Probing T_R at the LHC with long-lived staus.

Koichi Hamaguchi

based on, M.Endo, KH, K.Nakaji, [arXiv:1008.2307]
+ M.Endo, KH, K.Nakaji, in preparation

+ S.Asai, KH, S.Shirai, [arXiv: 0902.3754] PRL,103,141803

COSMO/CosPA 2010 at Tokyo U., September, 2010

Reheating Temperature T_R

$\sim$ highest temperature in the rad. dom. universe.

= one of the most important parameters of cosmology.

time	temperature	
??		inflation
??	T_R	**Reheating**
		⋮ (baryogenesis, dark matter? .....)
1 sec	1 MeV	Big Bang Nucleosynthesis
		⋮ (recombination, structure formation, ...)
10^{10}yr	3 K	today

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Possible probes of T_R

- Gravitational Wave Nakayama, Saito, Suwa, Yokoyama,'08
- CMB Martin, Ringeval,'10 <-- talk by C.Ringeval on Monday
- BBN with long-lived charged massive particle (for low TR). Takayama,'07
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Q: Any (indirect) hint from LHC ??

Main message of this talk:

The T_R can be determined at the LHC.

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If SUSY + gravitino DM + stau NLSP is realized in nature,

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At 7 TeV 1fb^{-1} (≃ within 2 years),
T_R > a few 10^8 GeV can be tested
in most of the parameter space!

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At 7
T_R >
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model dependent ?

.... Yes, but the model itself is testable at the LHC.

signal: metastable massive charged particle

(cf. L.Roszkowski's talk on Monday)

If observed, "gravitino DM + stau NLSP" is
(one of) the best candidates.

(The underlying supergravity may also be tested.
Buchmuller, KH, Ratz, Yanagida,'04)

Main message of this talk:

If **SUSY** + **gravitino DM** + **stau NLSP**
is realized in nature,

The **T_R** can be determined at the **LHC.**

At 7 TeV $1fb^{-1}$ ($\simeq$ within 2 years),
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Main message of this talk:

outline

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If SUSY + gravitino DM + stau NLSP is realized in nature,

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At 7 TeV 1fb^{-1} (≃ within 2 years),
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① SUSY + gravitino DM + stau NLSP

..... why ?

scenario: SUSY + gravitino DM + stau NLSP

why SUSY?

- naturalness, coupling unification, DM, ...
- most non-SUSY scenarios for BSM → low E cut-off

→ how to discuss T > cut off ??: inflation/reheating/baryogenesis....

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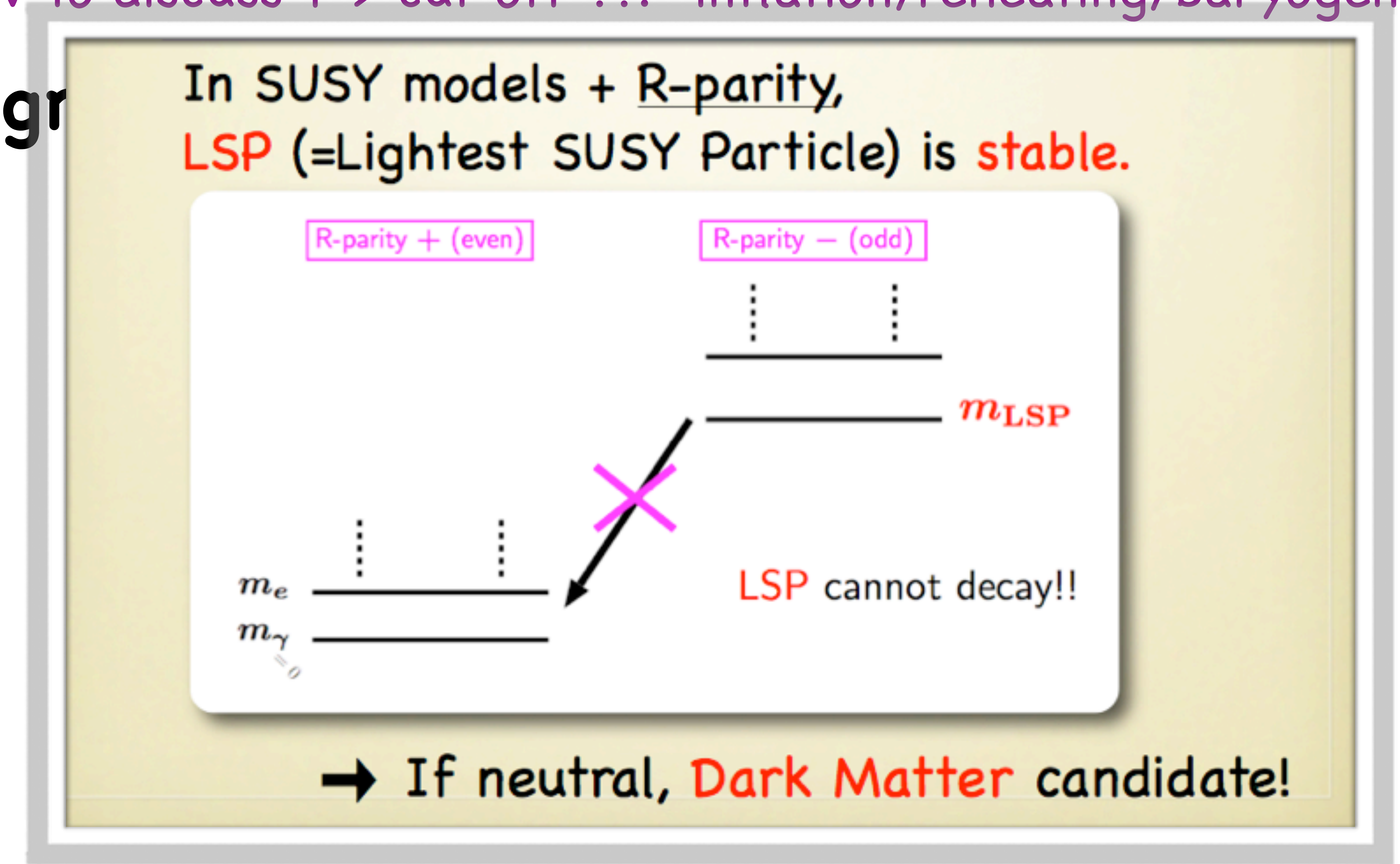

In SUSY models + R-parity,

LSP (=Lightest SUSY Particle) is stable.

LSP cannot decay!!

→ If neutral, Dark Matter candidate!

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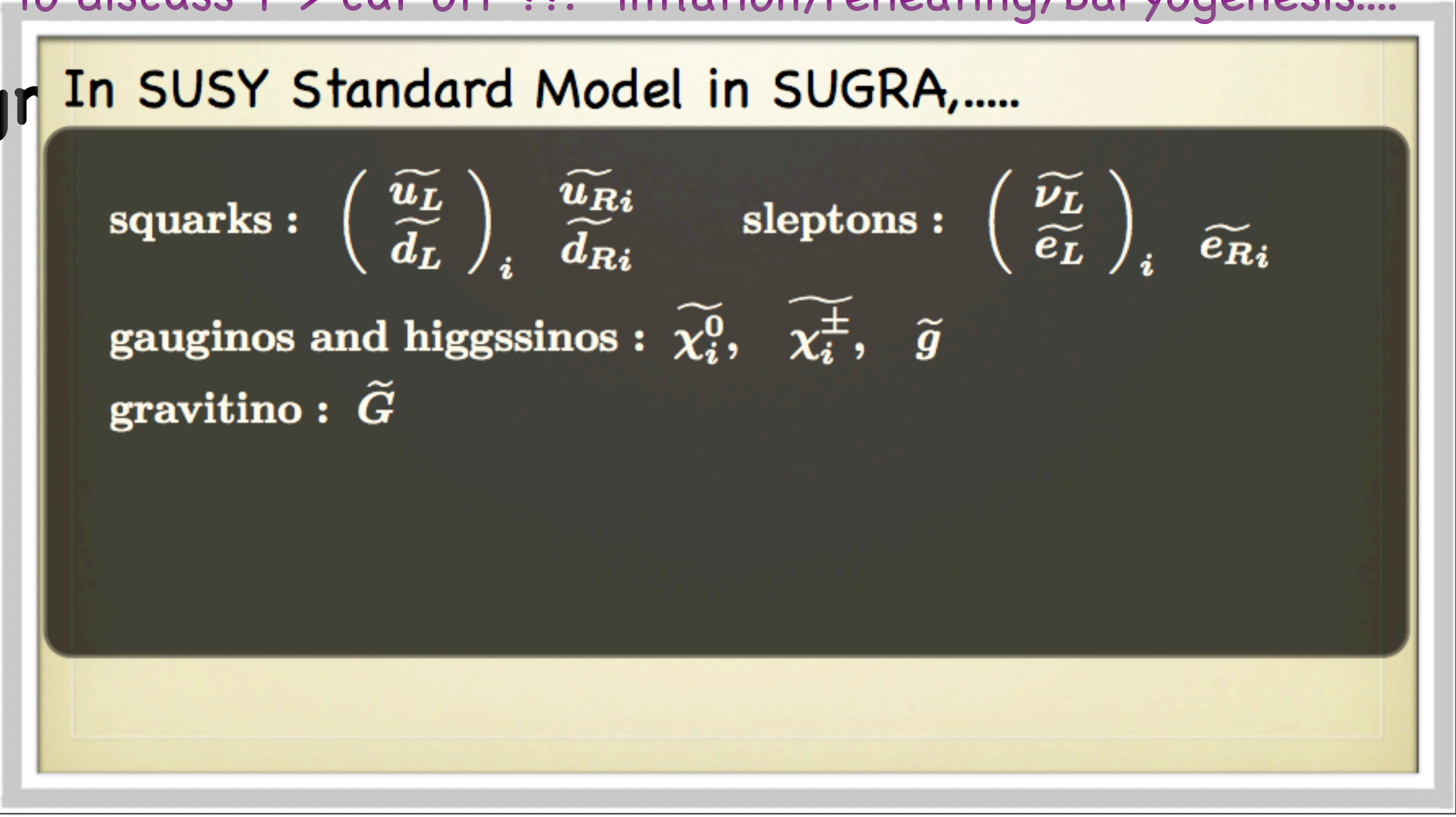

In SUSY Standard Model in SUGRA,.....

squarks : $\begin{pmatrix}\widetilde{u_L}\\ \widetilde{d_L}\end{pmatrix}_i$ $\begin{matrix}\widetilde{u_{Ri}}\\ \widetilde{d_{Ri}}\end{matrix}$ sleptons : $\begin{pmatrix}\widetilde{\nu_L}\\ \widetilde{e_L}\end{pmatrix}_i$ $\widetilde{e_{Ri}}$

gauginos and higgsinos : $\widetilde{\chi_i^0}$, $\widetilde{\chi_i^\pm}$, $\tilde{g}$

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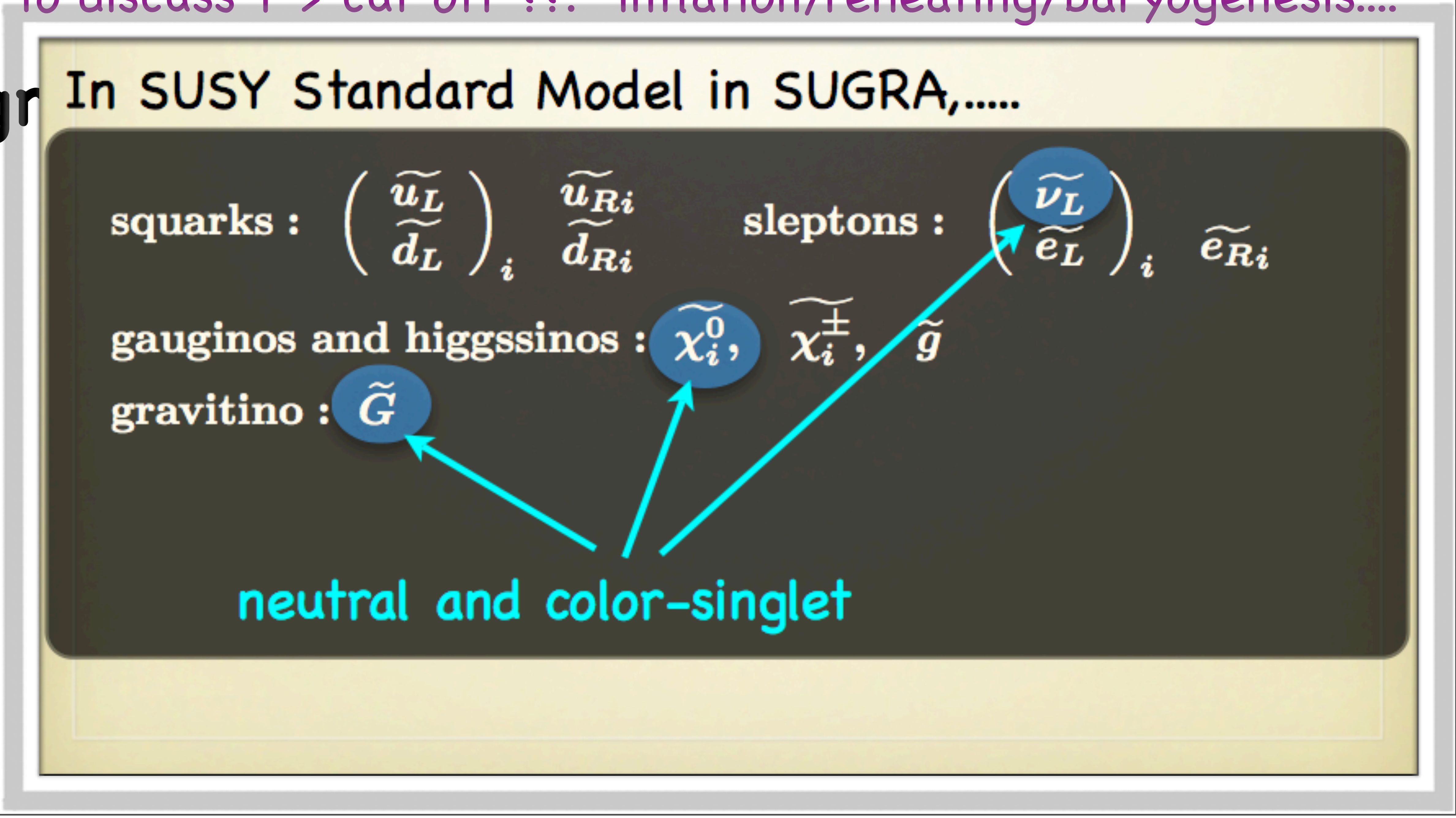

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neutral and color-singlet

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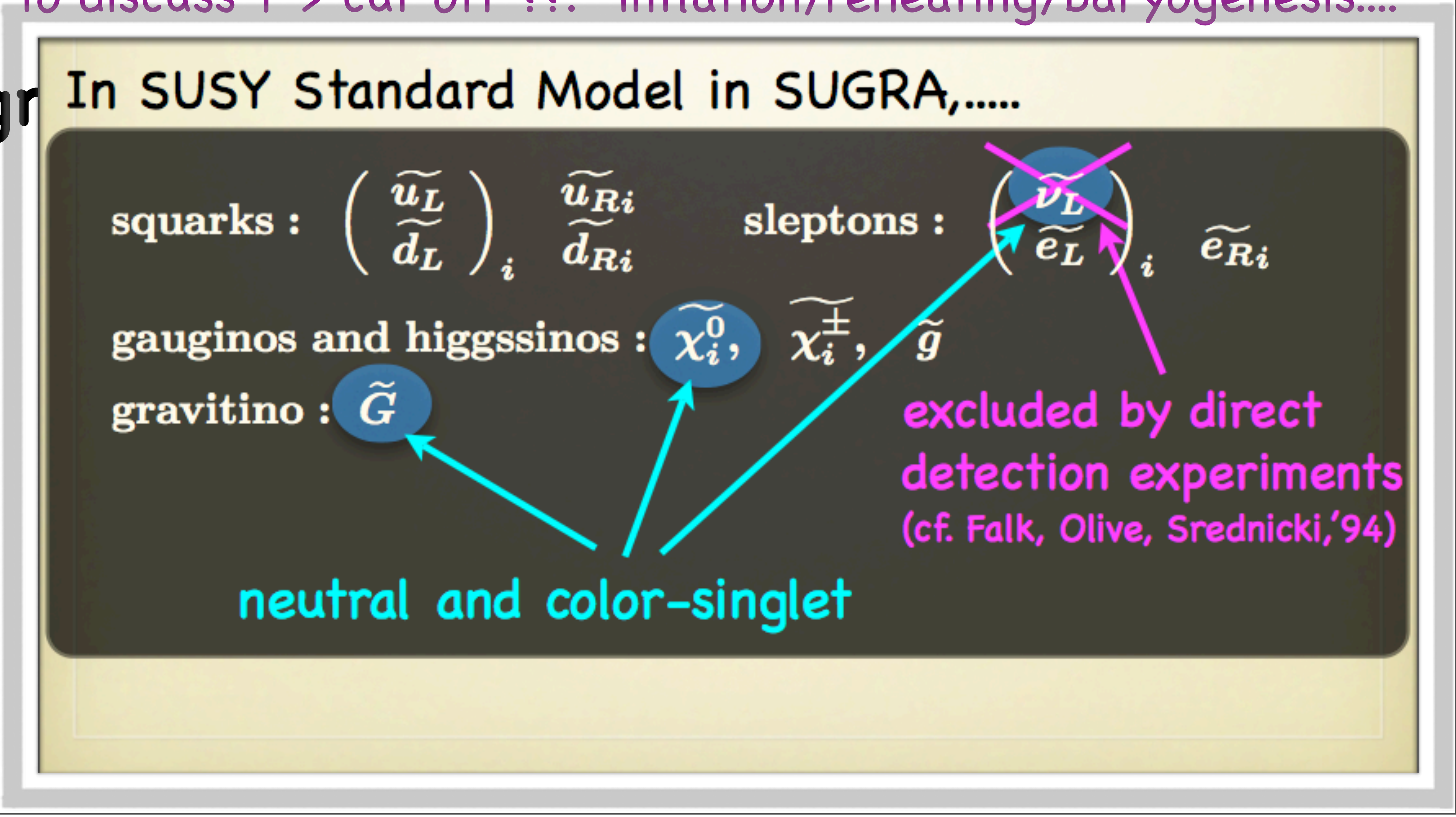

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excluded by direct detection experiments (cf. Falk, Olive, Srednicki,'94)

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→ only gravitino or neutralino are allowed.

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Note:

another interesting possibility: O(eV) gravitino + composite DM.

Nakamura, KH, Shirai, Yanagida,'09

Nakamura, Shirai, in preparation

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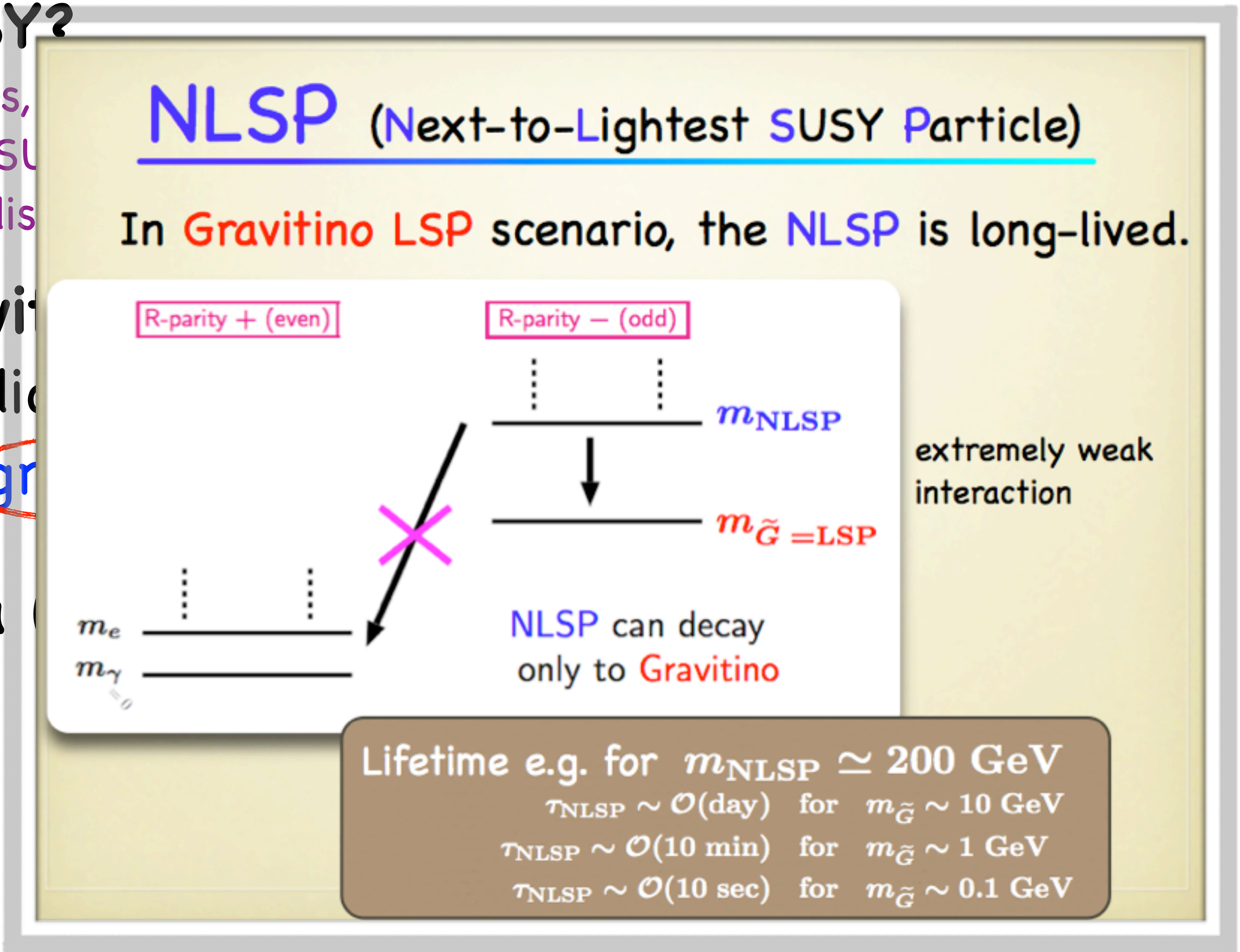
why stau (



