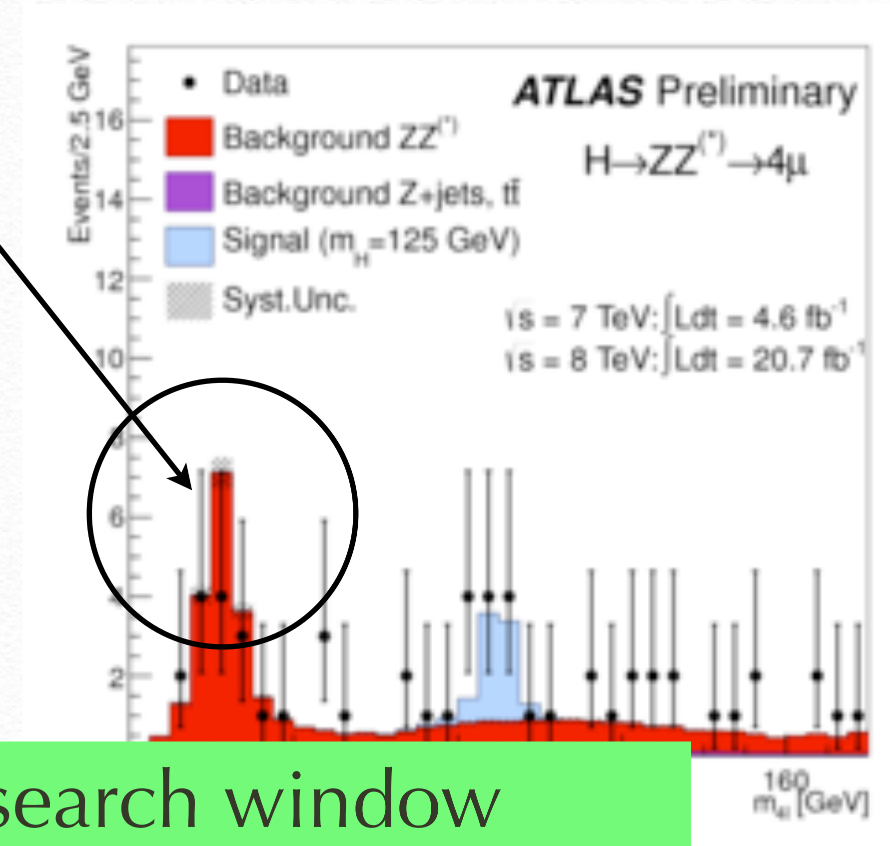
This is something
we have not seen before



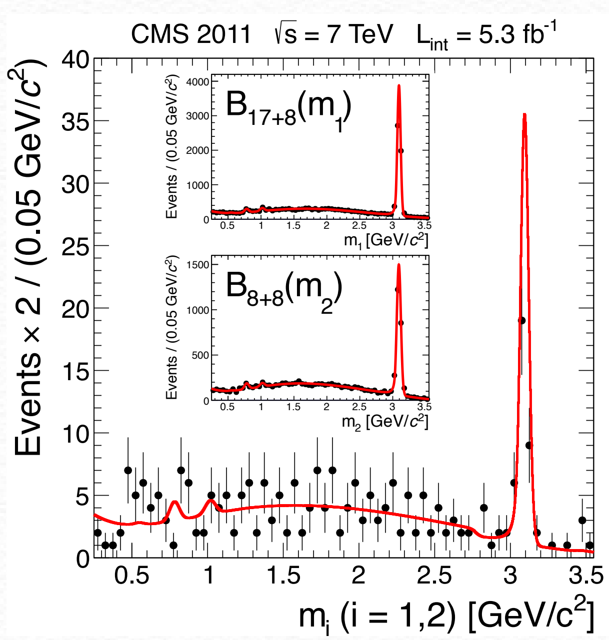




search of light Higgs
decaying into 2μ

PRL 109.121801

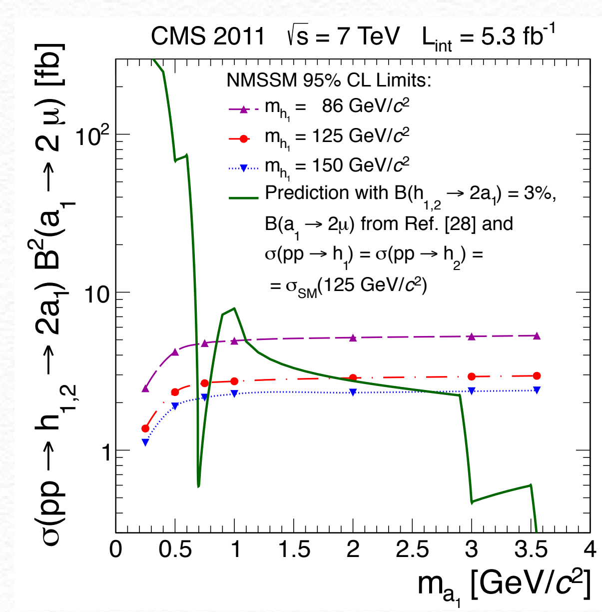



LHC open up new search window
for "anything decaying to leptons "




