הטכניון
מכון טכנולוגי לישראל
TECHNION
Israel Institute of Technology

BSM at Colliders

Sho IWAMOTO（岩本　祥）

18–19 Oct. 2016
“Search for New Physics through the Higgs boson” @ Gwangju

This 2-hour presentation is based on my works

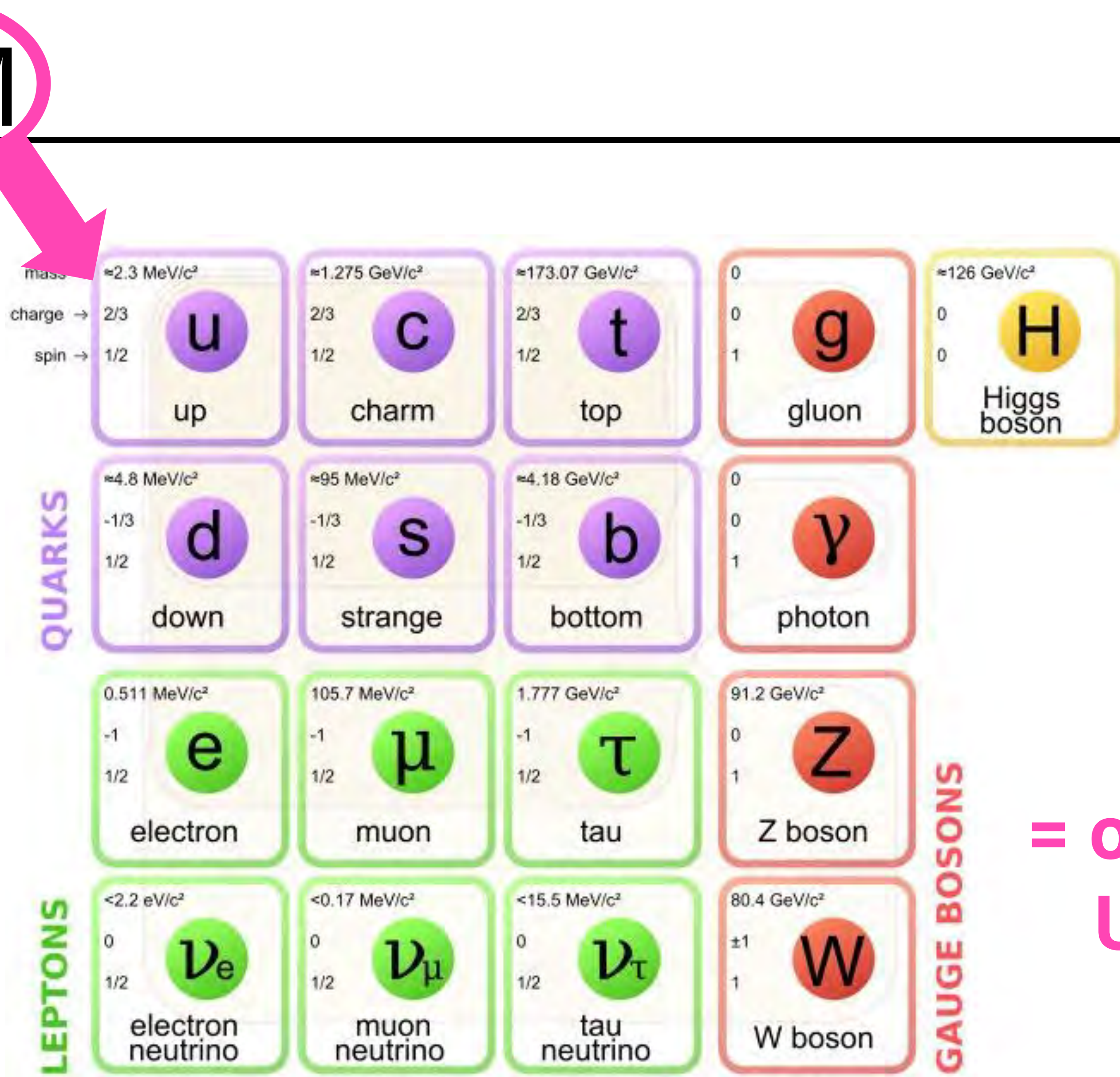
- M. Endo, K. Hamaguchi, SI, N. Yokozaki, *Higgs mass, muon g−2, and LHC prospects in gauge mediation models with vector-like matters* [1112.5653]
- M. Endo, K. Hamaguchi, SI, T. Yoshinaga, *Muon g−2 vs LHC in Supersymmetric Models* [1303.4256]
- J. L. Feng, SI, Y. Shadmi, S. Tarem, *Long-Lived Sleptons at the LHC and a 100 TeV Proton Collider* [1505.02996]
- M. Abdullah, J. L. Feng, SI, B. Lillard , *Heavy Bino Dark Matter and Collider Signals in the MSSM with Vector-like 4th-Generation Particles* [1608.00283]

and many works by others. Several citations could be missing; sorry for the incompleteness.