NLSP (Next-to-Lightest SUSY Particle)

In Gravitino LSP scenario, the NLSP is long-lived.

extremely weak interaction

NLSP can decay only to Gravitino

Lifetime e.g. for $m_{\rm NLSP} \simeq 200$ GeV

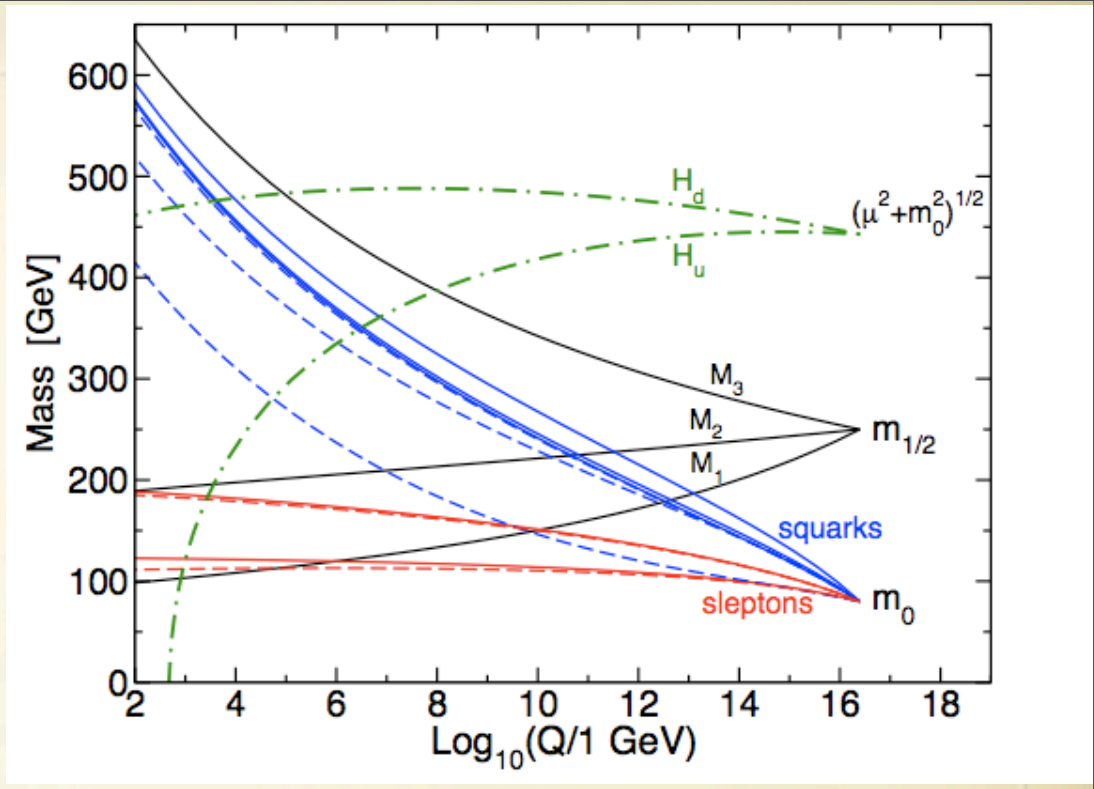
$\tau_{\rm NLSP} \sim \mathcal{O}(\text{day})$ for $m_{\tilde{G}} \sim 10$ GeV

$\tau_{\rm NLSP} \sim \mathcal{O}(10\text{ min})$ for $m_{\tilde{G}} \sim 1$ GeV

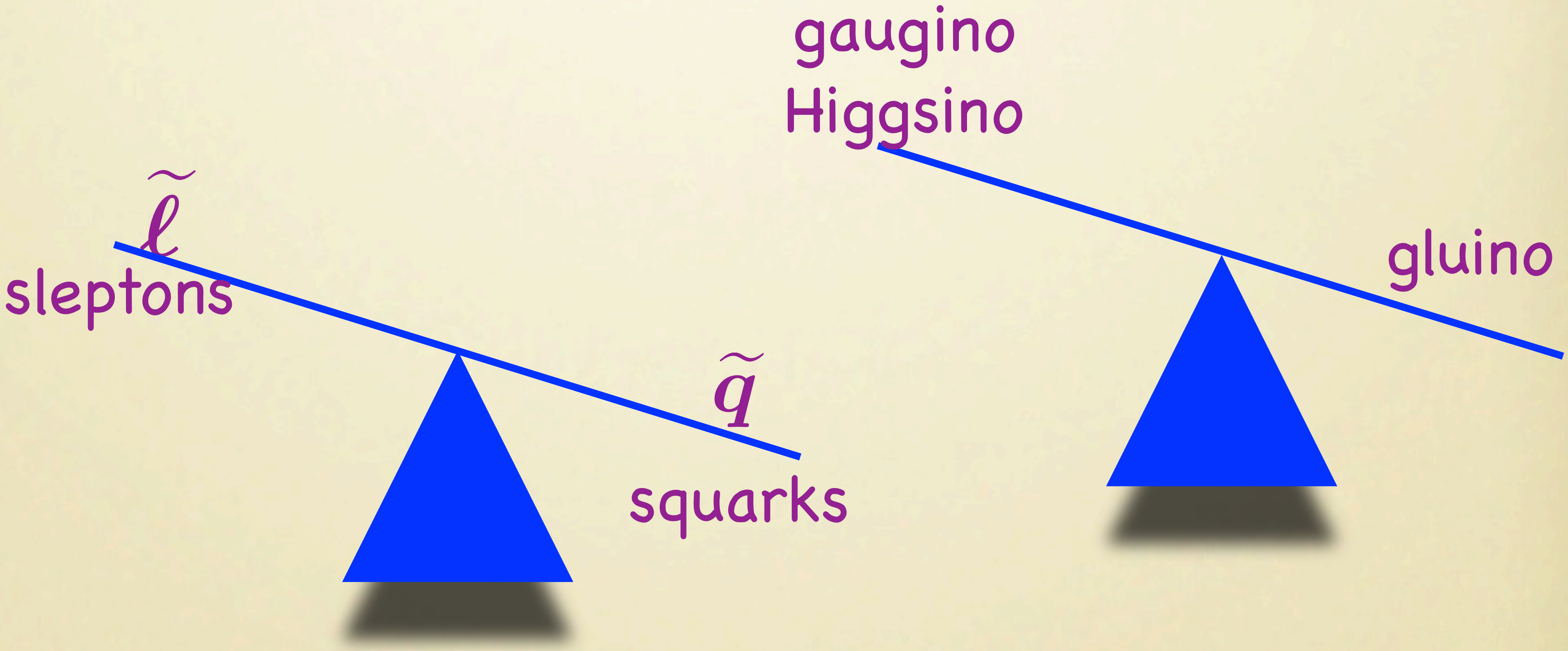
$\tau_{\rm NLSP} \sim \mathcal{O}(10\text{ sec})$ for $m_{\tilde{G}} \sim 0.1$ GeV

Why Stau NLSP ?

- In general, from RGE, tendency is
  - M(color singlet) < M(colored)



typical RG evolution (from S.P.Martin, hep-ph/9709356)



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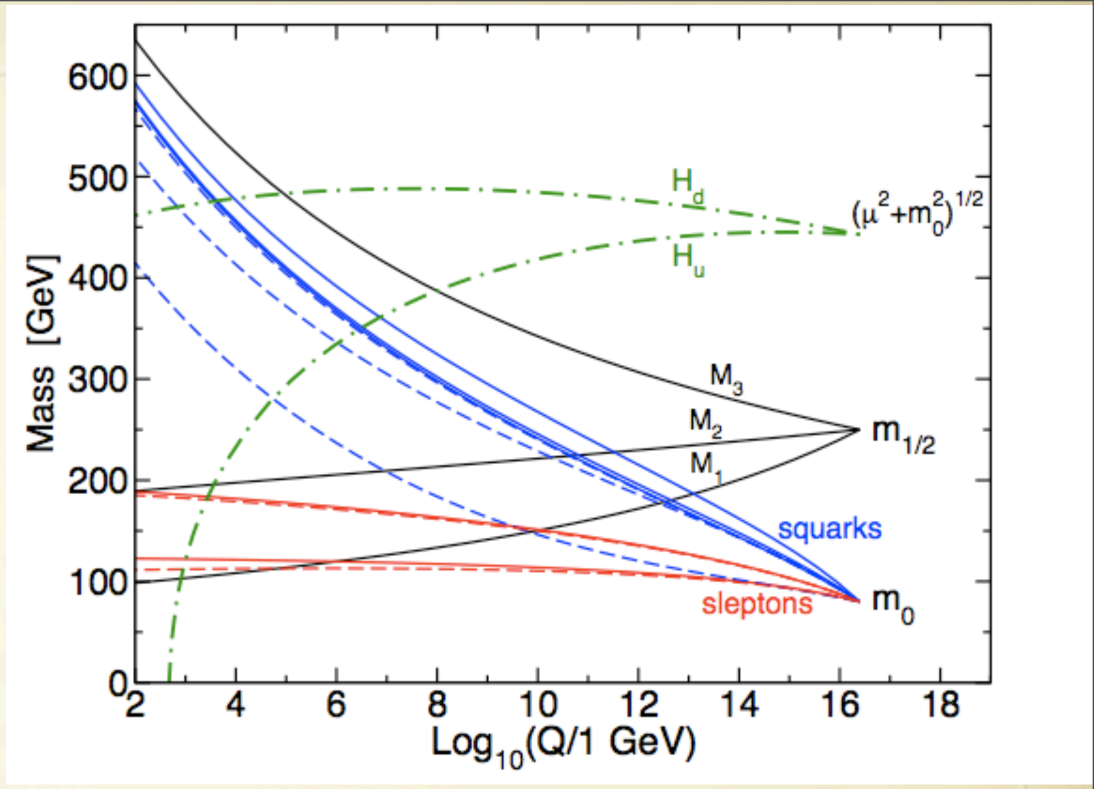

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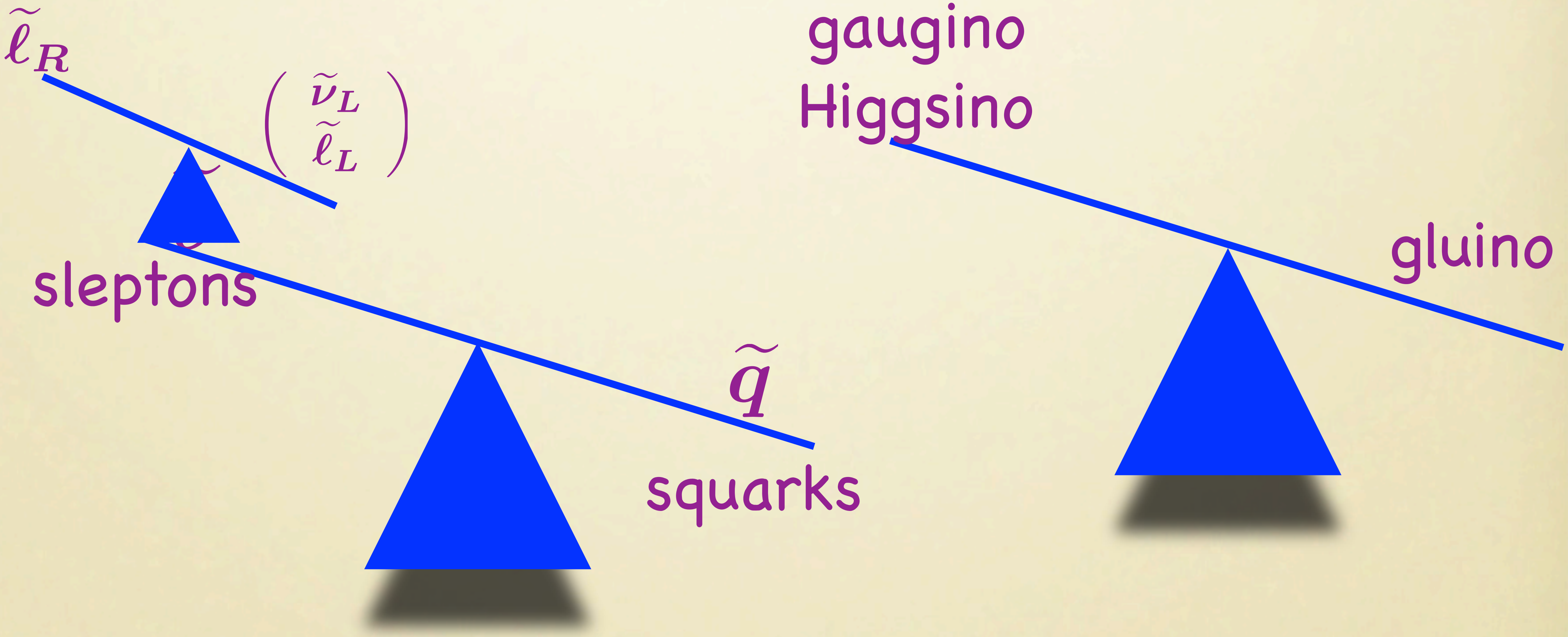

$\tilde{\ell}_R$

$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{\ell}_L \end{pmatrix}$

sleptons

$\tilde{q}$

squarks

gaugino

Higgsino

gluino

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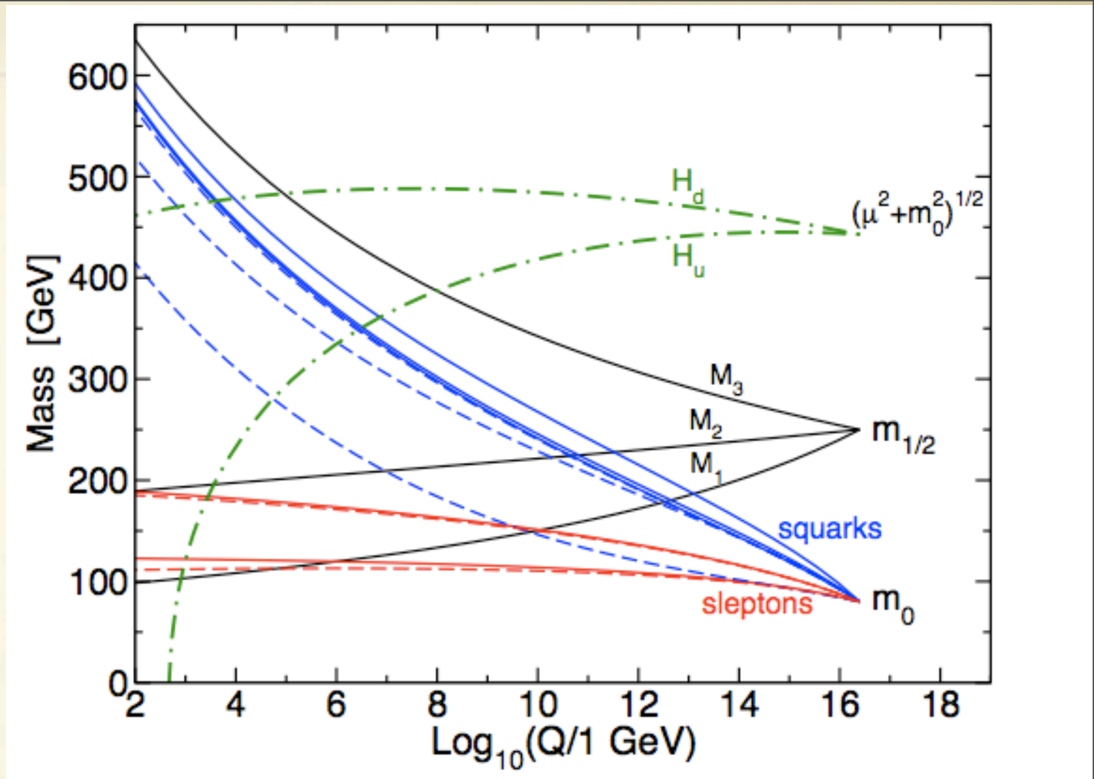
  - M(3rd family) < M(1st and 2nd family)



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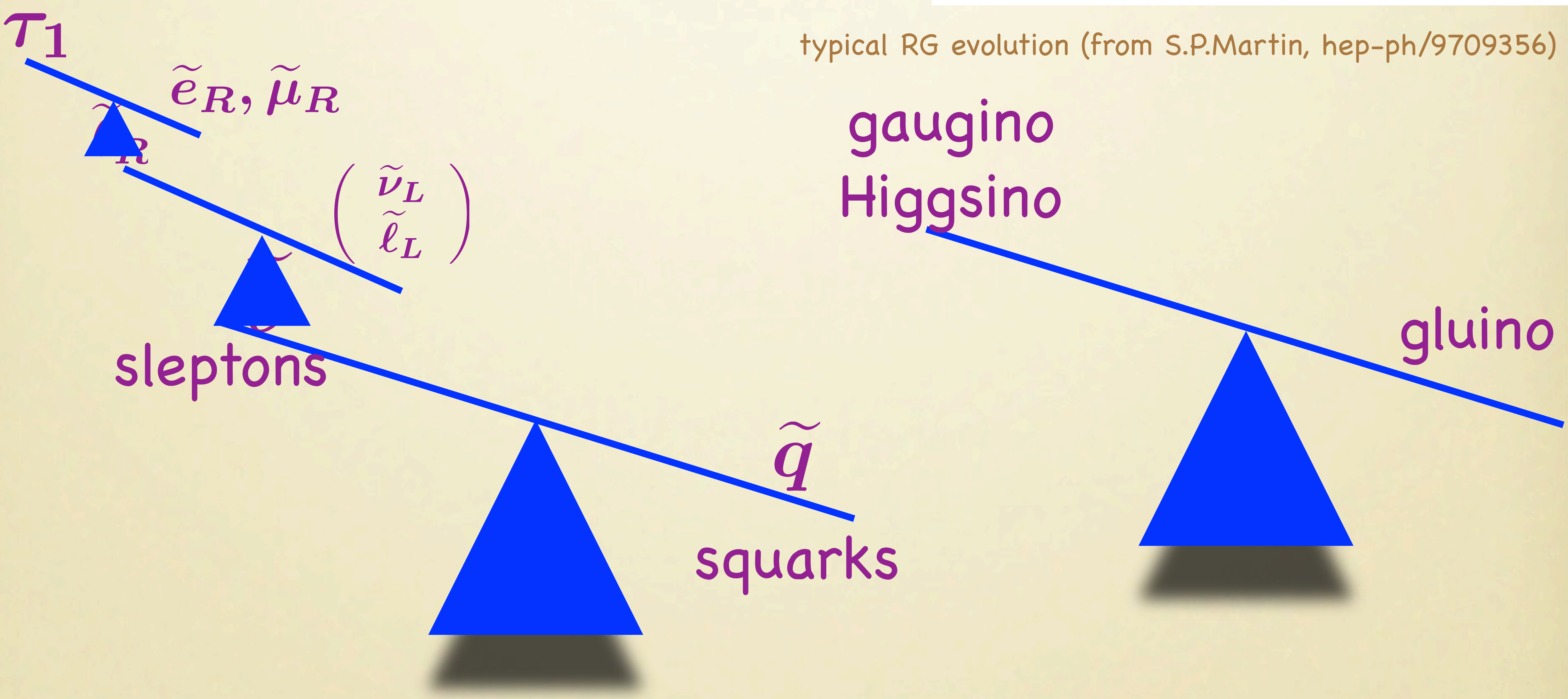

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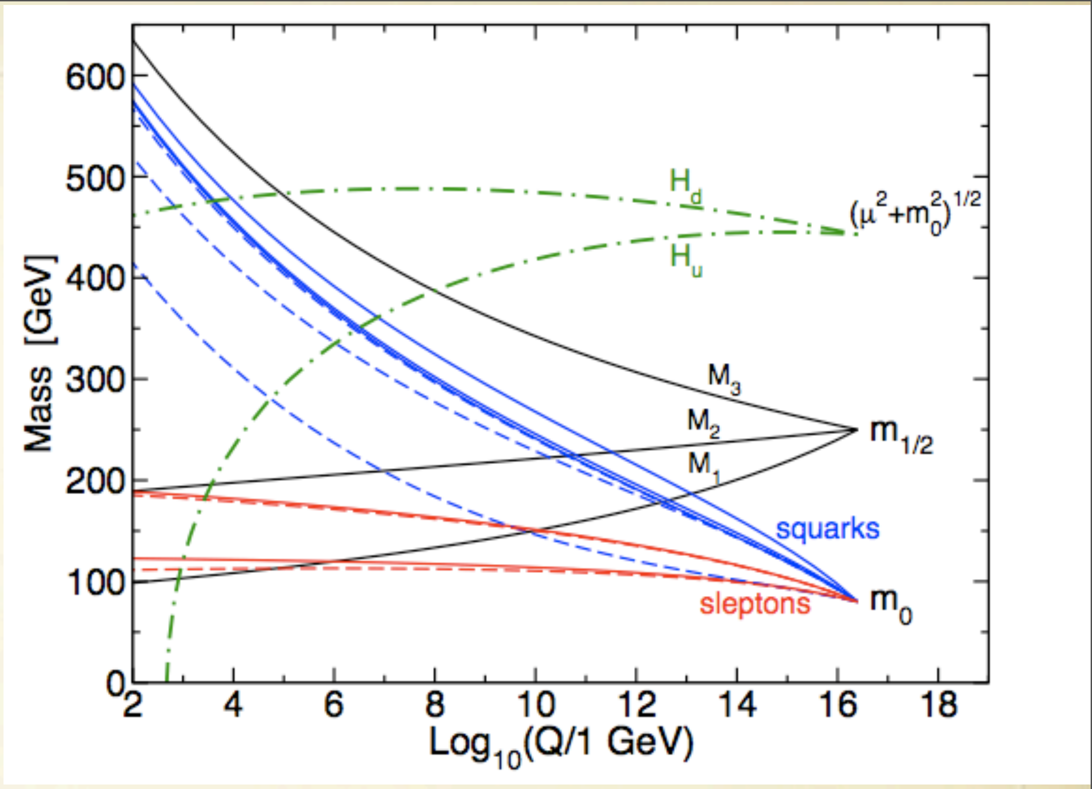