h→ a1 a1 →4μ

CMS 4μ search
1210.7619

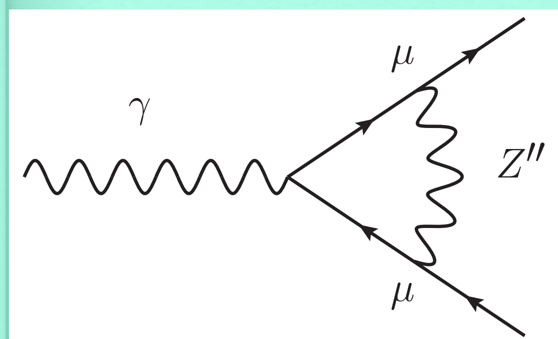



13年11月25日月曜日

# L(mu)-L(tau) Z″ modelfor $a_\mu$ deviation

Harigaya, Igari Takeuchi, Tobe, Nojiri 1311.0870

## contribution to muon g-2




He et al (1991)
Baek et al 2001)
Ma et al (2002)
Salvioni, et al (2010)

## improve SM fit a bit

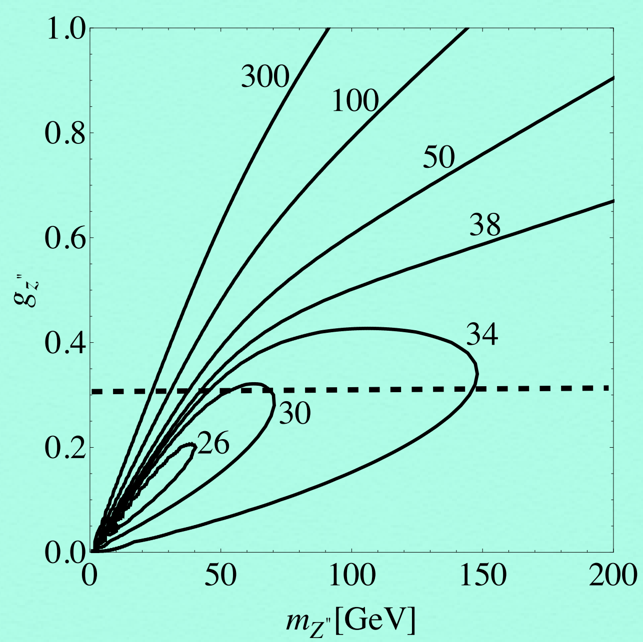
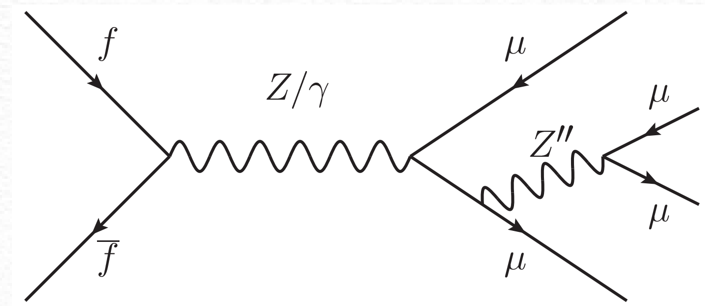
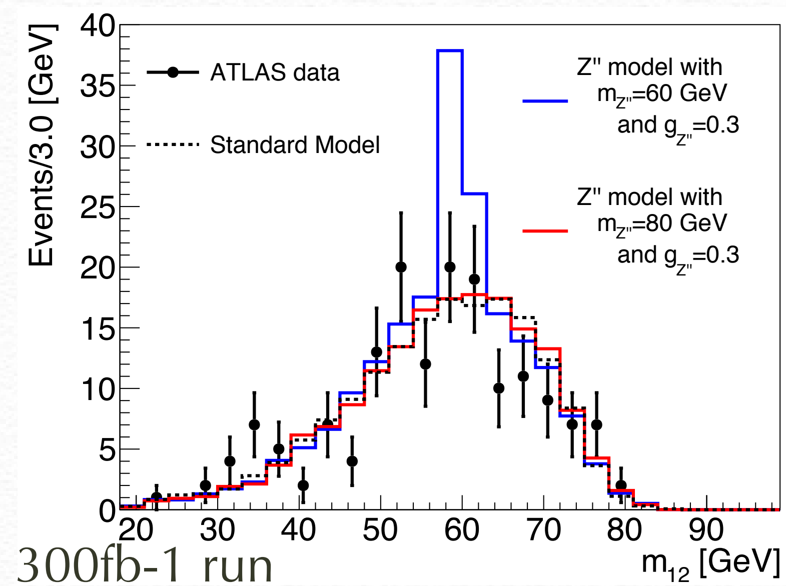



Figure 4: The total $\chi^2$ in the $(m_{Z''}, g_{Z''})$ plane.