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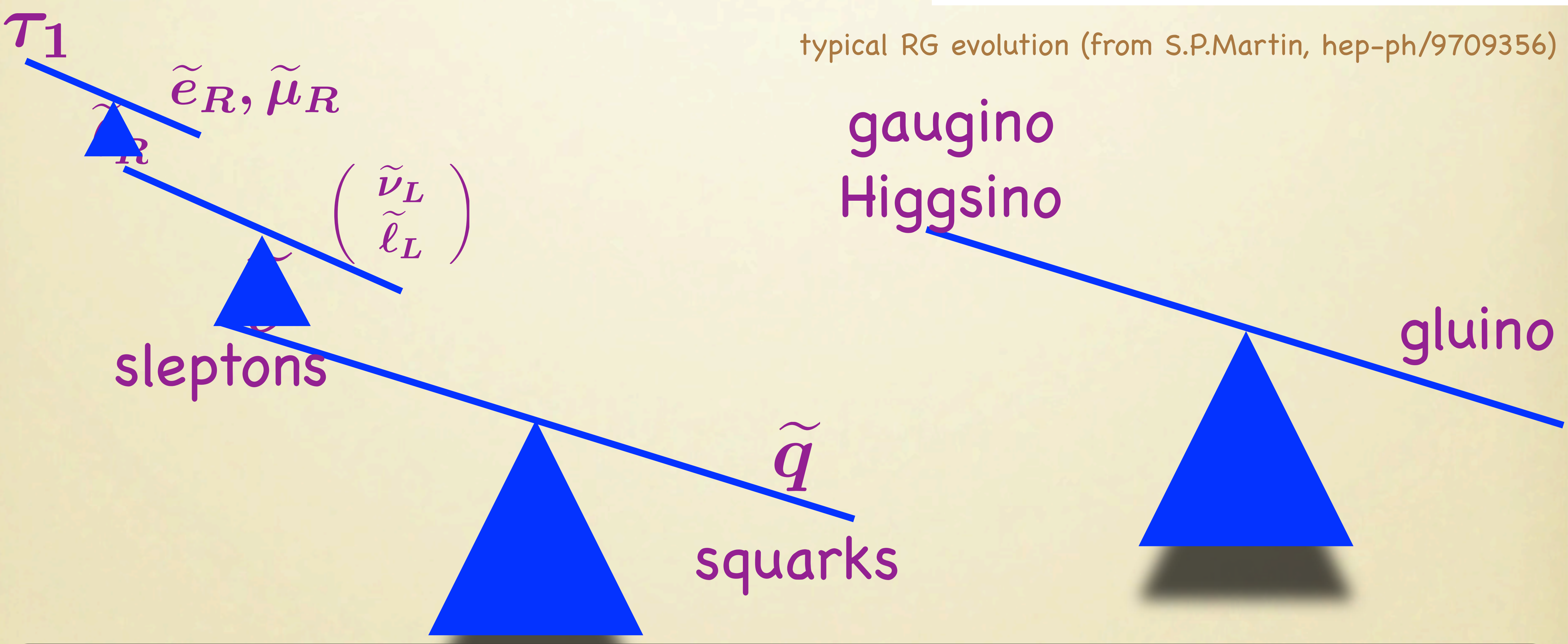

- In most cases, either Stau or Neutralino is the NLSP

scenario: SUSY + gravitino DM + stau NLSP

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→ how to discuss T > cut off ??: inflation/reheating/baryogenesis....

why gravitino DM ? cf. talk by L.Covi

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→ **stau = long-lived charged particle.**

important for cosmology and collider.

②

T_R determination at the LHC with long-lived staus.

..... in gravitino DM scenario with stau NLSP.

M.Endo, KH, K.Nakaji, in progress
\+ S.Asai, KH, S.Shirai,'09

See also related works:
Choi, Roszkowski, Ruiz De Austri,'07
Steffen,'08

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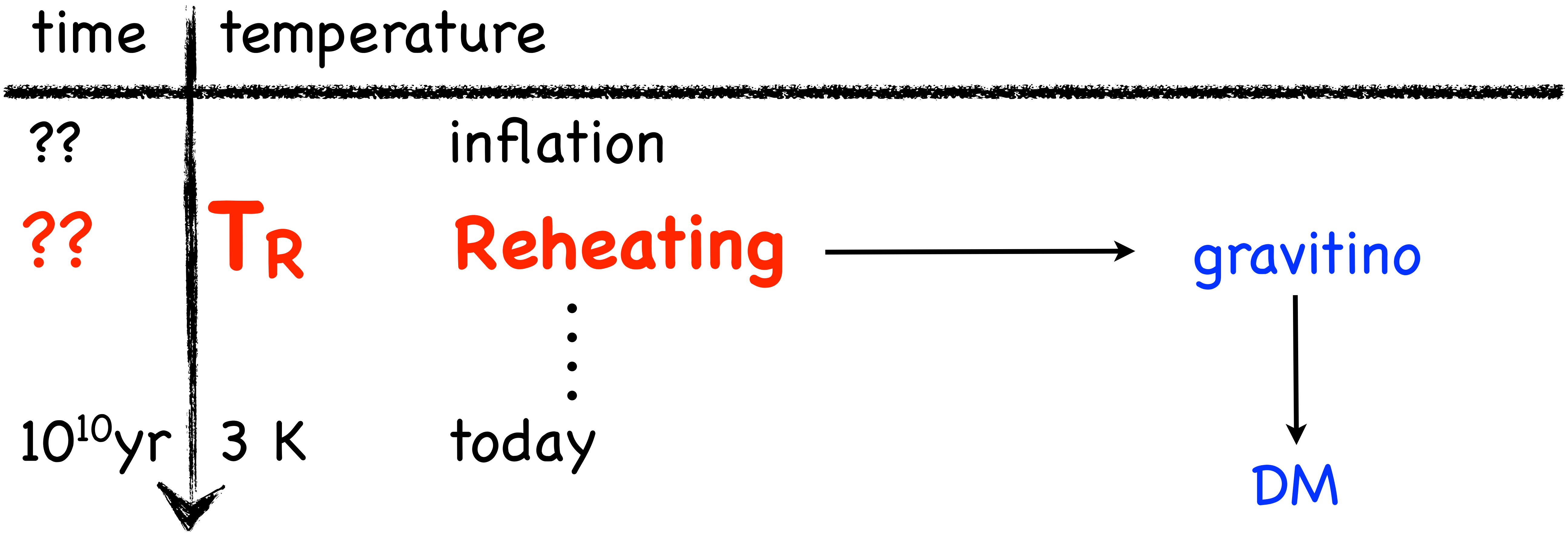
POINT: gravitino abundance is determined by T_R



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assumption

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measure at LHC

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determined !!

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see staus at the LHC

<u>step 2</u>

measure stau mass

<u>step 3</u>

measure stau lifetime

<u>step 4</u>

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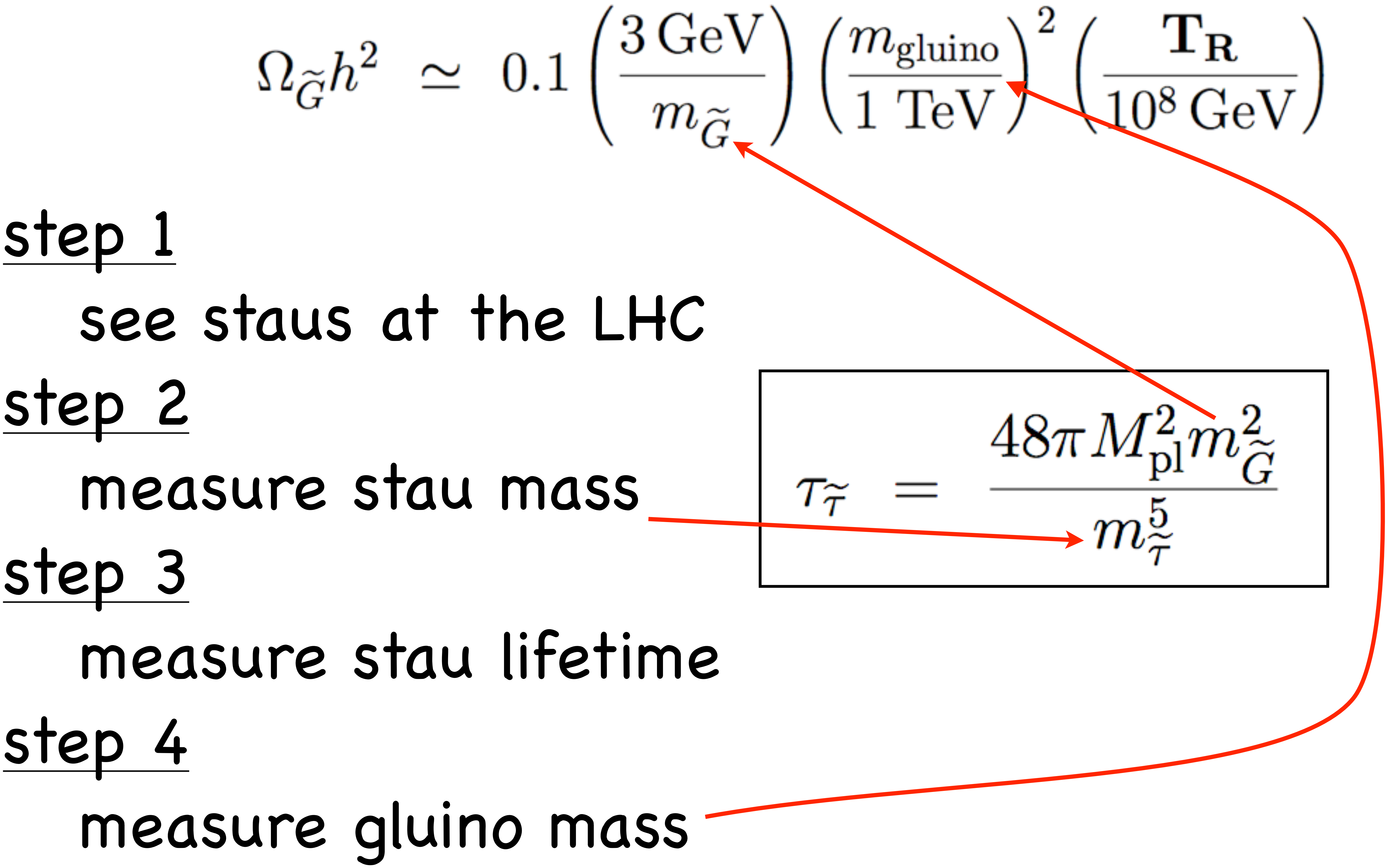

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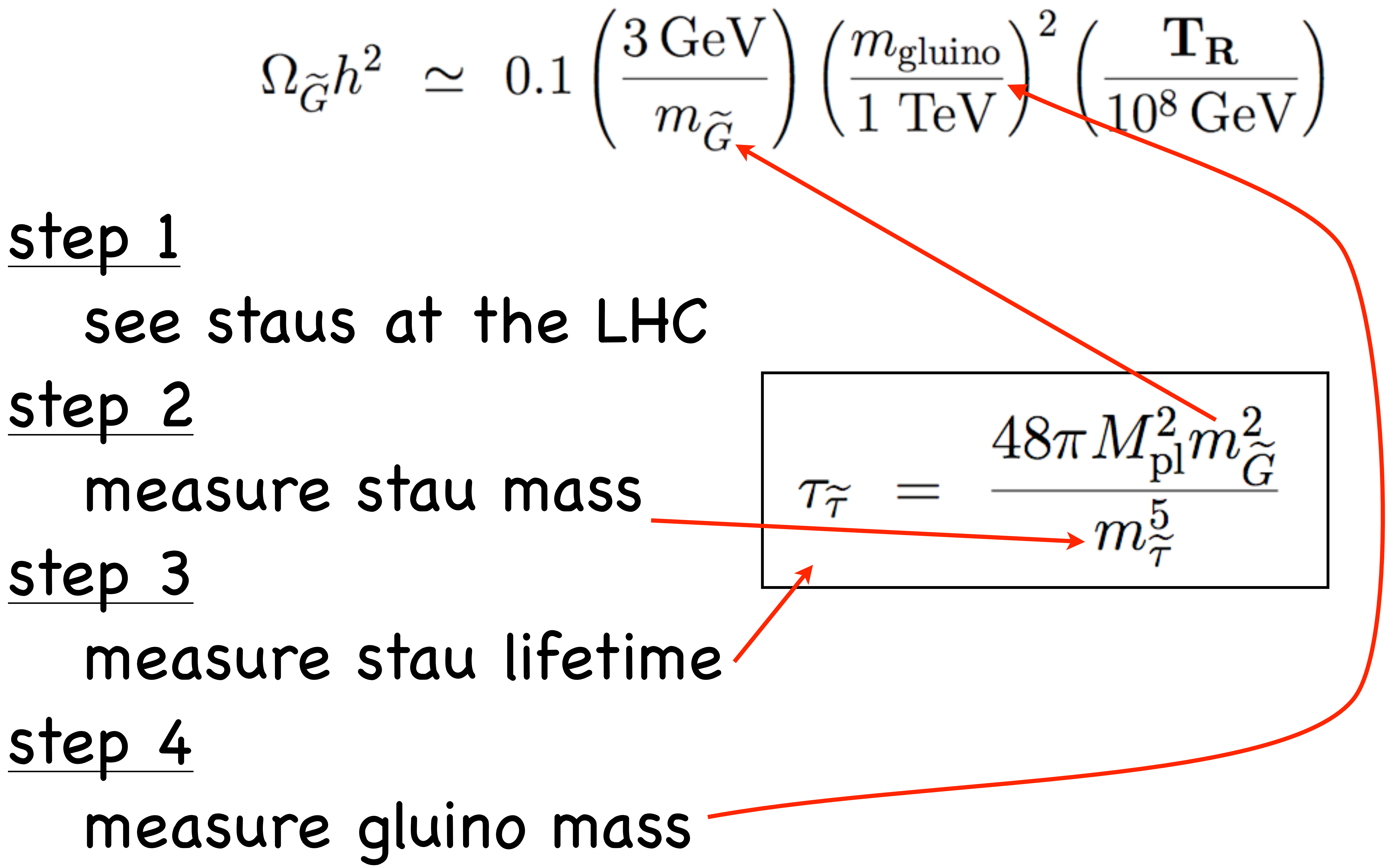

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T_R determination at the LHC with long-lived staus.

$\Omega_{\tilde{G}} h^2$

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see staus

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measure s

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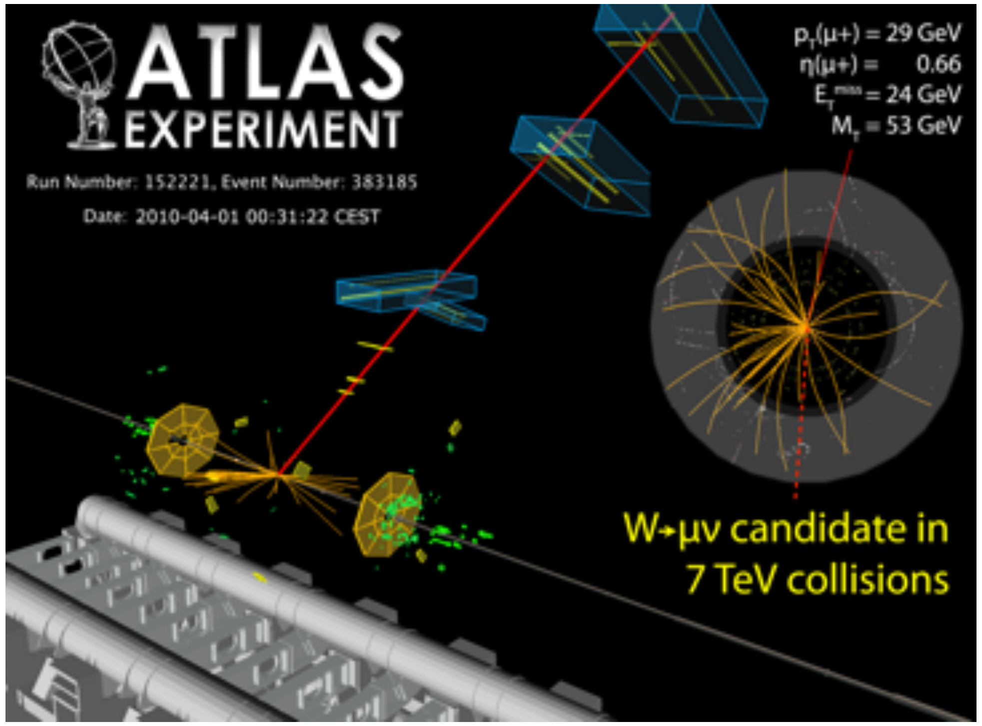
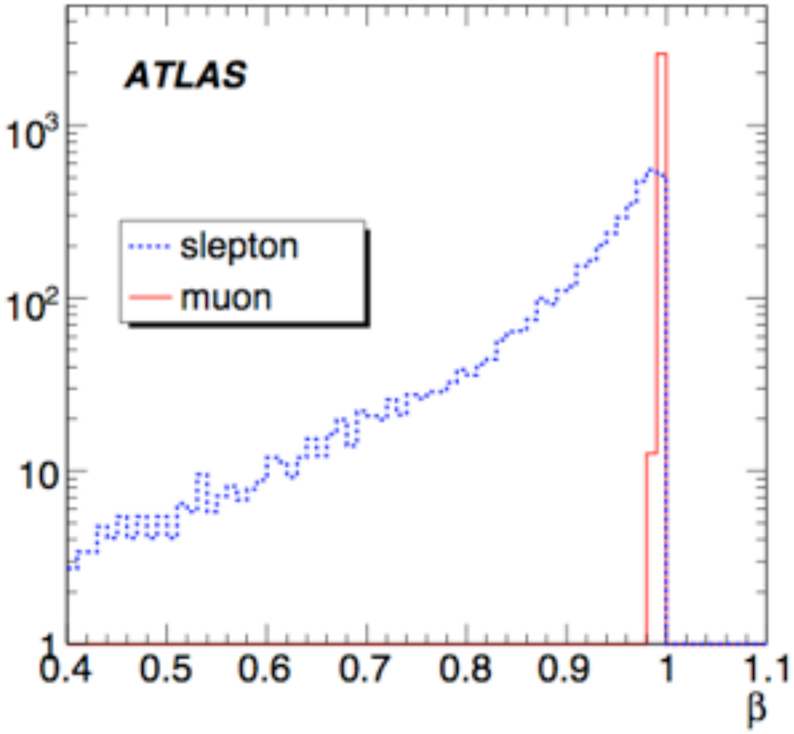
heavy charged particle

(like muon)

low velocity (≠ muon)

cf. Talk by S.Asai





ATLAS, 0901.0512

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

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see staus at the LHC

step 2

measure stau mass

step 3

measure stau lifetime

step 4

measure gluino mass

T_R determ… s.

Ω

step 1

see sta

step 2

by velocity measurement

(+ momentum masurement)

mass = p/(βγ)

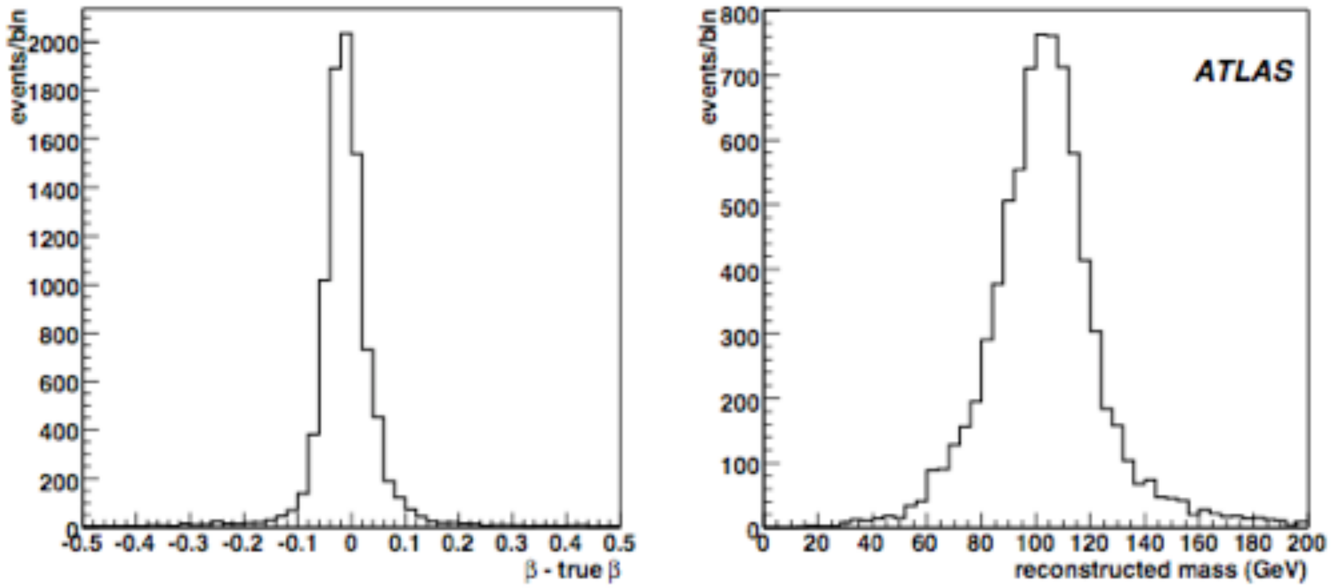

Figure 18: β resolution and reconstructed mass for sleptons from the GMSB5 sample.