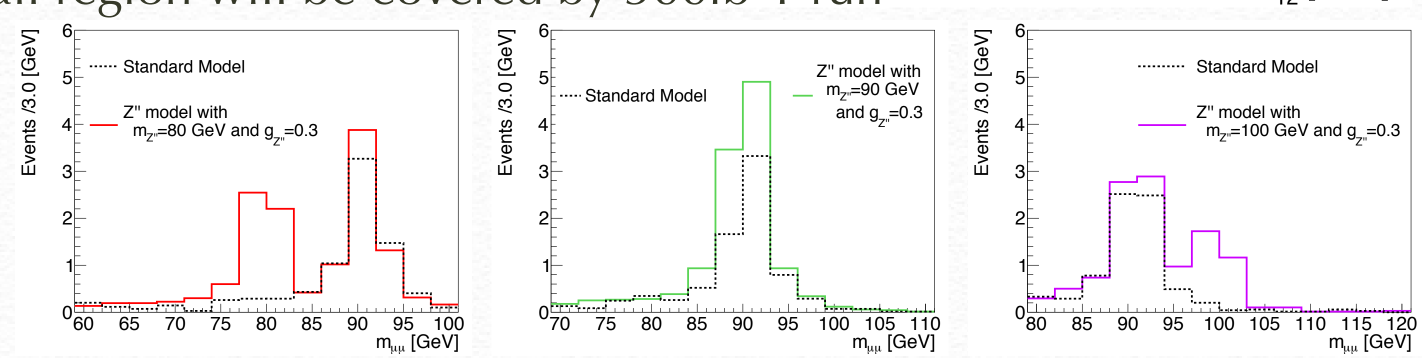
## At LHC




REAL data !
60GeV Z″ must
be excluded
from H→ZZ→ 4μ
data




all region will be covered by 300fb-1 run




(a) (b) (c)

Figure 9: The $(m_{\mu\mu})$ distributions in the $2\mu2\tau$ channel at $\sqrt{s} = 14$ TeV for the SM (dashed line) and for the $Z''$ model with $m_{Z''} = 80,\ 90,$ and 100 GeV (solid lines, from left to right). The integrated luminosity of 300 fb$^{-1}$ is assumed.

# dark matter and Baryon number

- Dark matter and Baryon may be related in asymmetric dark matter model

$$m_{\rm DM} = \frac{30}{97}\frac{79}{22}\frac{\Omega_{\rm DM}}{\Omega_b}\frac{m_N}{Q_{\rm DM}} \simeq \frac{5.7\,{\rm GeV}}{Q_{\rm DM}}.$$

ϕ: interaction to kill symmetric component mix with Higgs boson !

$$\mathcal{L} = i\,\overline{\chi}(\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu\phi'\partial^\mu\phi' - m_{\phi'}^2\phi'^2) - \kappa\overline{\chi}\chi\phi' - V(H',\phi'),$$

Ibe, Matsumoto, Yanagida Phys. Lett B708(2012)112

from CMS 2μ

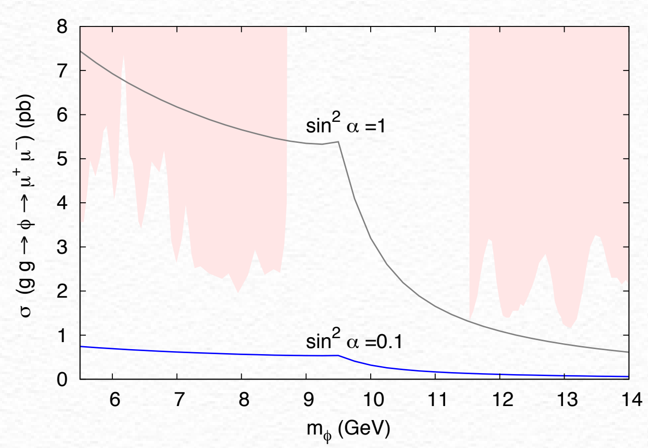
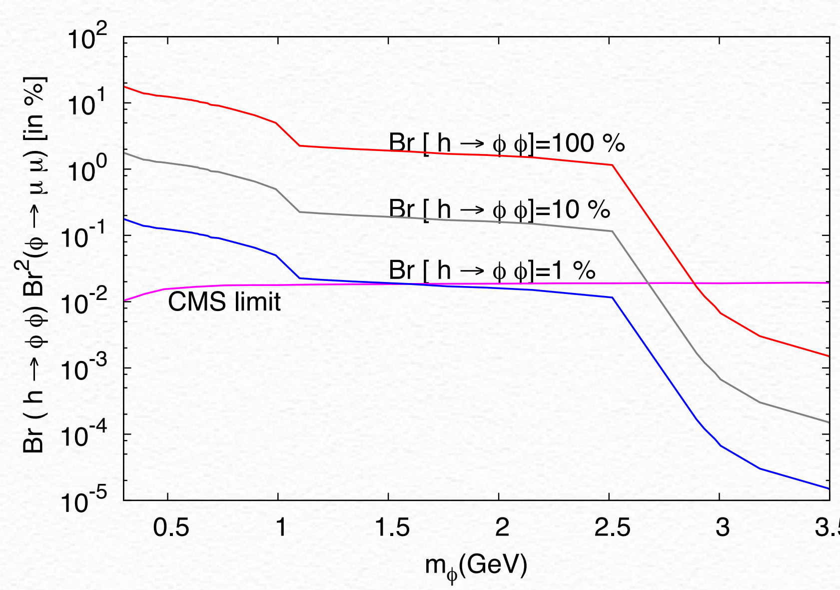



Figure 3: $\sigma(gg \to \phi) \times$ Br $(\phi \to \mu\mu)$ as a function of the mediator mass. The shaded region is excluded by the CMS di-muon resonance search at 7 TeV LHC (with 1.3 fb$^{-1}$ data). The black and blue curves correspond to $\sin^2\alpha = 1$ and 0.1 respectively.

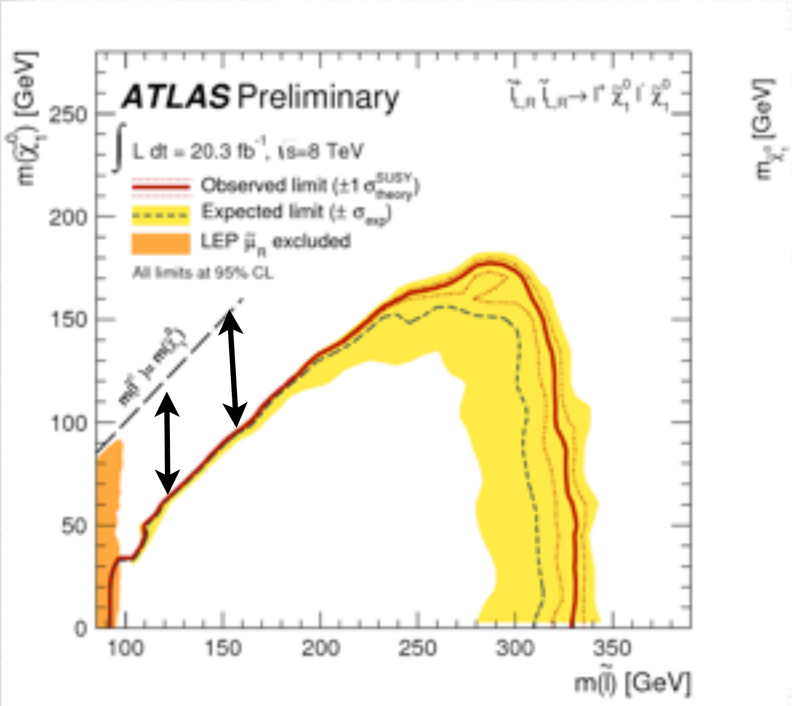