ATLAS, 0901.0512

measure stau mass

step 3

measure stau lifetime

step 4

measure gluino mass

T_R determination at the LHC with long-lived staus.

$$\Omega_{\tilde{G}}h^2 \simeq 0.1\left(\frac{3\,\mathrm{GeV}}{m_{\tilde{G}}}\right)\left(\frac{m_{\mathrm{gluino}}}{1\ \mathrm{TeV}}\right)^2\left(\frac{\boxed{\mathrm{T_R}}}{10^8\,\mathrm{GeV}}\right)$$

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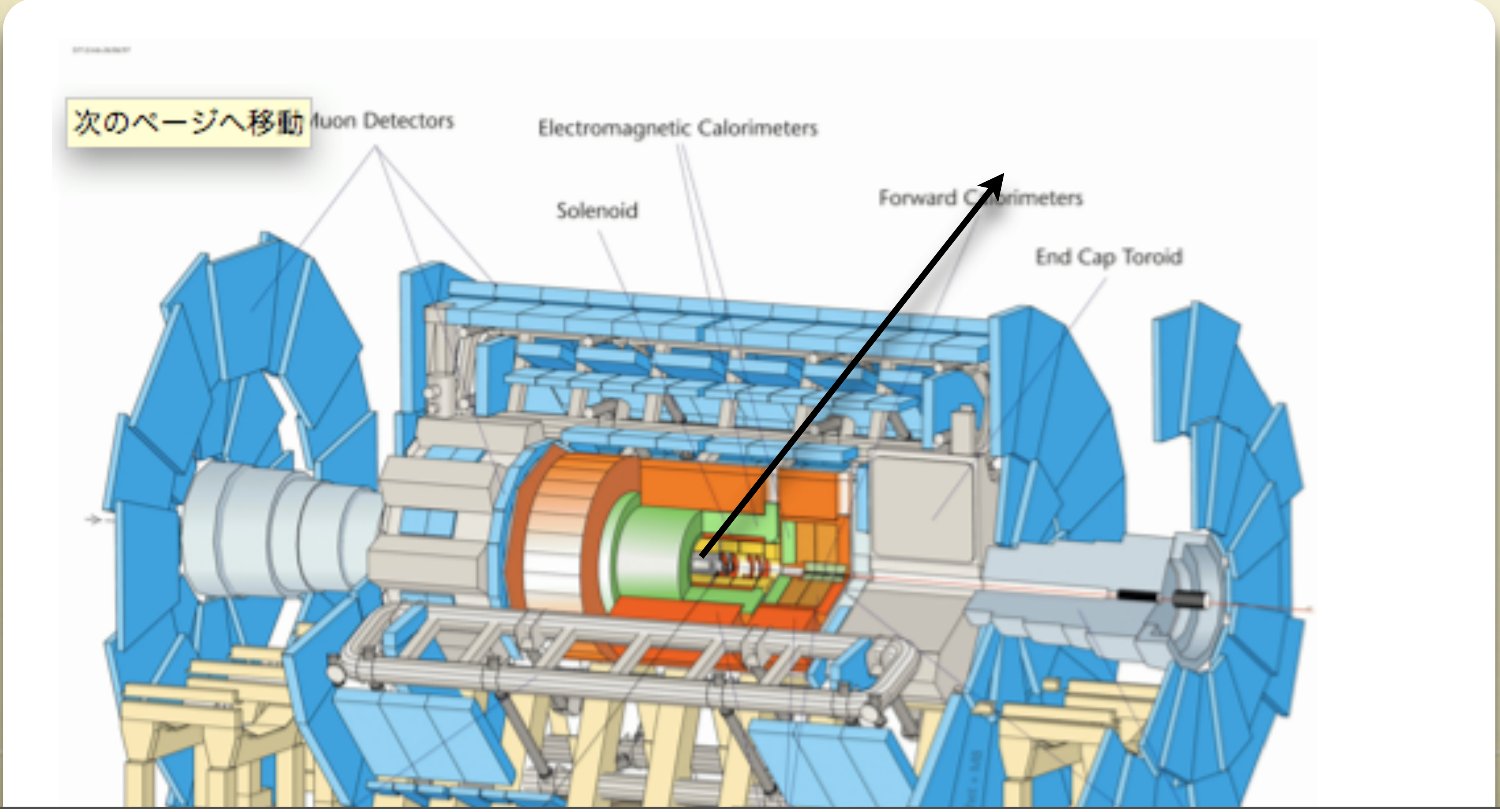
stau lifetime measurement [Asai, KH, Shirai,'09]

- typically most of staus have large velocity and escape from detector.



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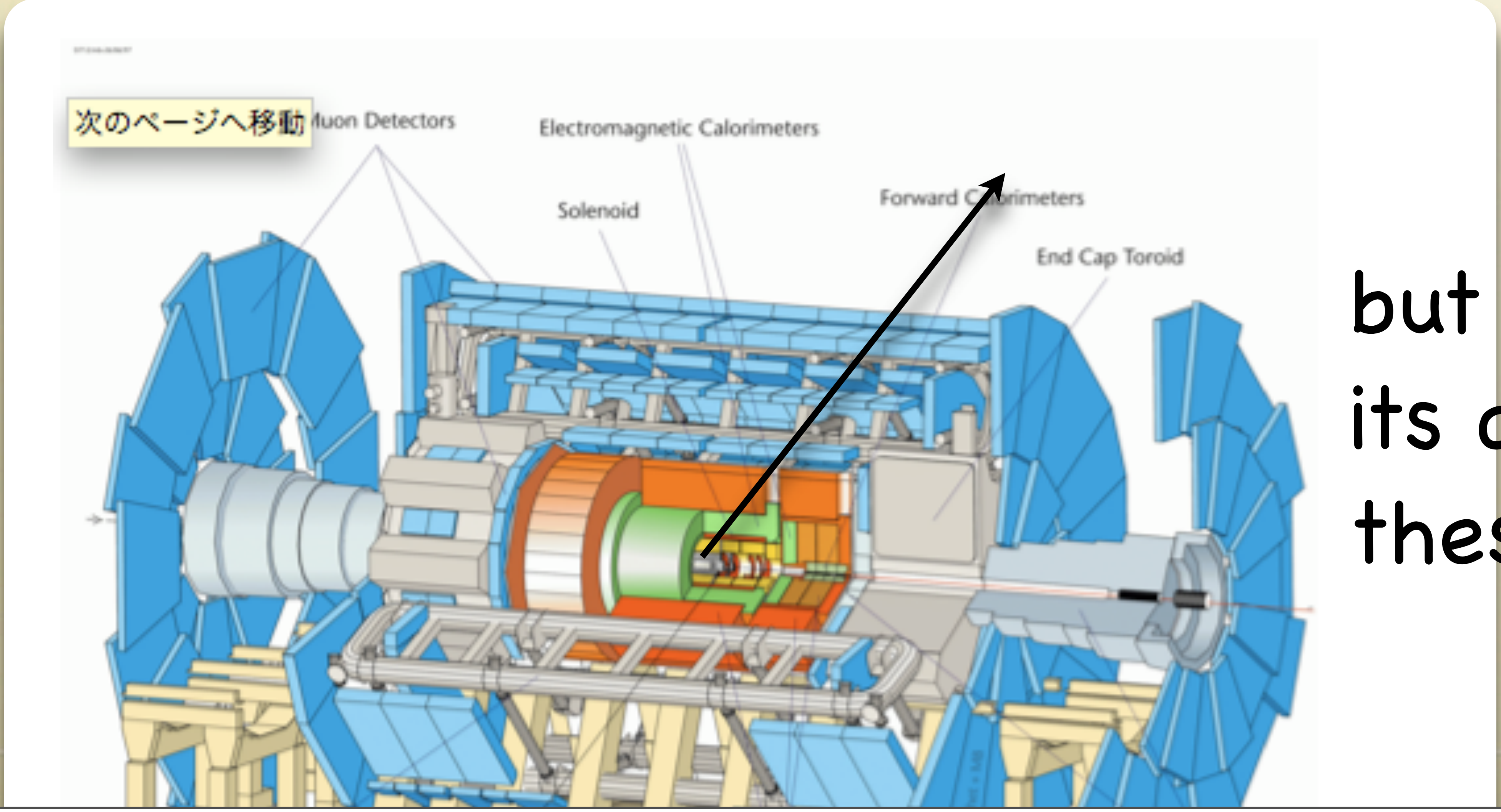
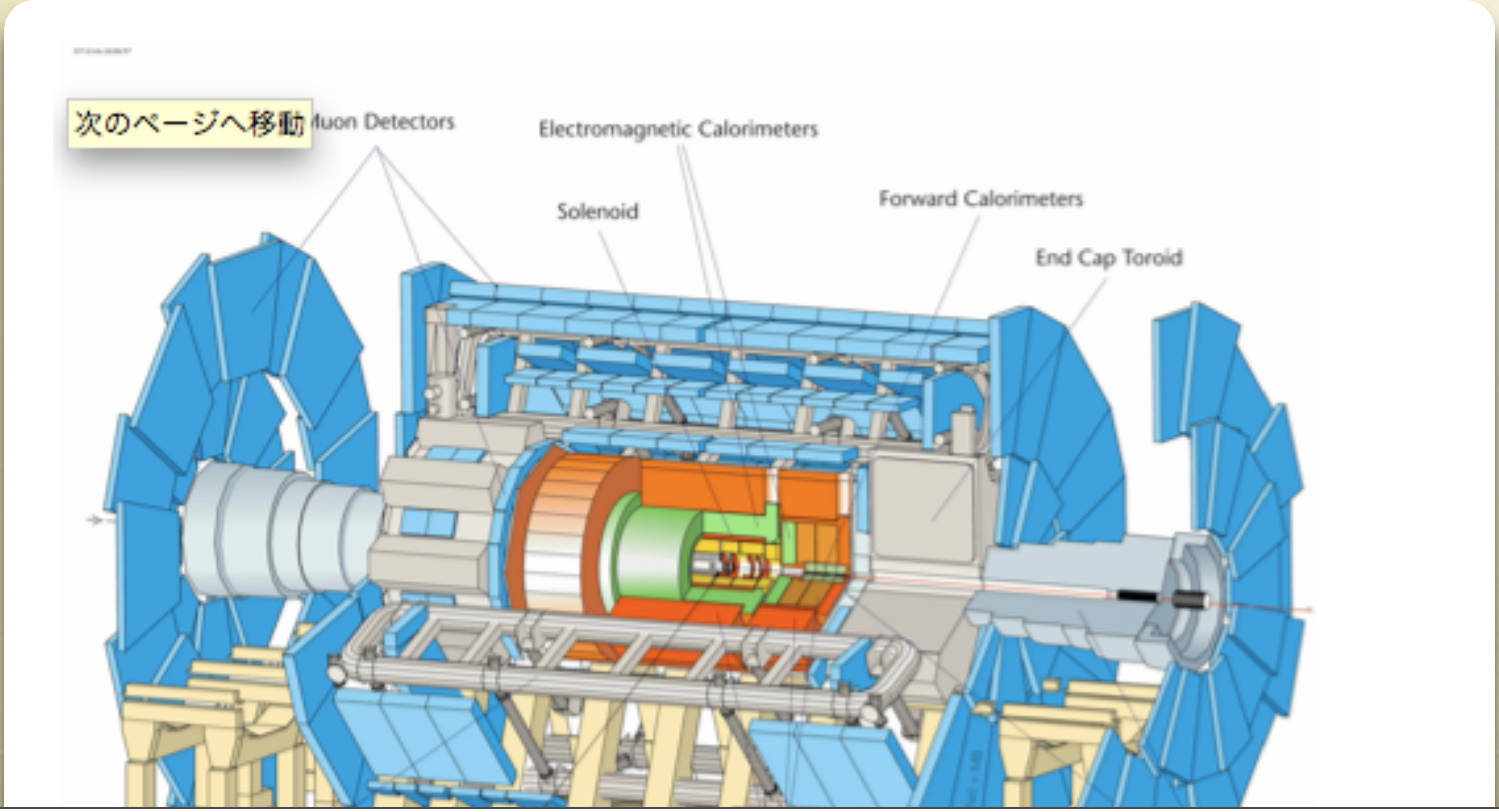


but we can't see its decay in these events.....

stau lifetime measurement [Asai, KH, Shirai,'09]

- typically most of staus have large velocity and escape from detector.
- but some of them have sufficiently small velocity and stop at calorimeters.



stau lifetime measurement [Asai, KH, Shirai,'09]

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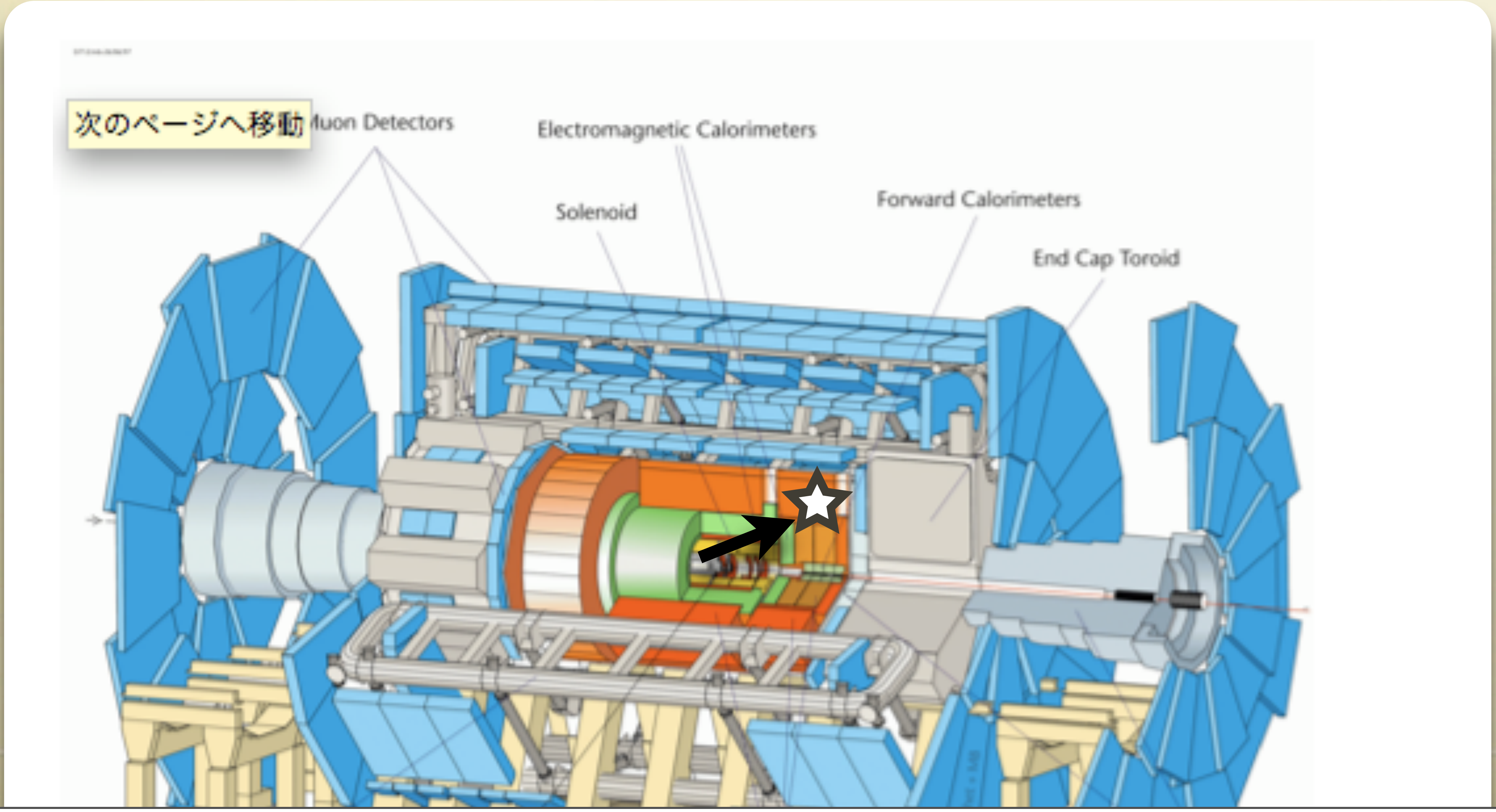


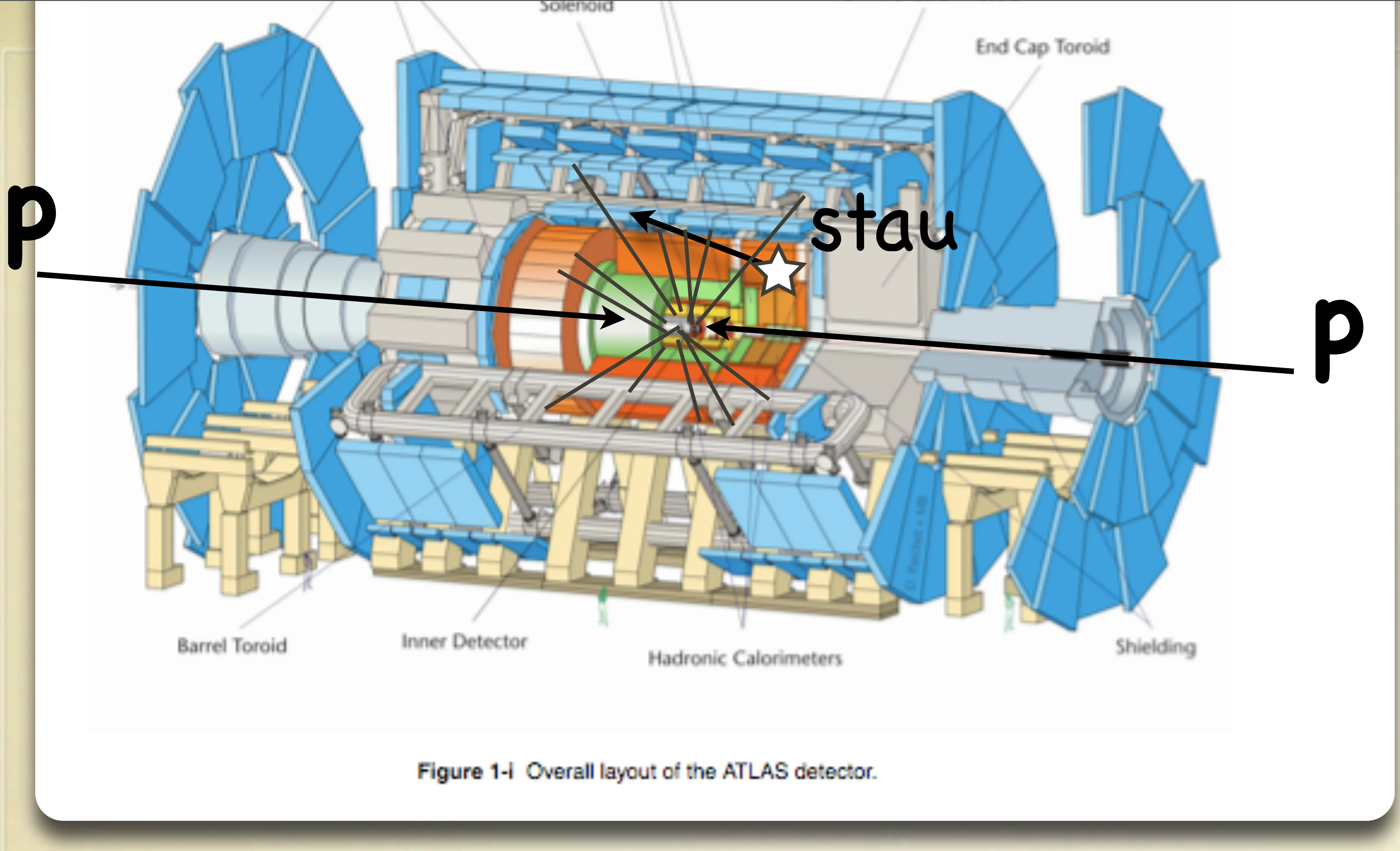


Figure 1-i Overall layout of the ATLAS detector.

- but their late-time decay has wrong timing and wrong direction;
- difficult to reject backgrounds
- difficult to trigger.

..... during pp collision.