from CMS 4μ

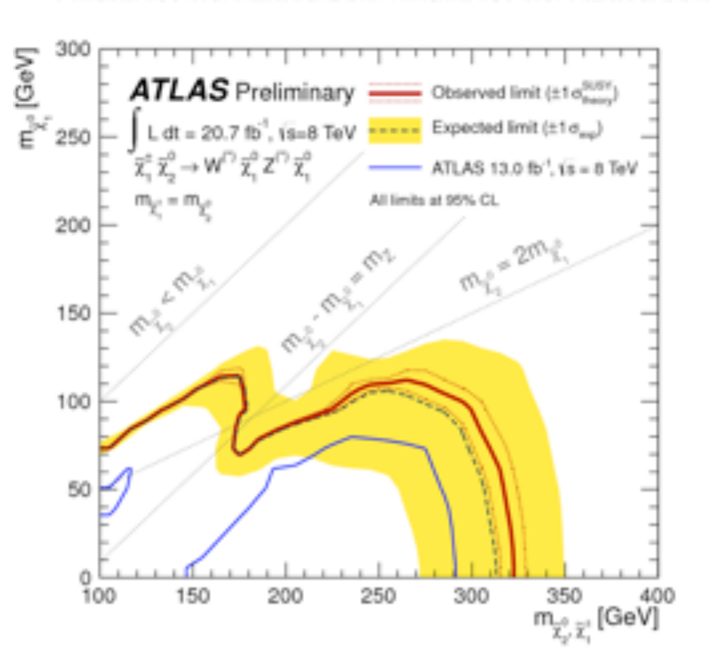



Bhattacherjee Matsumoto, Mukhopadhyay Nojiri
JHEP10(2013)032 arXiv 1306.5878

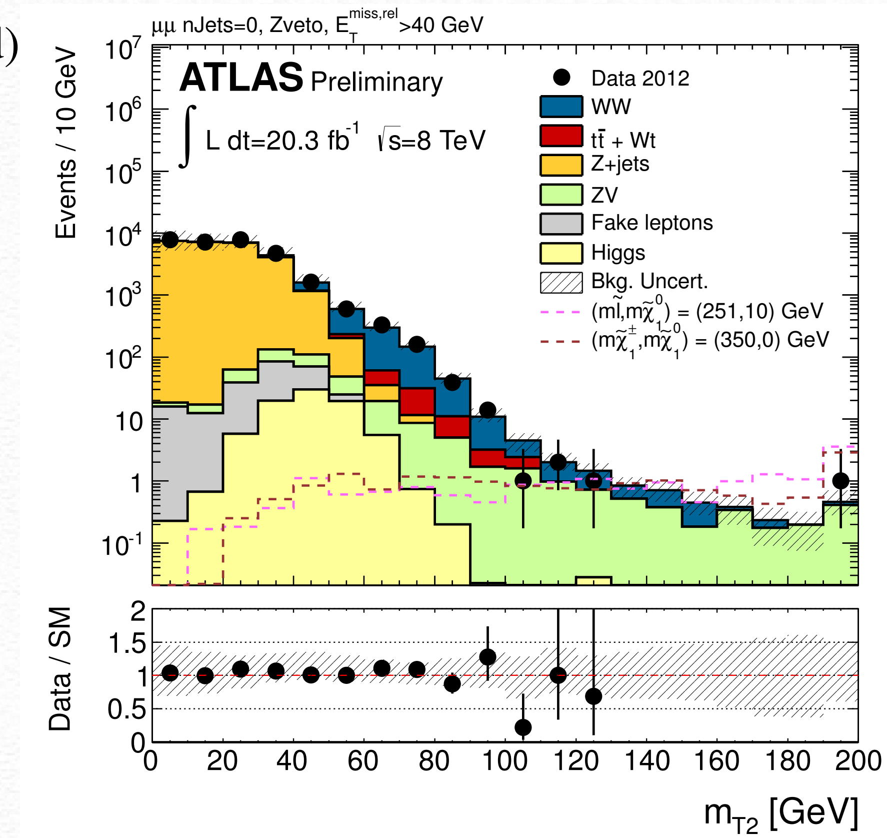
13年11月25日月曜日

# EW SUSY and dark matter

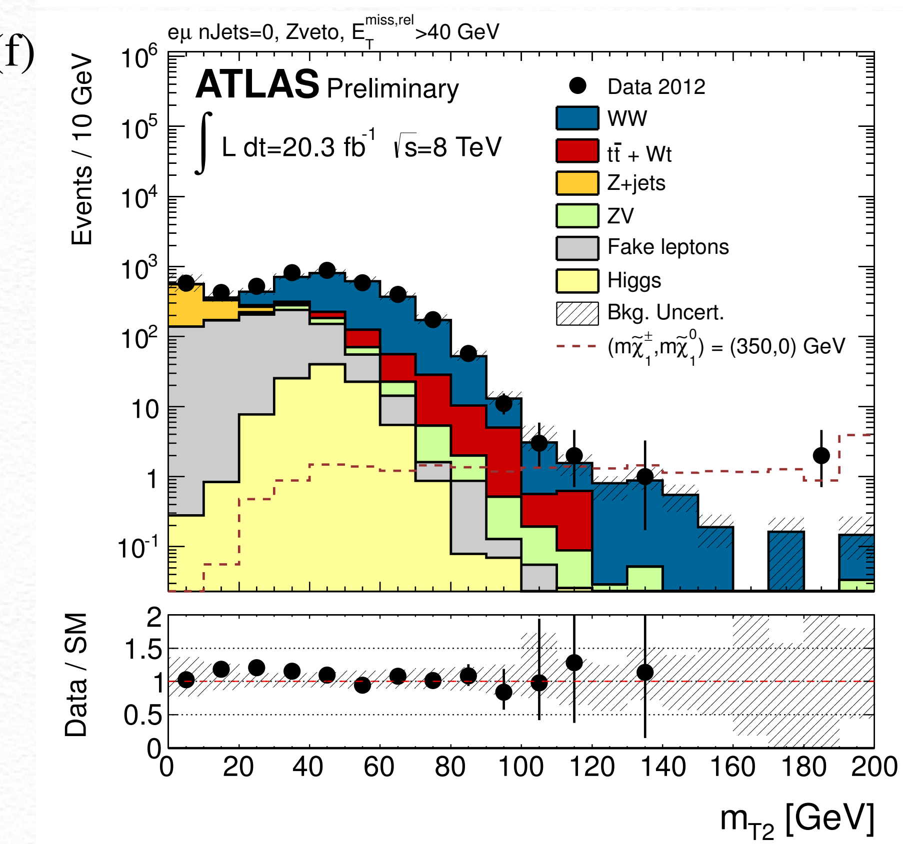



d)




(f)




Reach up to 350 GeV!

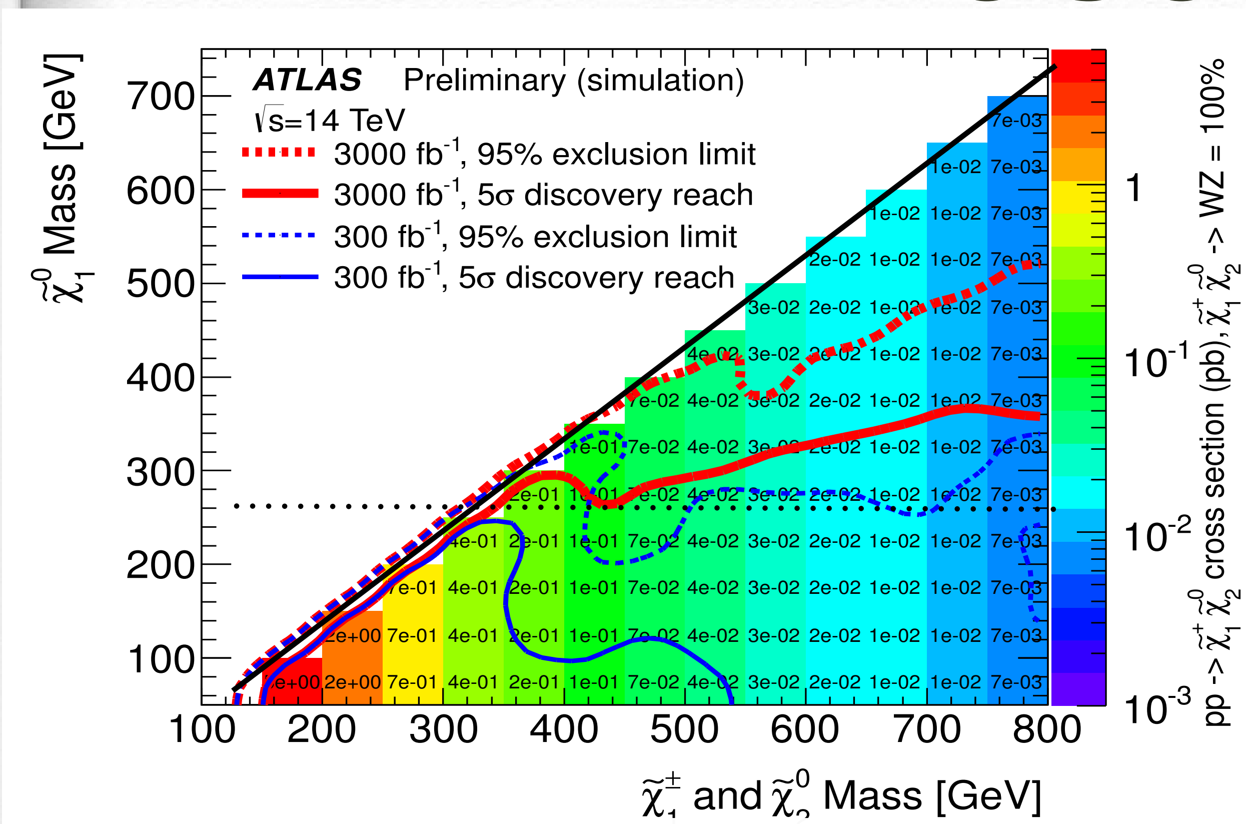
Note however

Mass difference 50 GeV required due to the overlap with W and Z's

LHC seems not to sensitive about tau channel

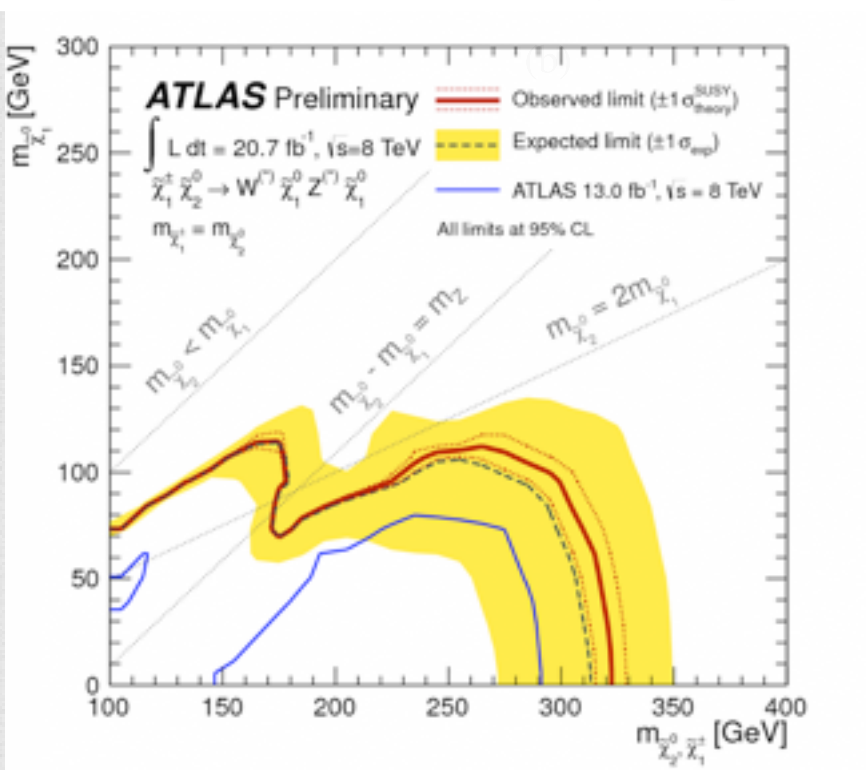
(ILC is more sensitive to those.)

# EW SUSY at HL-LHC




extension at HL-LHC (up to $3000 fb^{-1}$) because lepton trigger rate will be kept

**LHC will be sensitive to Lepton channel !**



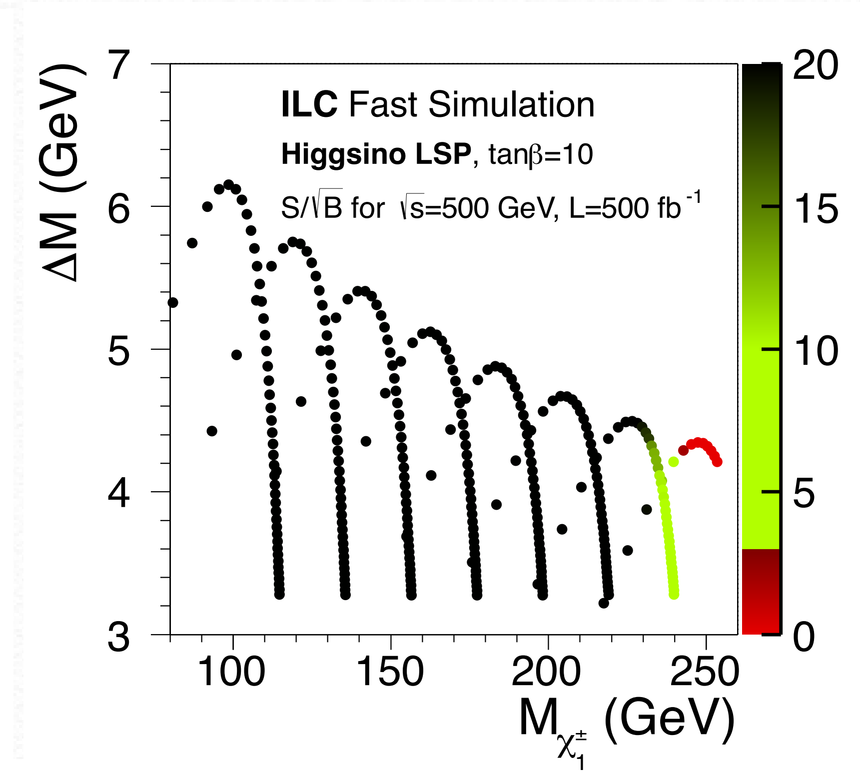

current limit

| Object(s) | Trigger | Estimated Rate | |
|---|---|---|---|
| | | no L1Track | with L1Track |
| $e$ | EM20 | 200 kHz | 40 kHz |
| $\gamma$ | EM40 | 20 kHz | 10 kHz* |
| $\mu$ | MU20 | > 40 kHz | 10 kHz |
| $\tau$ | TAU50 | 50 kHz | 20 kHz |
| $ee$ | 2EM10 | 40 kHz | < 1 kHz |
| $\gamma\gamma$ | 2EM10 | as above | ~5 kHz* |
| $e\mu$ | EM10_MU6 | 30 kHz | < 1 kHz |
| $\mu\mu$ | 2MU10 | 4 kHz | < 1 kHz |
| $\tau\tau$ | 2TAU15I | 40 kHz | 2 kHz |
| Other | JET + MET | ~ 100 kHz | ~ 100 kHz |
| Total | | ~ 500 kHz | ~ 200 kHz |