Idea:

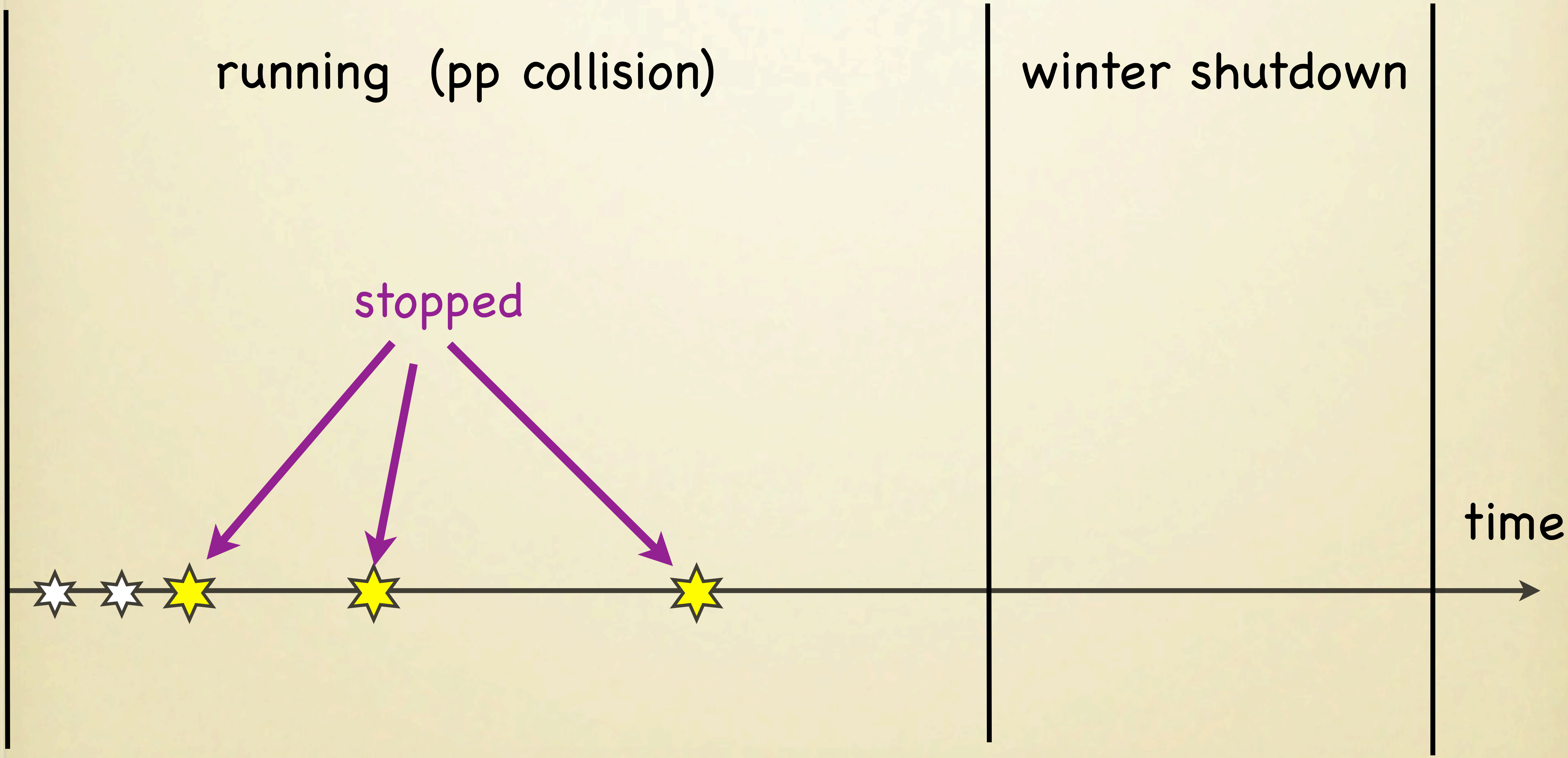
use periods of no pp collision !!

two possible strategies:

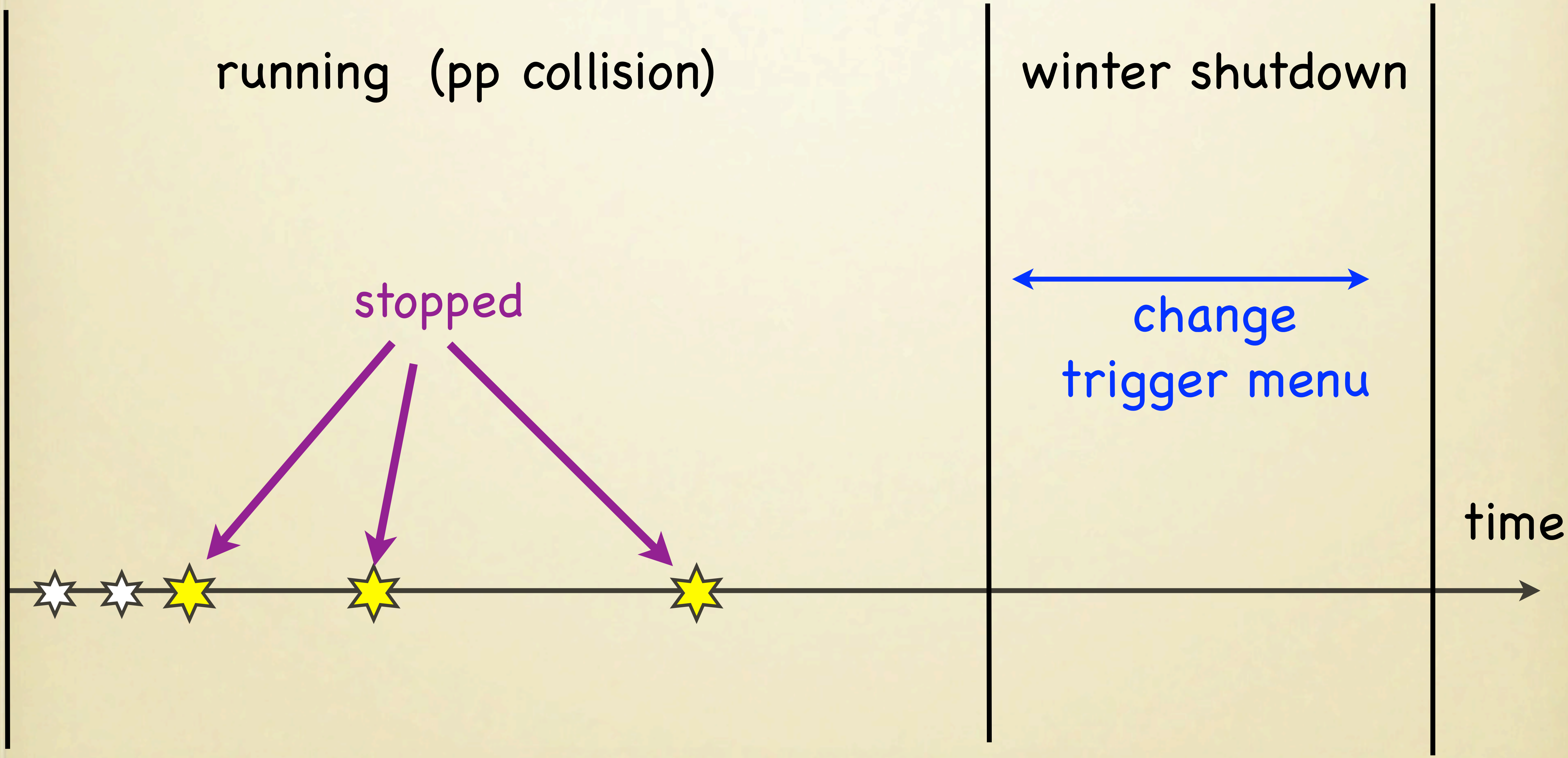
- for long lifetime: use shutdown time.
- for short lifetime: use beam-dump signal.

(or use empty bunch.)

- for long lifetime: use shutdown time



- for long lifetime: use shutdown time



running (pp collision)

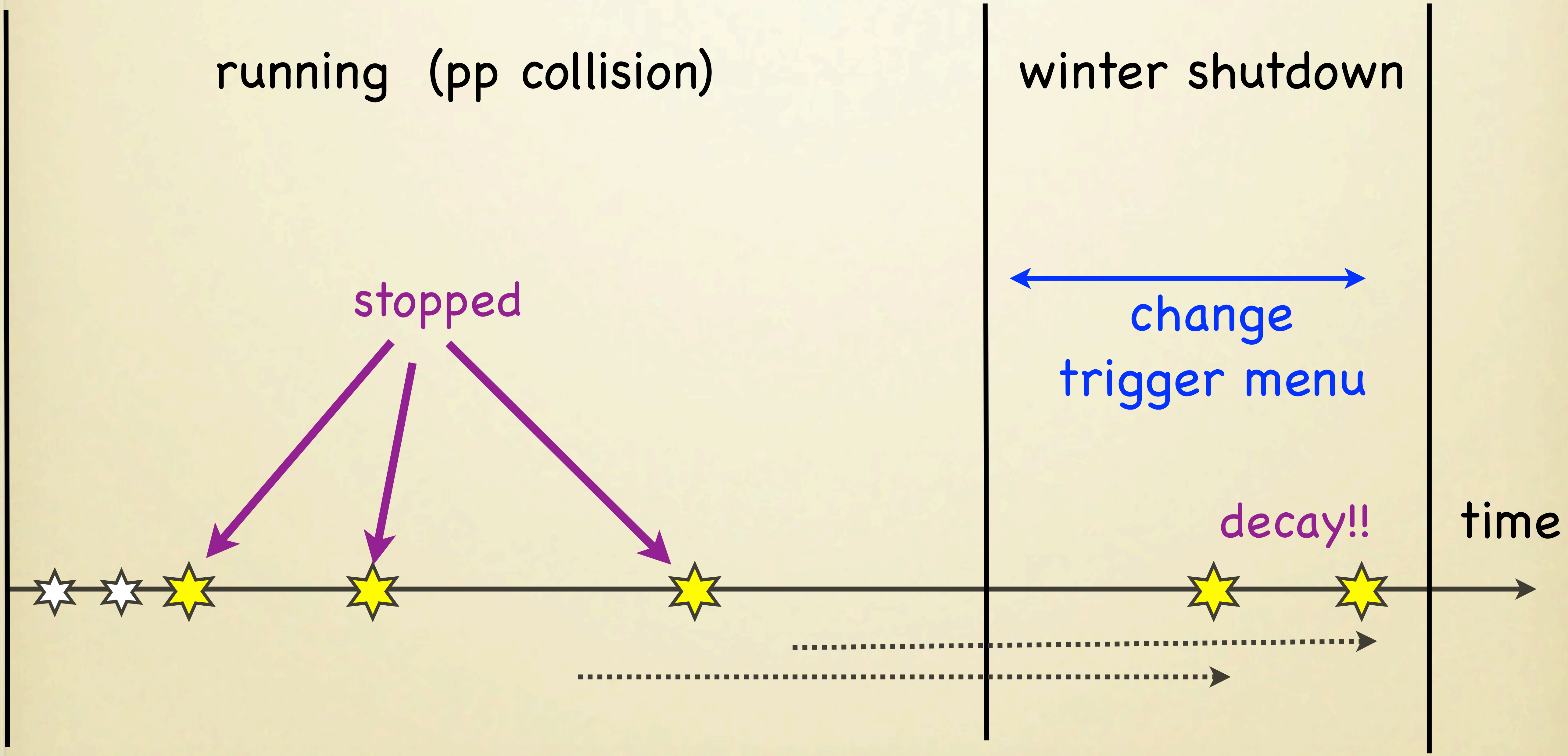
winter shutdown

stopped

change trigger menu

time

- for long lifetime: use shutdown time



running (pp collision)

winter shutdown

stopped

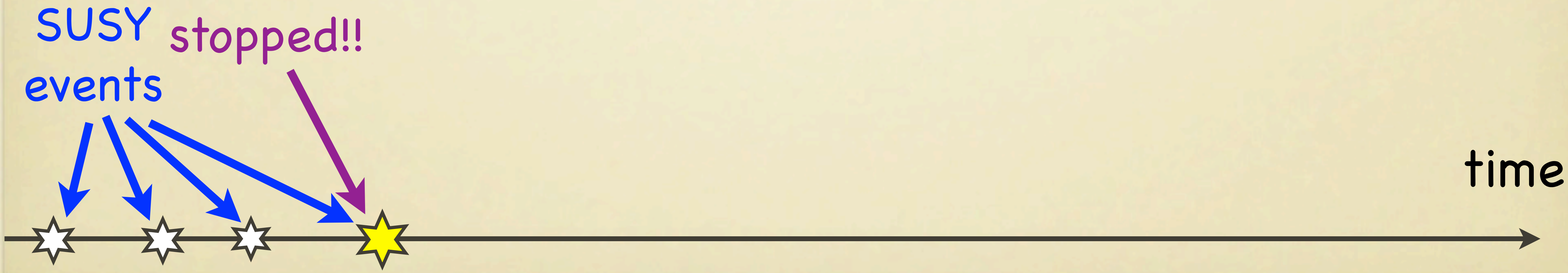
change trigger menu

decay!!

time

• for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.



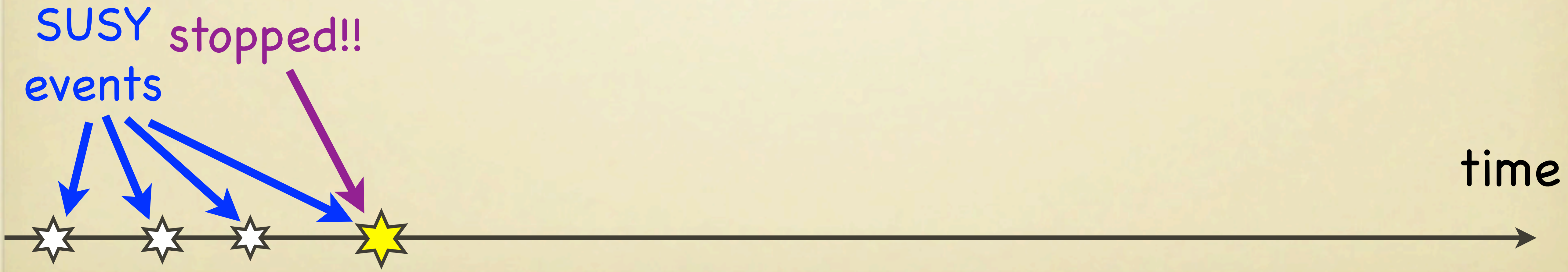
• for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.

(1) missing ET > 100 GeV
(2) 1 jet PT > 100 GeV + 2 jets PT > 50 GeV

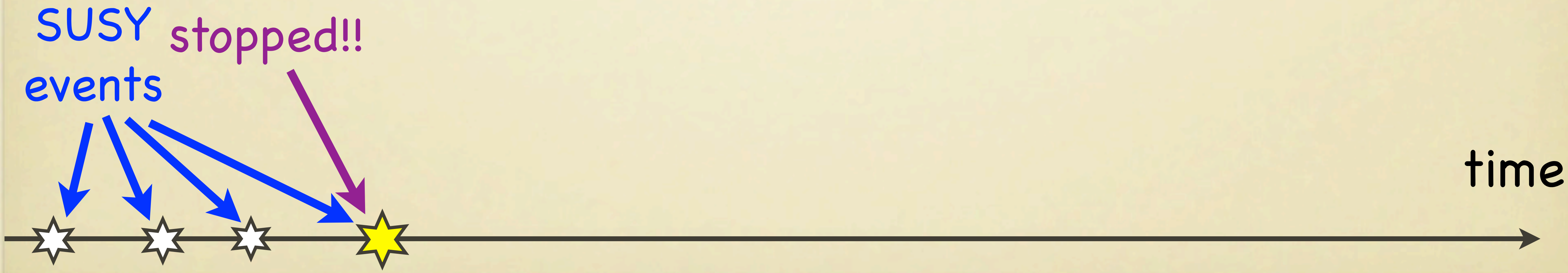
(3) isolated track with PT > 0.1 m(stau).

(4) extrapolate the track to calorimeter and energy deposit < 0.2 p(stau).
(5) extrapolate the track to muon system and no muon track.



• for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.

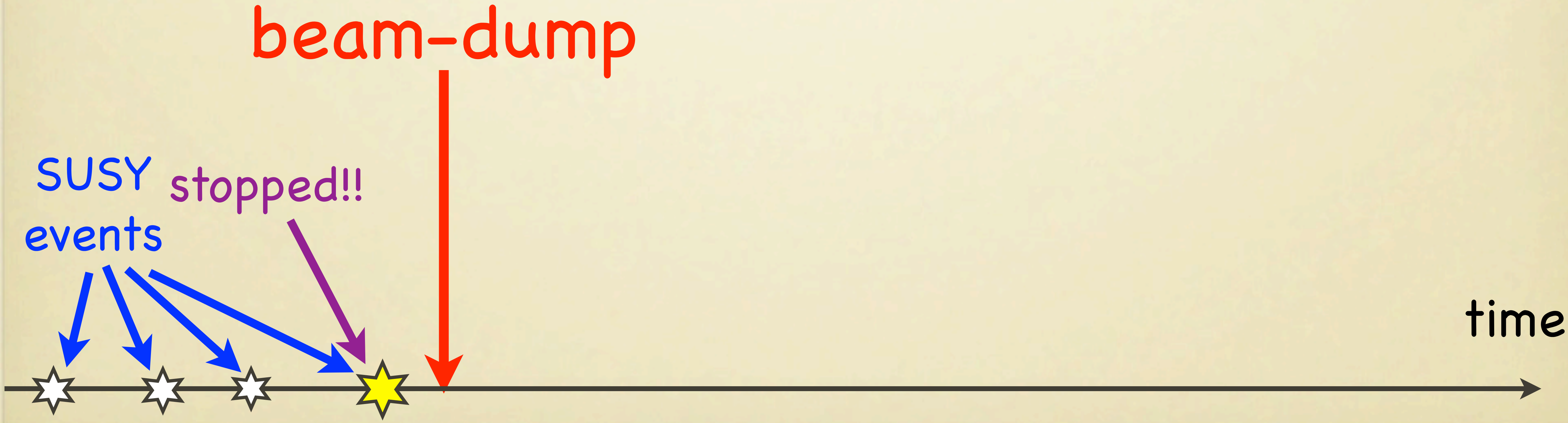


- for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.

trigger

(II) send a beam-dump signal, which immediately stops the pp collision.



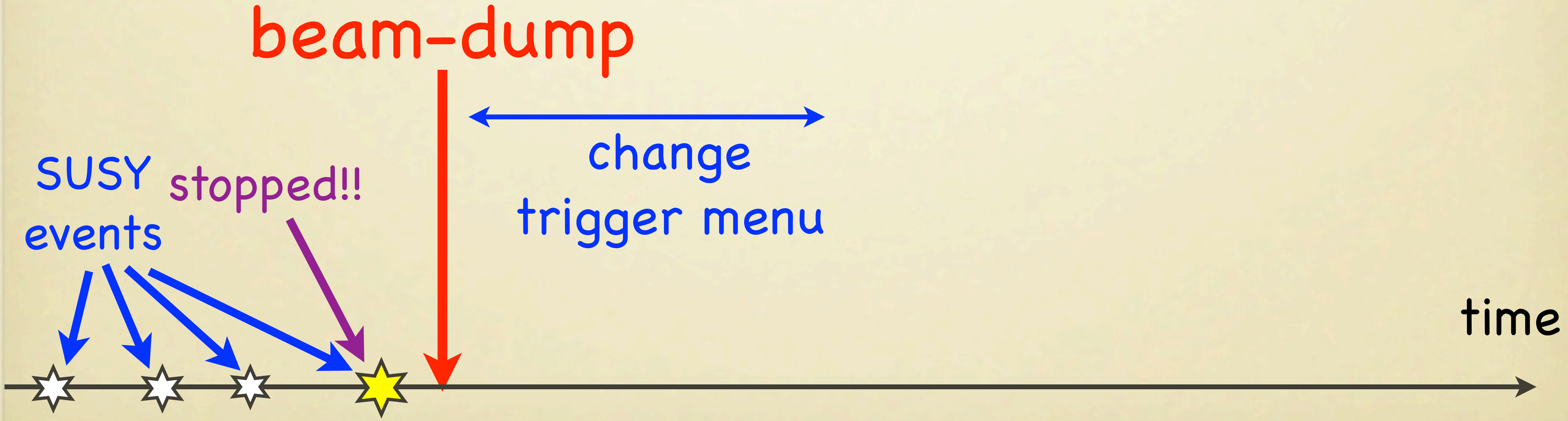
• for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.

(II) send a beam-dump signal, which immediately stops the pp collision.

trigger

(III) change the trigger menu to the one optimized for stau decay.



• for short lifetime: use beam-dump signal.

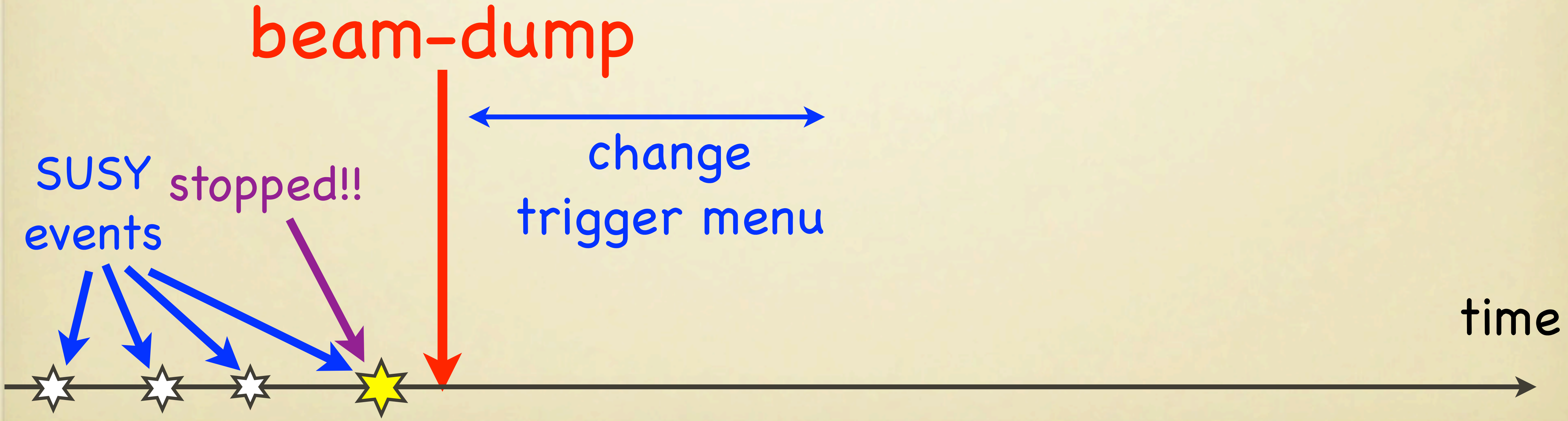
(I) select the stopping event by online Event Filter.

trigger

(II) send a beam-dump signal, which immediately stops the pp collision.

(III) change the trigger menu to the one optimized for stau decay.

(IV) wait for stau decay.