Table 2.3: The expected Level-1 trigger rates at $7 \times 10^{34}$ $cm^{-2} s^{-1}$ for the baseline scali

# ILC for higgsino and wino

1307.5248 Baer et al for Snowmass




(b)

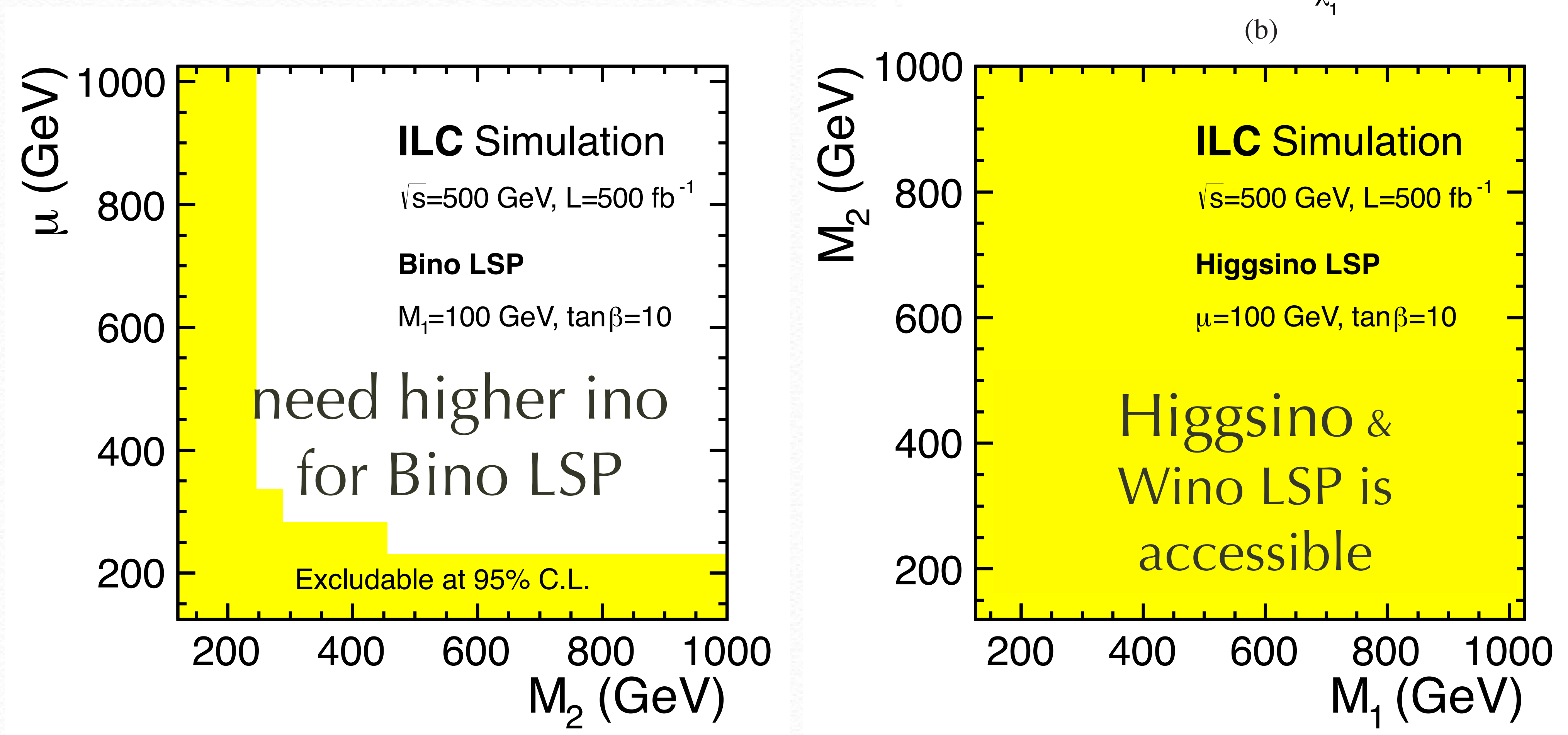



Figure 7: Exclusion reach for electroweakinos at the ILC studied with fast simulation. Left: the case of Bino LSP. Right: the case of Higgsino LSP. The shaded region (yellow) is the expected exclusion reach at 95% confidence level.

# conclusion

- Existing BSM starts being constrained. Extended models are not so simple-- if they are correct answer, why?
- The success of LHC is based on QCD/MC technology
- after 13TeV run, there will be HL-LHC run. With low threshold of leptons, we study EW sector of new physics strongly.
- ILC, if can be build, will allow us to study it further.