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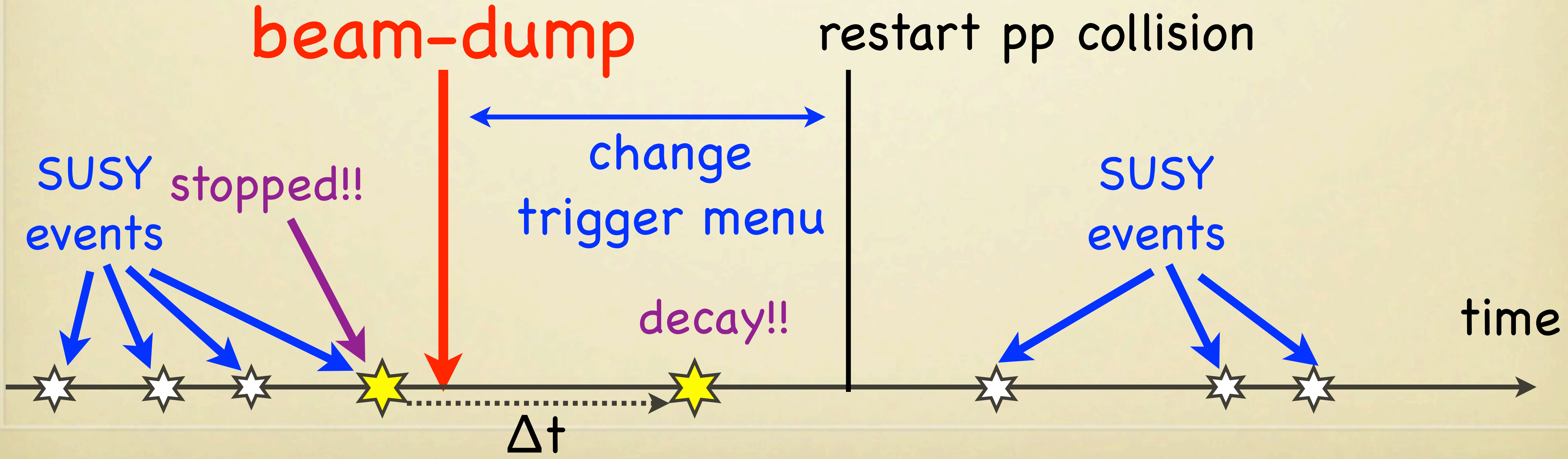
(IV) wait for stau decay.



•lifetime measurement: Result

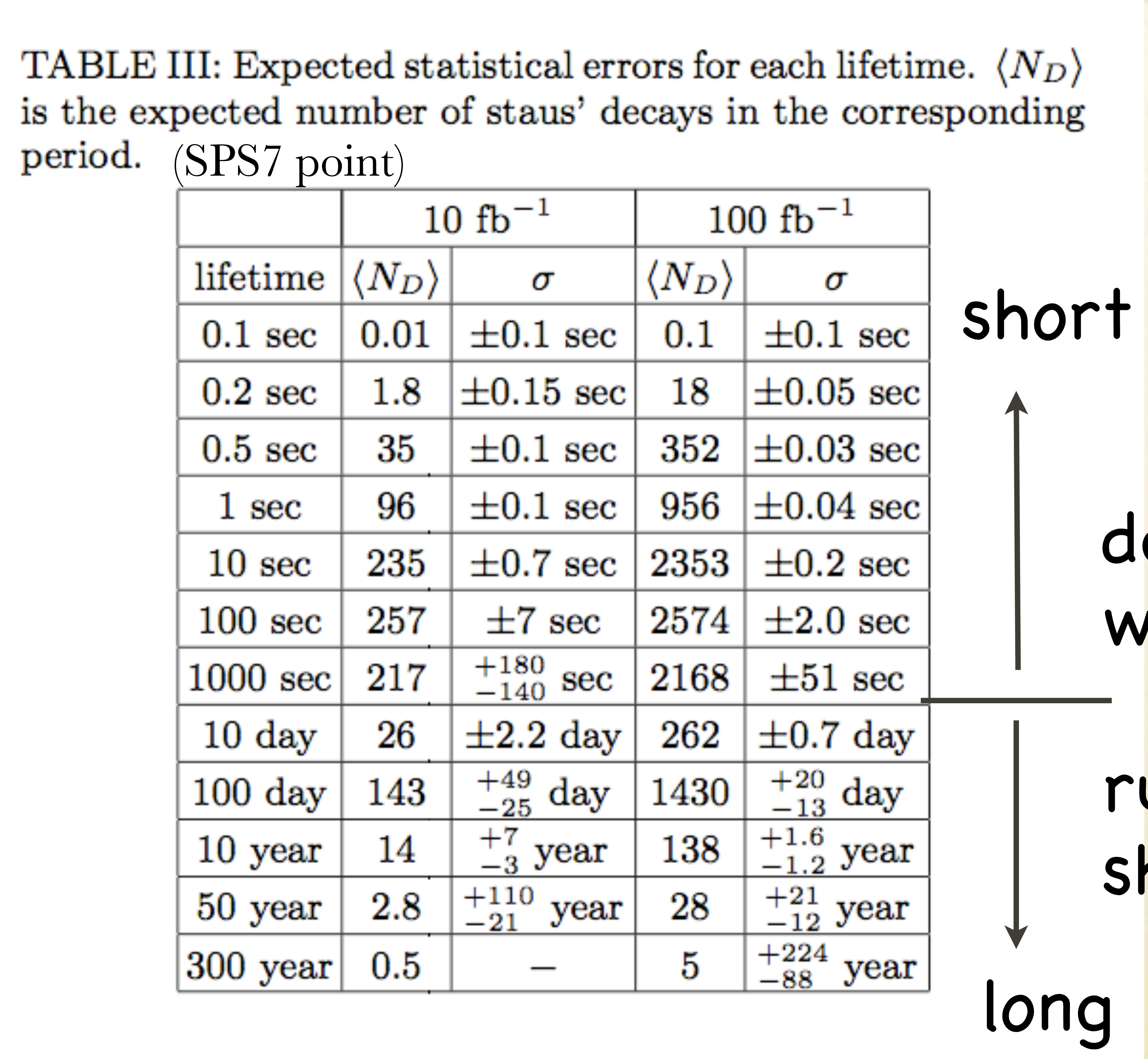


TABLE III: Expected statistical errors for each lifetime. $\langle N_D \rangle$ is the expected number of staus' decays in the corresponding period. (SPS7 point)

	10 fb^{-1}		100 fb^{-1}	
lifetime	$\langle N_D \rangle$	σ	$\langle N_D \rangle$	σ
0.1 sec	0.01	±0.1 sec	0.1	±0.1 sec
0.2 sec	1.8	±0.15 sec	18	±0.05 sec
0.5 sec	35	±0.1 sec	352	±0.03 sec
1 sec	96	±0.1 sec	956	±0.04 sec
10 sec	235	±0.7 sec	2353	±0.2 sec
100 sec	257	±7 sec	2574	±2.0 sec
1000 sec	217	$^{+180}_{-140}$ sec	2168	±51 sec
10 day	26	±2.2 day	262	±0.7 day
100 day	143	$^{+49}_{-25}$ day	1430	$^{+20}_{-13}$ day
10 year	14	$^{+7}_{-3}$ year	138	$^{+1.6}_{-1.2}$ year
50 year	2.8	$^{+110}_{-21}$ year	28	$^{+21}_{-12}$ year
300 year	0.5	–	5	$^{+224}_{-88}$ year

short

long

assumption

dead time: 1 sec
waiting time: 30 min.

running: 200 days
shutdown: 100 days

O(0.1 sec .... 100 years) can be probed!!

TR determination at the LHC with long-lived staus.

$$\Omega_{\tilde{G}} h^2 \simeq 0.1 \left(\frac{3\,\mathrm{GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\mathrm{gluino}}}{1\ \mathrm{TeV}} \right)^2 \left(\frac{\boxed{\mathbf{T_R}}}{10^8\,\mathrm{GeV}} \right)$$

step 1

see staus at the LHC

step 2

measure stau mass

step 3

measure stau lifetime

step 4

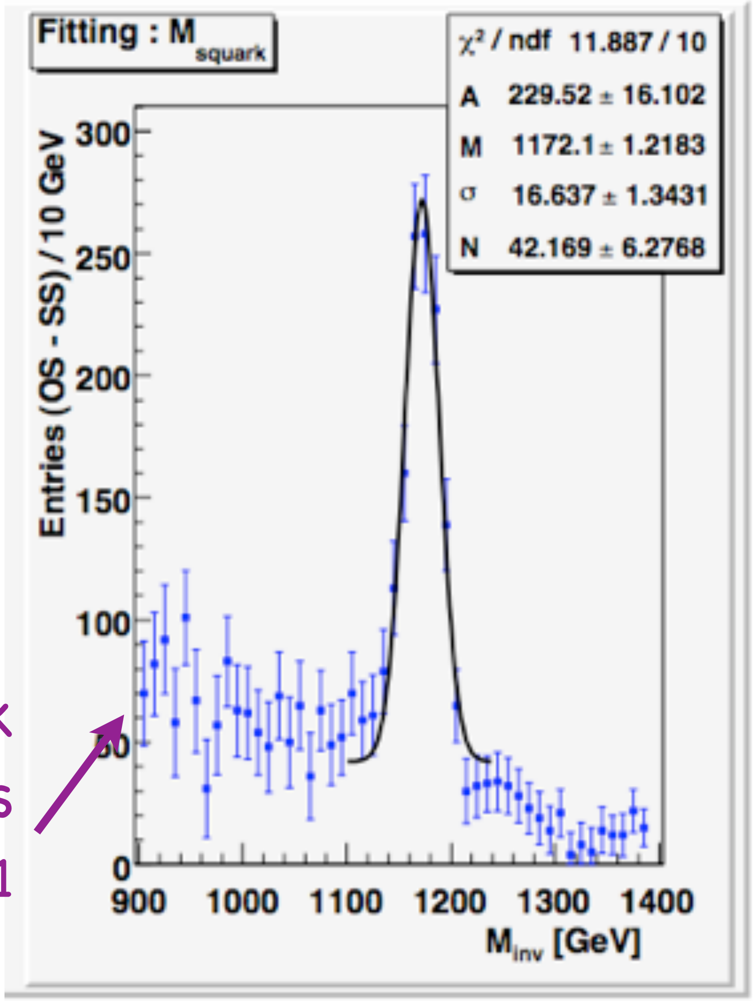
measure gluino mass

T_R determination at the LHC with long-lived staus.

$$\Omega_{\tilde{G}}h^2 \simeq 0.1 \Big(\frac{3\,\mathrm{GeV}}{m_{\tilde{G}}}$$

by invariant mass method

[cf. Ito, Kitano, Moroi,'09]



squark mass @100fb^-1

Gluino mass is more difficult but should be possible at high luminosity

<u>step 1</u>

see staus at the LHC

<u>step 2</u>

measure stau mass

<u>step 3</u>

measure stau lifetime

<u>step 4</u>

measure gluino mass

T_R determination at the LHC with long-lived staus.

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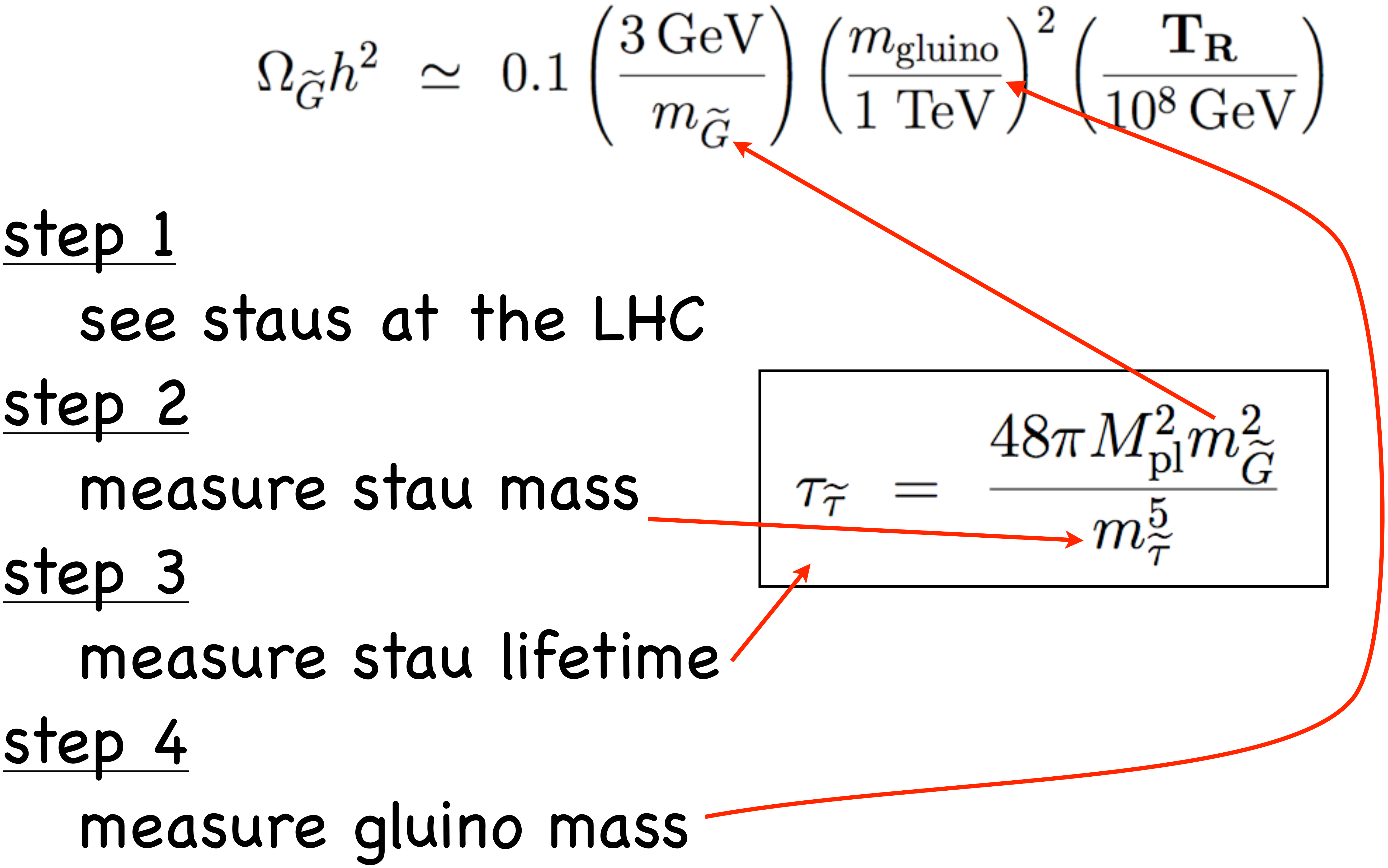

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step 1

see staus at the LHC

step 2

measure stau mass

step 3

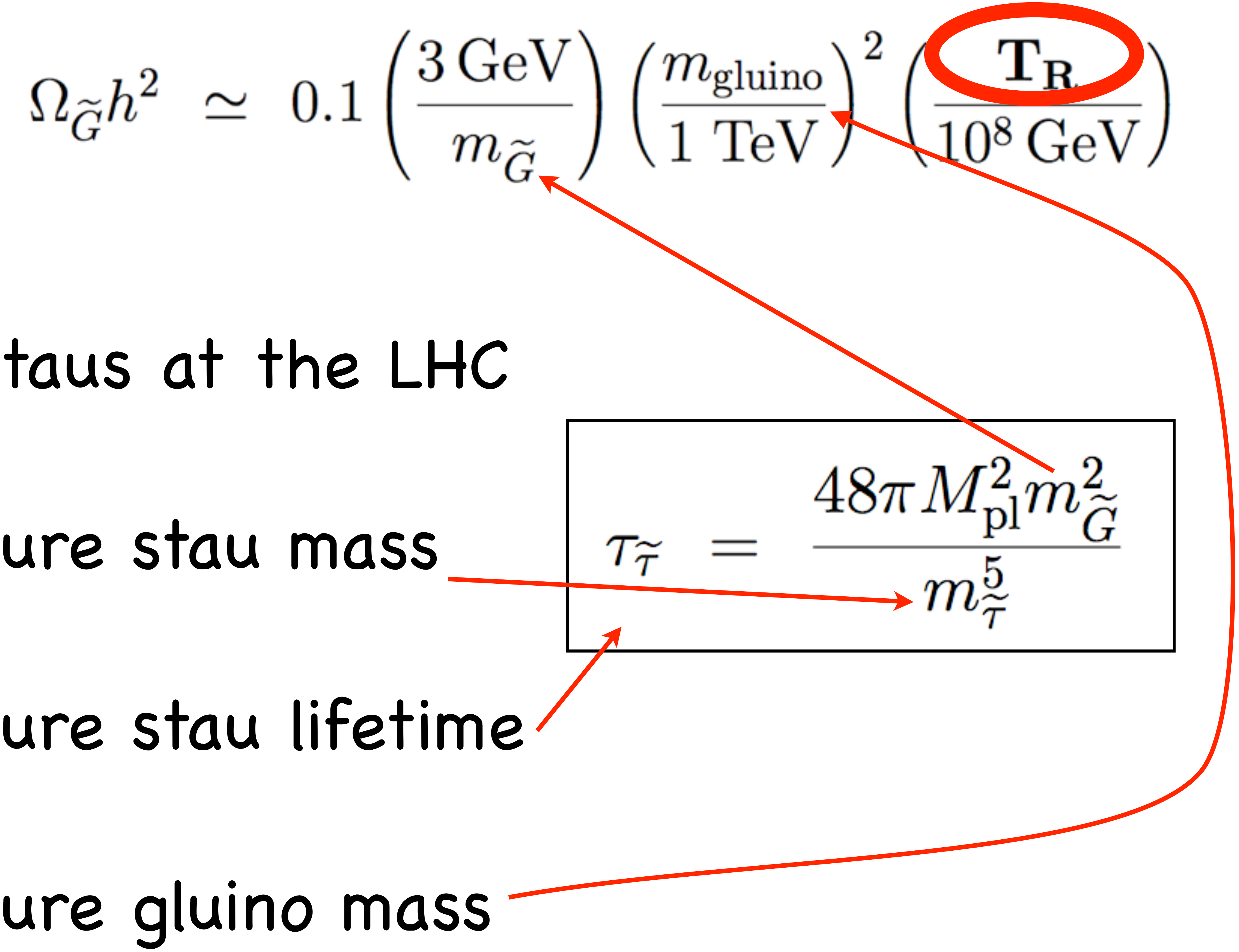
measure stau lifetime

step 4

measure gluino mass

$$\boxed{\tau_{\tilde{\tau}} = \frac{48\pi M_{\mathrm{pl}}^2 m_{\tilde{G}}^2}{m_{\tilde{\tau}}^5}}$$

T_R determination at the LHC with long-lived staus.



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step 1

see staus at the LHC

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step 1

see staus at the LHC

step 2

measure stau mass

step 3

measure stau lifetime

step 4

measure gluino mass

- Which range of parameters is accessible?
- Which range of T_R can be tested?
- Is it possible at the early stage (7TeV) ?

③

Probing high T_R scenario at the LHC with long lived stau.

M.Endo, KH, K.Nakaji, arXiv:1008.2307

See also earlier works:
Choi, Roszkowski, Ruiz De Austri,'07
Steffen,'08

Probing high T_R scenario at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307

Logic

Probing high T_R scenario at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307

Logic

(1) For a given stau mass

→ upper bound on gravitino mass

$$m_{\tilde{G}} \leq m_{\tilde{G}}^{\max}(m_{\tilde{\tau}})$$

Probing high T_R scenario at the LHC with long lived stau.

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→ upper bound on gravitino mass

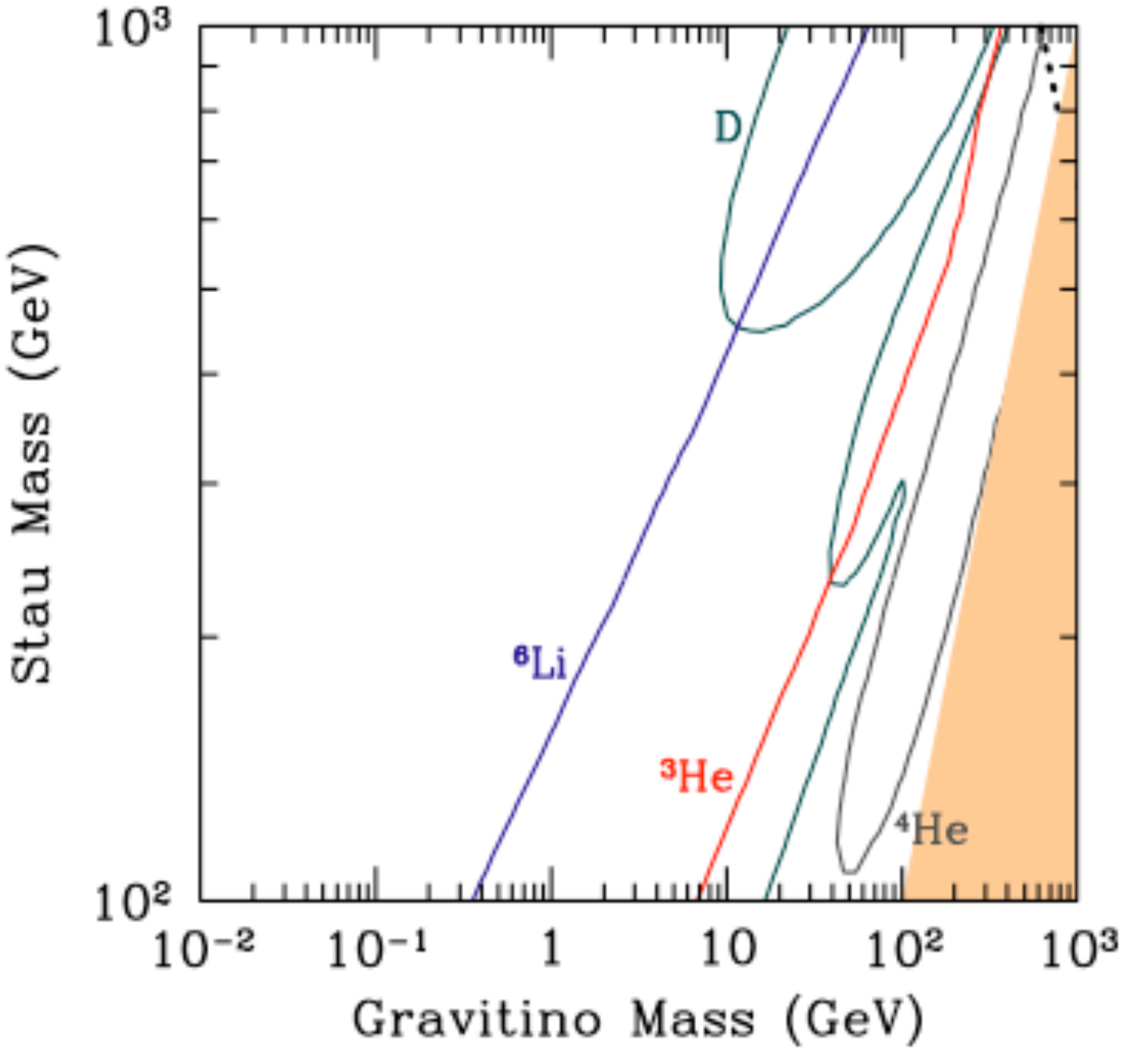
$$m_{\tilde{G}} \leq m_{\tilde{G}}^{\max}(m_{\tilde{\tau}})$$

$$\text{BBN}: \ \text{constraint on} \ (Y_{\tilde{\tau}}, \tau_{\tilde{\tau}})$$

$$Y_{\tilde{\tau}} = Y_{\tilde{\tau}}(m_{\tilde{\tau}})$$

$$\tau_{\tilde{\tau}} = \tau_{\tilde{\tau}}(m_{\tilde{\tau}}, m_{\tilde{G}})$$

$$\Longrightarrow \text{constraint on} \ (m_{\tilde{\tau}}, m_{\tilde{G}})$$



Kawasaki, Kohri, Moroi, Yotsuyanagi,'08

Probing high T_R scenario at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307

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Probing high T$_R$ scenario at the LHC with long lived stau.

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(2) + for a given T_R

→ upper bound on gluino mass

Fujii, Ibe, Yanagida,'04

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M.Endo, KH, K.Nakaji,
arXiv:1008.2307

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→ upper bound on gluino mass

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M.Endo, KH, K.Nakaji,
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Logic

(1) For a given stau mass

→ upper bound on gravitino mass

$$m_{\tilde{G}} \;\leq\; m_{\tilde{G}}^{\rm max}\,(m_{\tilde{\tau}})$$

$$\Omega_{\tilde{G}}h^2 \;\simeq\; 0.1\left(\frac{3\,{\rm GeV}}{m_{\tilde{G}}}\right)\left(\frac{T_R}{10^8\,{\rm GeV}}\right)\left(\frac{m_{\rm gluino}}{1\,{\rm TeV}}\right)^2 \quad = \;\Omega_{\rm DM}h^2 = 0.11$$

(2) + for a given T_R

→ upper bound on gluino mass

Fujii, Ibe, Yanagida,'04

Probing high T_R scenario at the LHC with long lived stau.

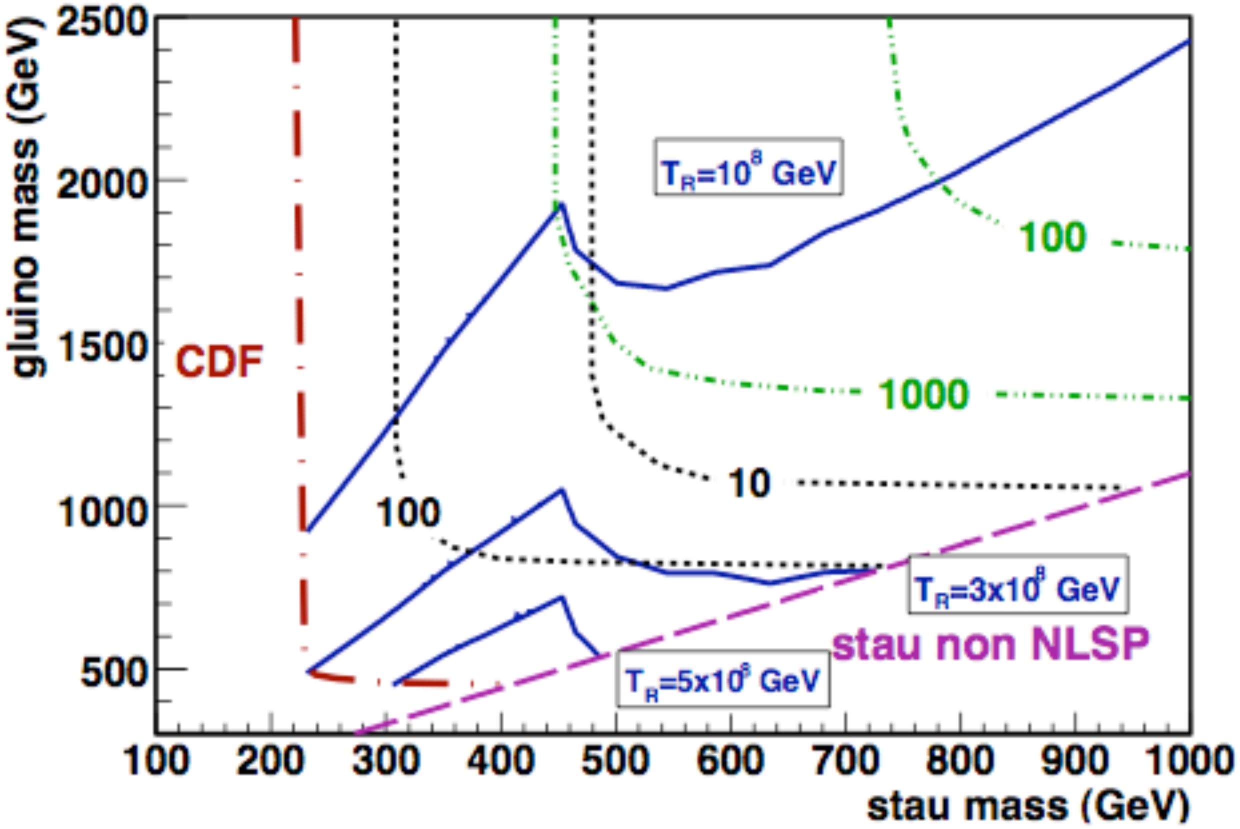
M.Endo, KH, K.Nakaji,
arXiv:1008.2307

Result

Probing high T_R scenario at the LHC with long lived stau.

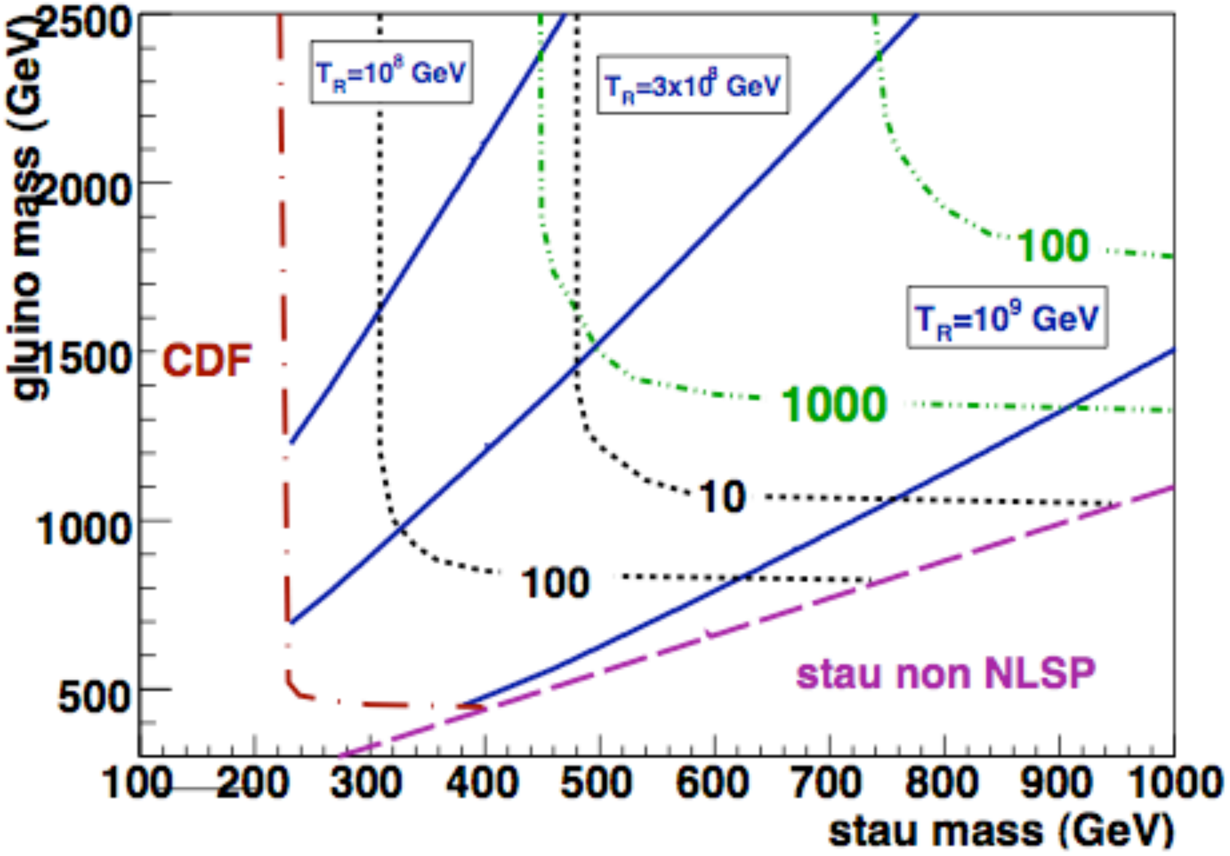
M.Endo, KH, K.Nakaji,
arXiv:1008.2307

Result



(a) = normal case

(in most cases) Stau annihilation is dominated by Electroweak process



(b) = reduced Ystau

Stau annihilation is dominated by enhanced Higgs coupling

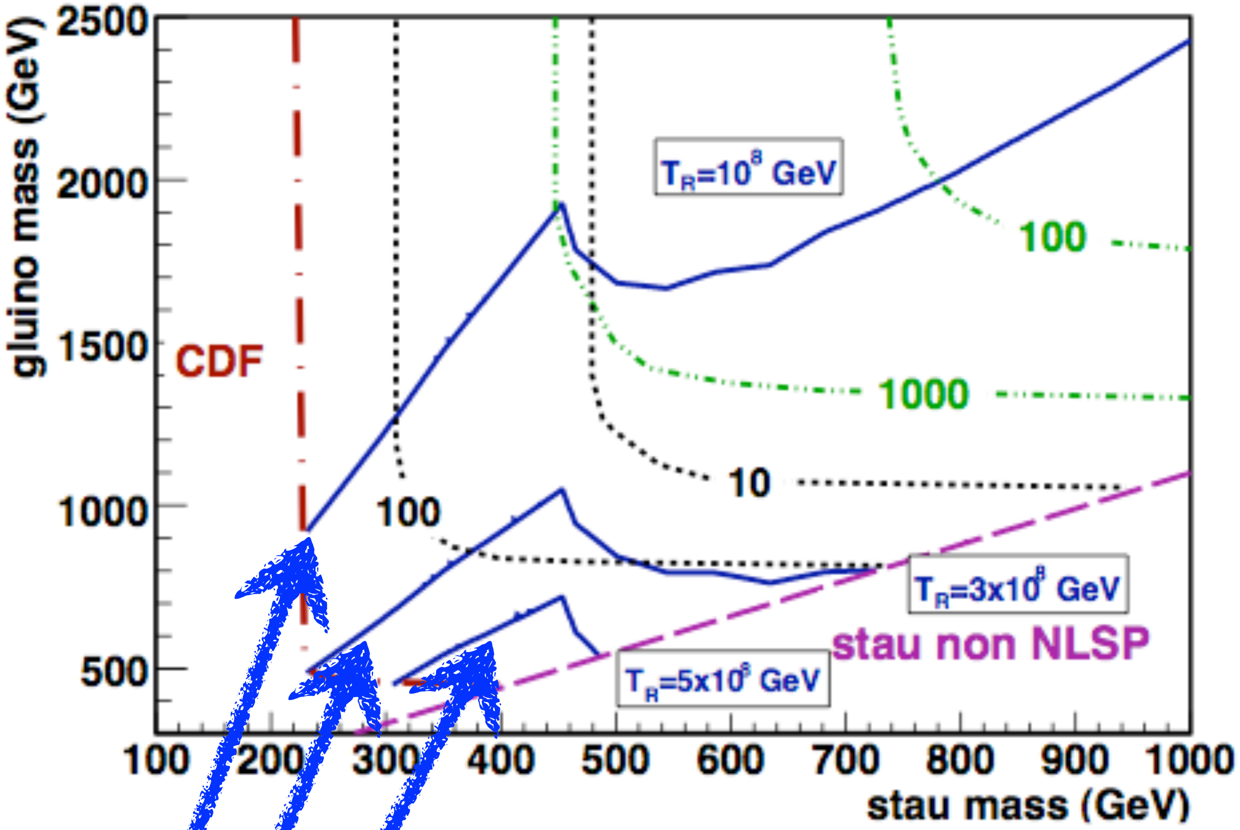
see, Ratz, Schmidt-Hoberg, Winkler,'08
Pradler, Steffen,'08

Note: take m(bino)=m(wino)=1.1m(stau)
to have conservative bound on TR.

Probing high T_R scenario at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307

Result



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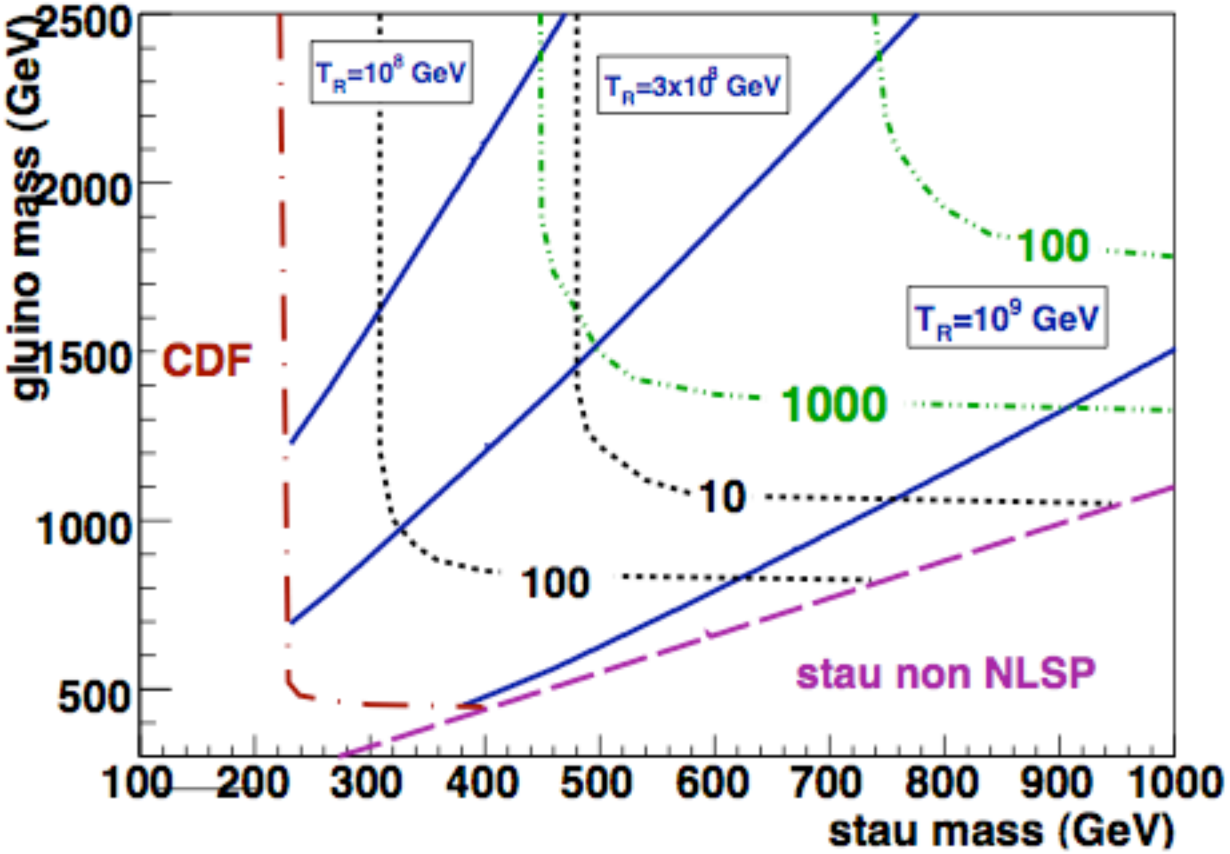


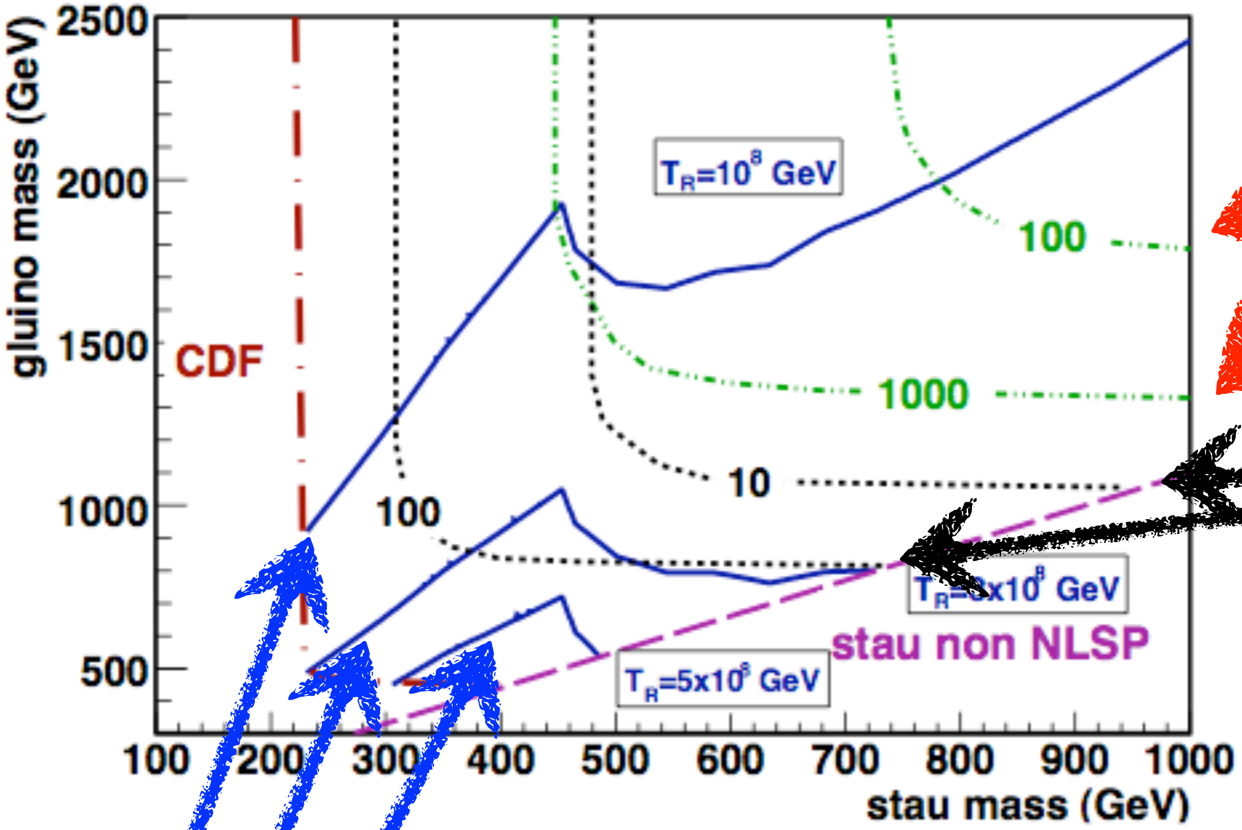
(b) = reduced Ystau

upper bound on the gluino mass for given TR

Probing **high T_R scenario** at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307

Result



(a)

# of produced staus
at 14 TeV 10fb^{-1}

# of produced staus
at 7 TeV 1fb^{-1}

upper bound on the gluino mass for given TR

Probing **high T_R scenario** at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
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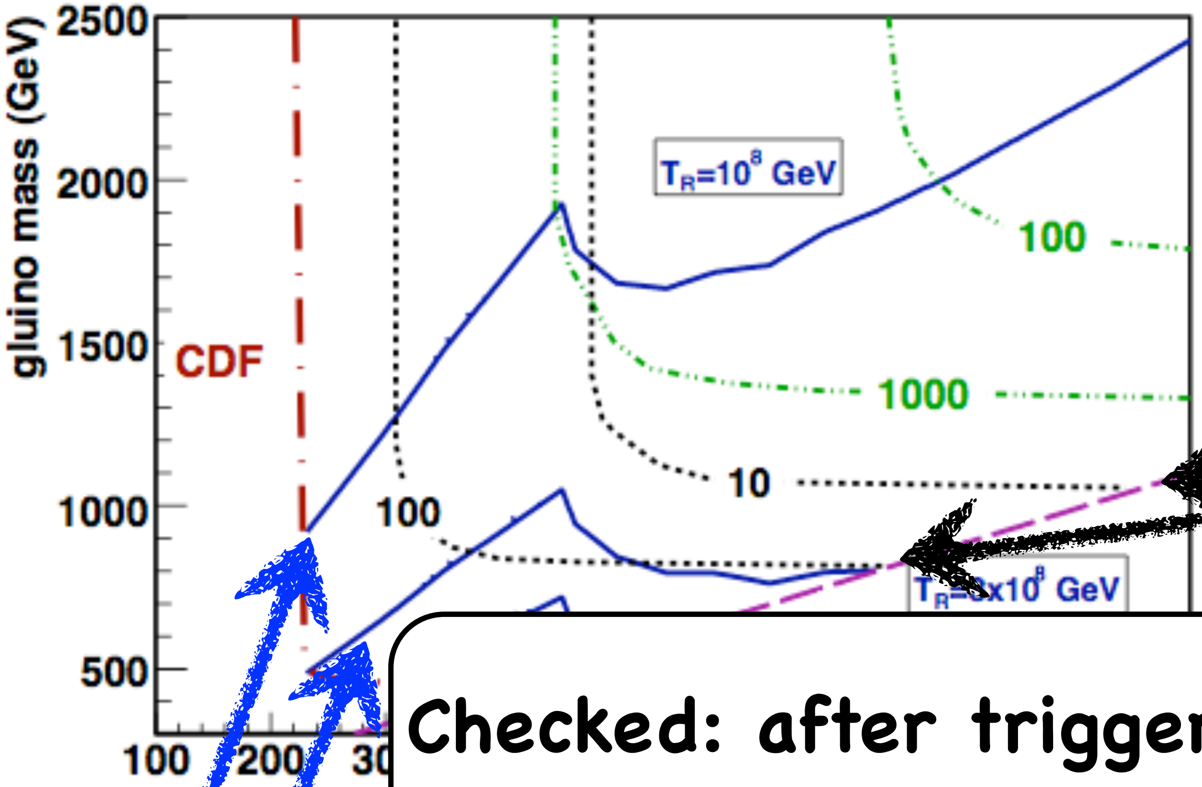
Result



# of produced staus
at 14 TeV 10fb^{-1}

# of produced staus
at 7 TeV 1fb^{-1}

upper b

Checked: after triggers and cuts, 20-50% events remain.

trigger assumption:

>=1 isolated e (pT>20GeV), or
>=1 isolated mu (pT>40GeV), or
>=1 isolated tau (pT>100GeV), or
>=1 isolated stau (pT>40 GeV and β>0.7, eta<1.0 or β>0.8, eta<2.8), or
>=2 staus (pT>40 GeV and β>0.7, eta<1.0 or β>0.8, eta<2.8)

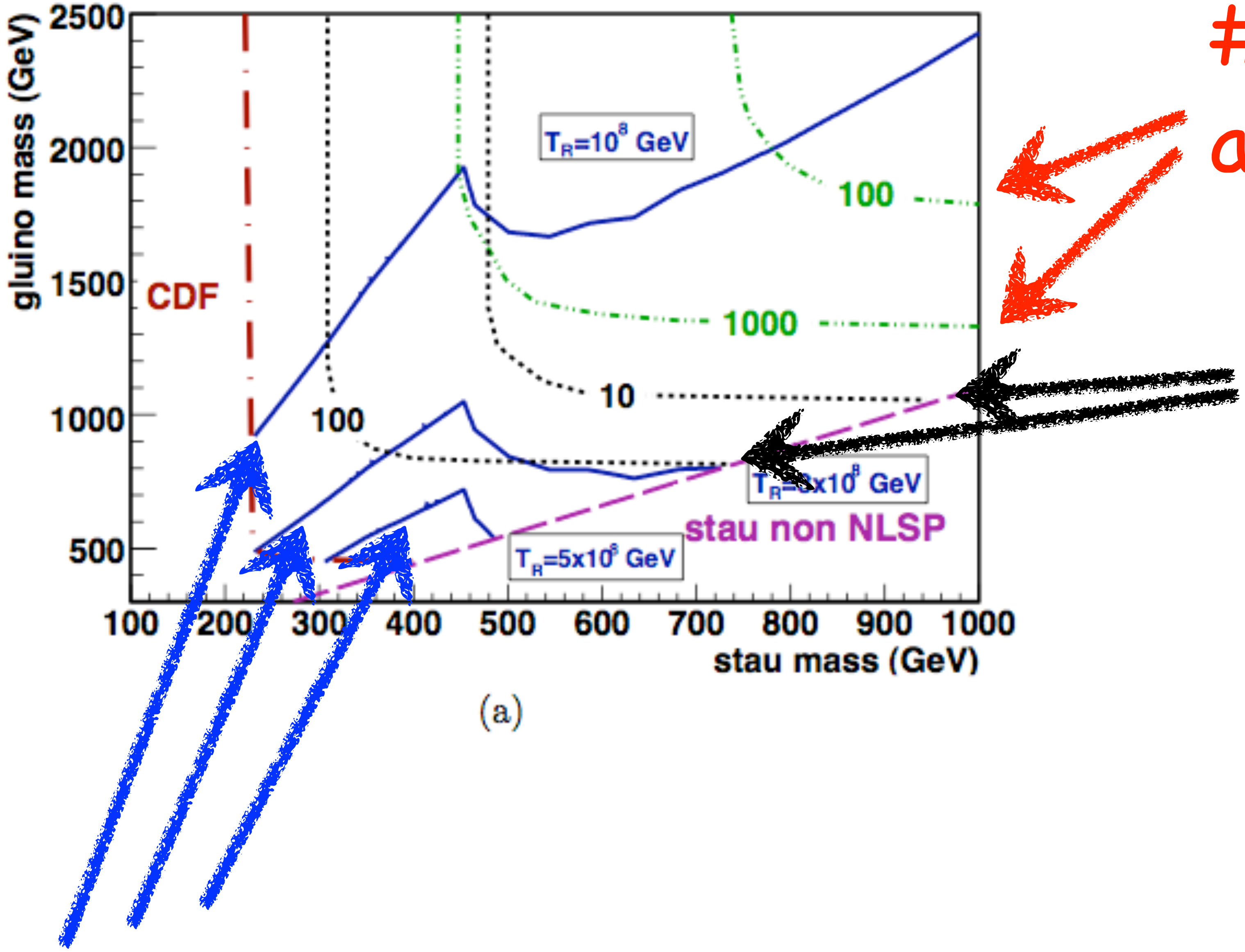
stau cuts assumptions:

pT > 20 GeV & eta < 2.5 & 0.5 < β < 0.9 **-> almost background free!**

Probing **high T_R scenario** at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307

Result



# of produced staus
at 14 TeV 10fb^{-1}

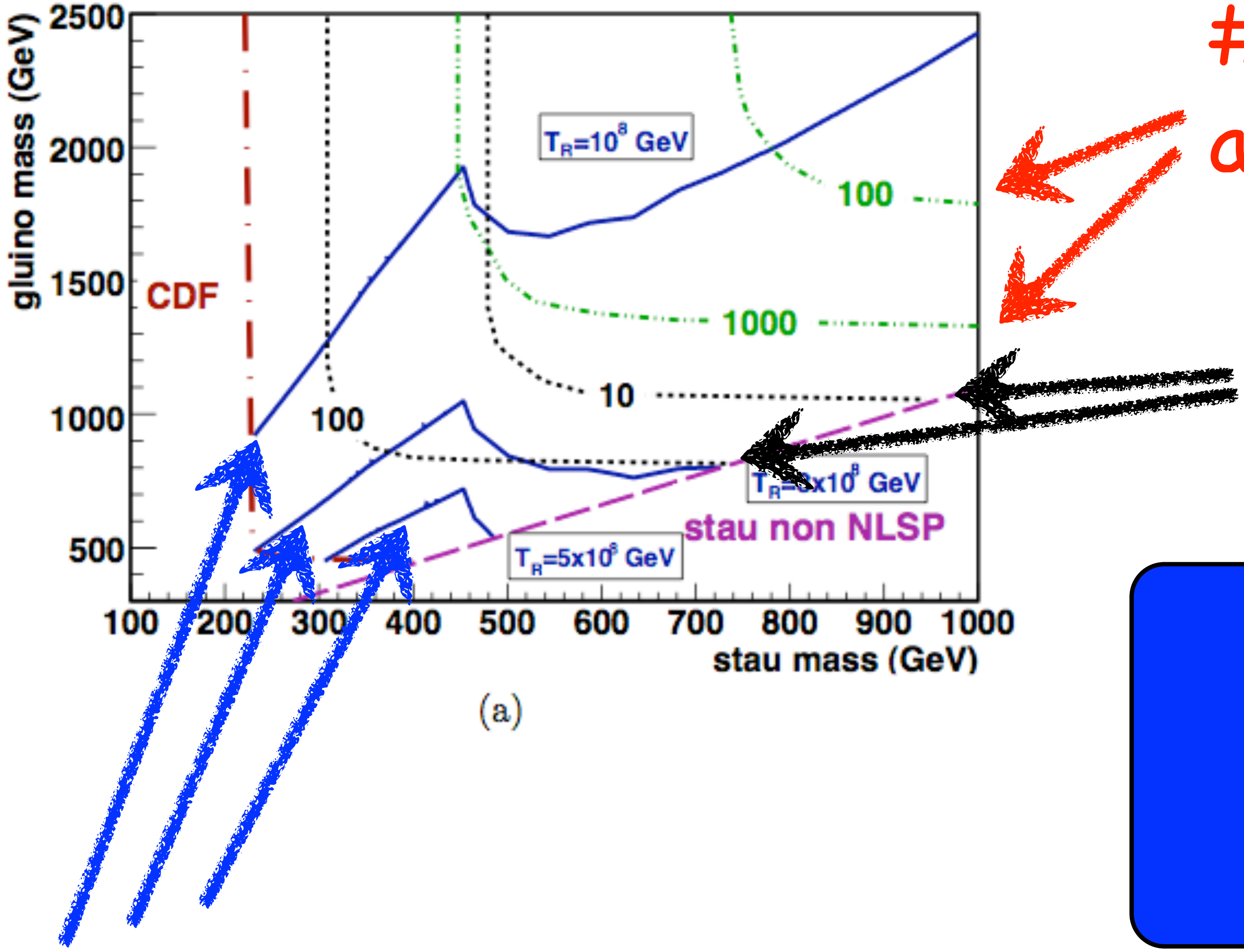
# of produced staus
at 7 TeV 1fb^{-1}

upper bound on the gluino mass for given TR

Probing high T_R scenario at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307

Result



(a)

\# of produced staus
at 14 TeV $10fb^{-1}$

\# of produced staus
at 7 TeV $1fb^{-1}$

TR > a few 10^8 GeV
can be probed
at 7 TeV $1fb^{-1}$!!!

upper bound on the gluino mass for given TR

SUMMARY

Main message of this talk:

If **SUSY** + **gravitino DM** + **stau NLSP**
is realized in nature,

The T_R can be determined at the **LHC**.

At 7 TeV 1fb^{-1} ($\simeq$ within 2 years),
T_R > a few 10^8 GeV can be tested
in most of the parameter space!

L H C !

Let's Have a Coffee !

additional slides

SUMMARY

If metastable heavy charged particle
will be observed at the LHC,

→ SUSY + gravitino DM + stau NLSP
is the leading candidate, (which can be tested)

the T_R can be determined at the **LHC**,

(assuming no dilution, and OmegaDM=OmegaG)

at 7 TeV 1fb^{-1} (≃ within 2 years),
T_R > a few 10^8 GeV can be tested
in most of the parameter space!

Reheating Temperature T_R

$\sim$ highest temperature in the rad. dom. universe.

= one of the most important parameters of cosmology.

- determined by inflaton decay rate:

$$\Gamma_\phi \sim m_\phi^3/M_\mathrm{P}^2$$

$$\longrightarrow \quad T_R \sim \sqrt{\Gamma_\phi M_\mathrm{P}} \sim 10^{10}\,\mathrm{GeV}(m_\phi/10^{13}\,\mathrm{GeV})^{3/2}$$

- important for baryogenesis:
  (e.g. thermal Leptogenesis $\longrightarrow \quad T_R > \mathcal{O}(10^9\,\mathrm{GeV})$

- typically most of staus have large velocity and escape from detector.
- but some of them have sufficiently small velocity and stop at calorimeters.

example of SUSY model point SPS7 (σ_{SUSY} = 3.5 pb)

from Asai, KH, Shirai '09

(See related work "stopping gluino", Arvanitaki et.al.)

TABLE II: The number of stopping staus for 10 fb^{-1}.

with cuts	without cuts
400	805

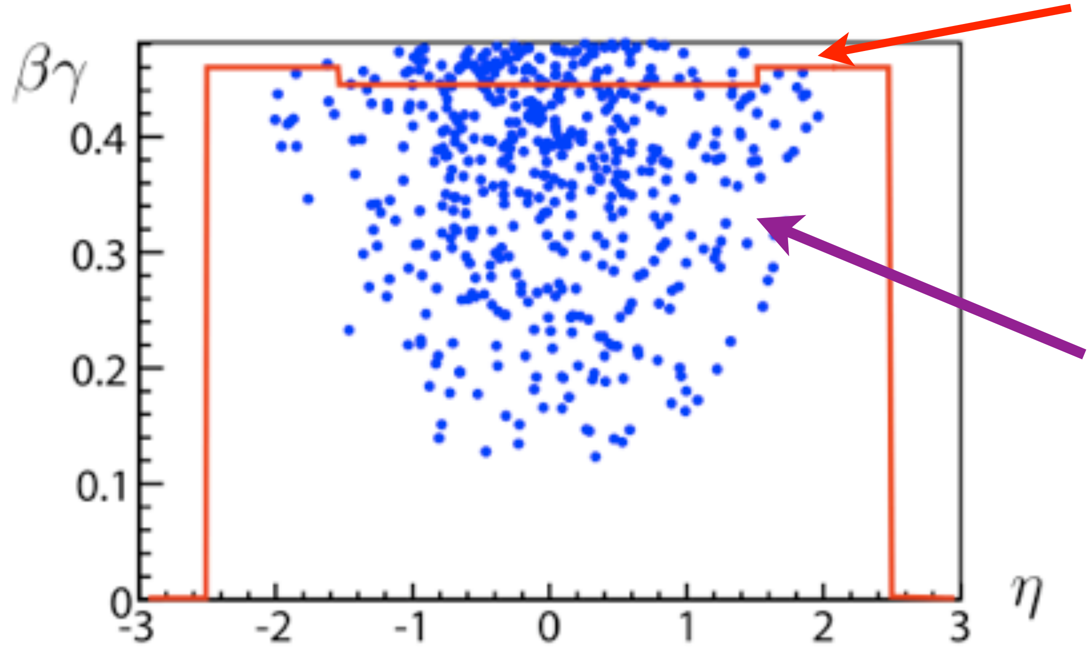


FIG. 1: $\eta - \beta\gamma$ distribution of the staus. The red line shows the limit for the stau to stop in the detector.

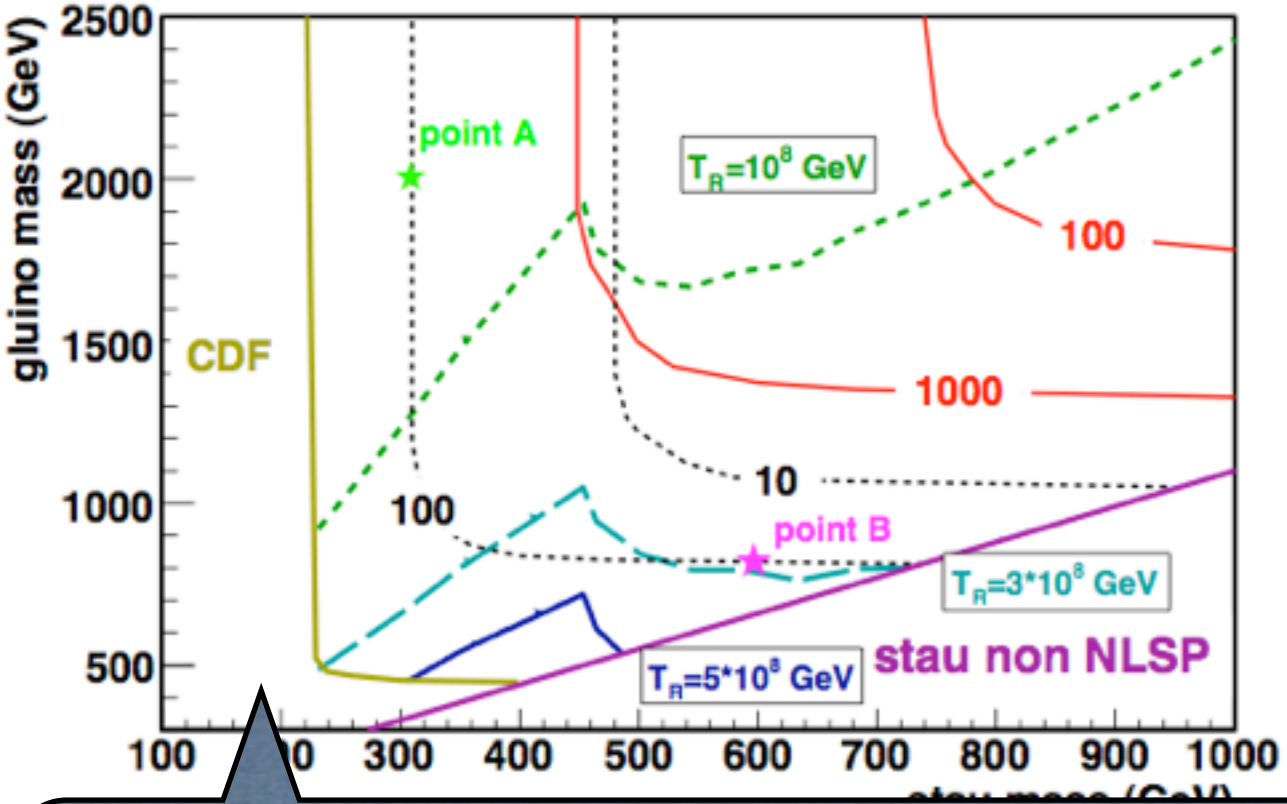
assume (ATLAS):
Fe 1440mm (barrel)
Cu 1400mm (end-cap)

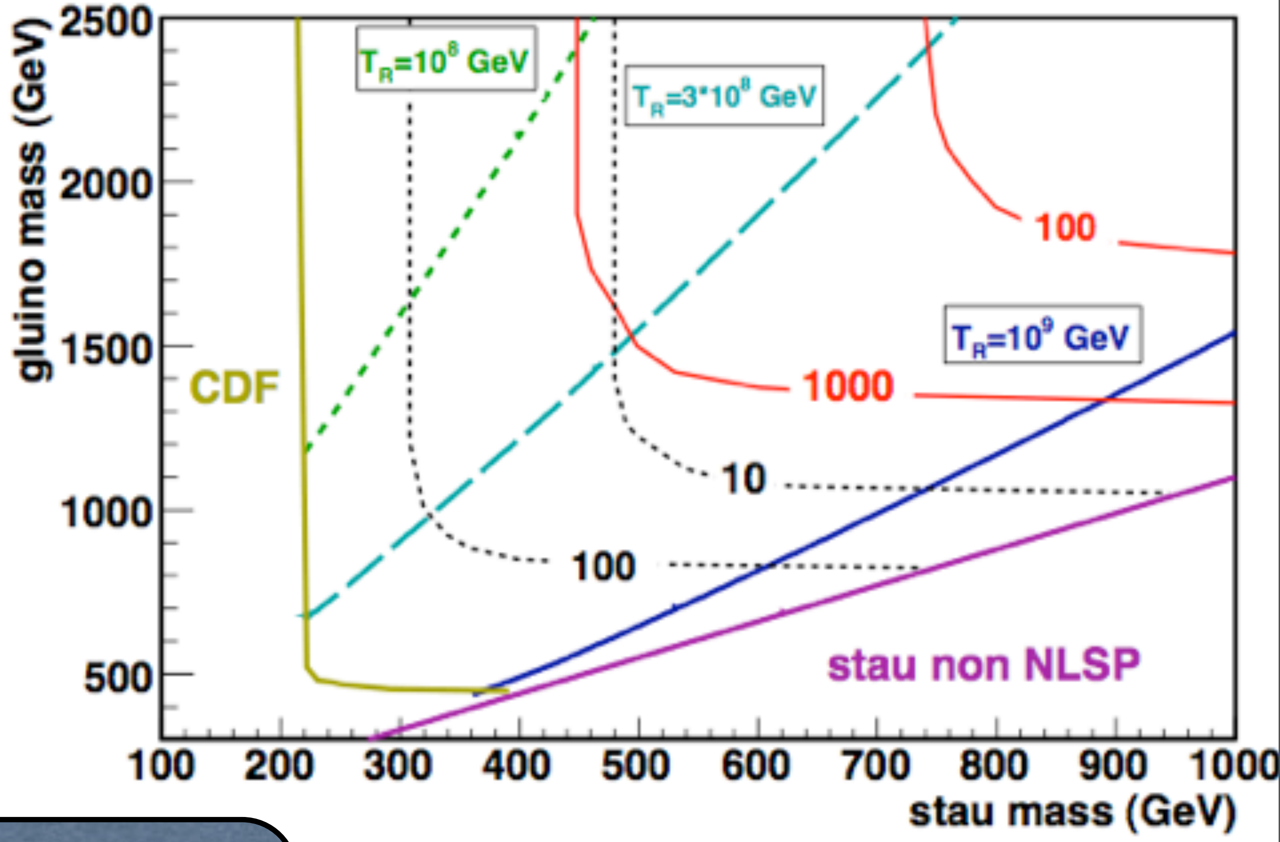
stopped events

- about 1% of total SUSY events
- a few per day (for 10^{33}/cm^2 s)

Probing high T_R scenario at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307





(b)= reduced Ystau

CDF bound .....using [PRL 103, 021802 (2009)]
production cross section of CHAMPS with

- eta < 0.7
- pT > 40 GeV
- 0.4 < β < 0.9
- sum(ET, R<0.4) /pT < 0.1

should be less than 10 fb (2 sigma)