BSM at Colliders?

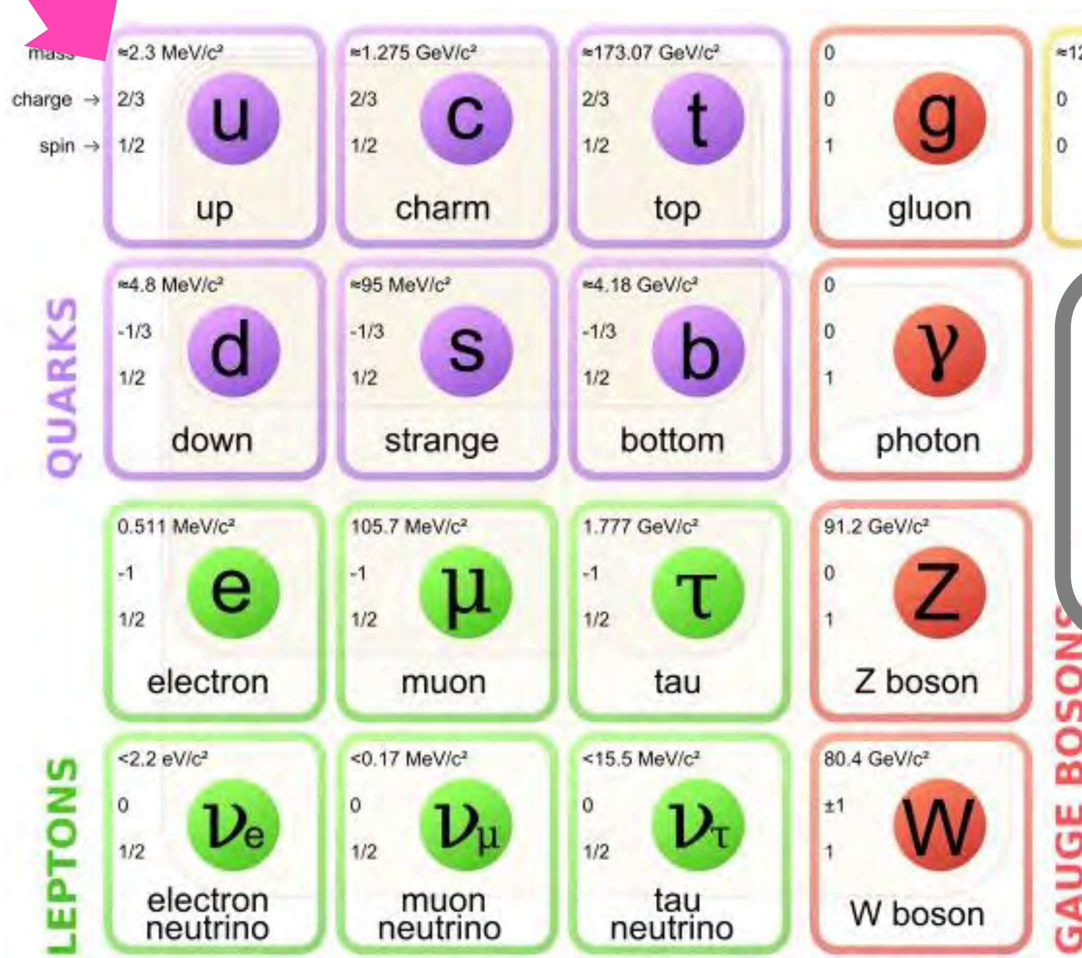
BSM ?

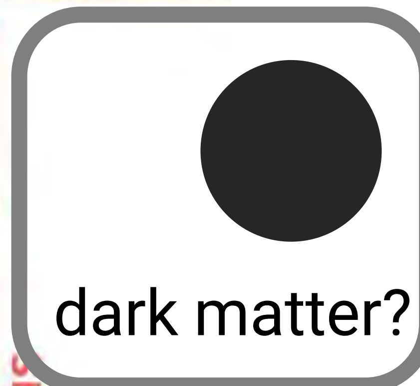
BSM ?



= our Universe

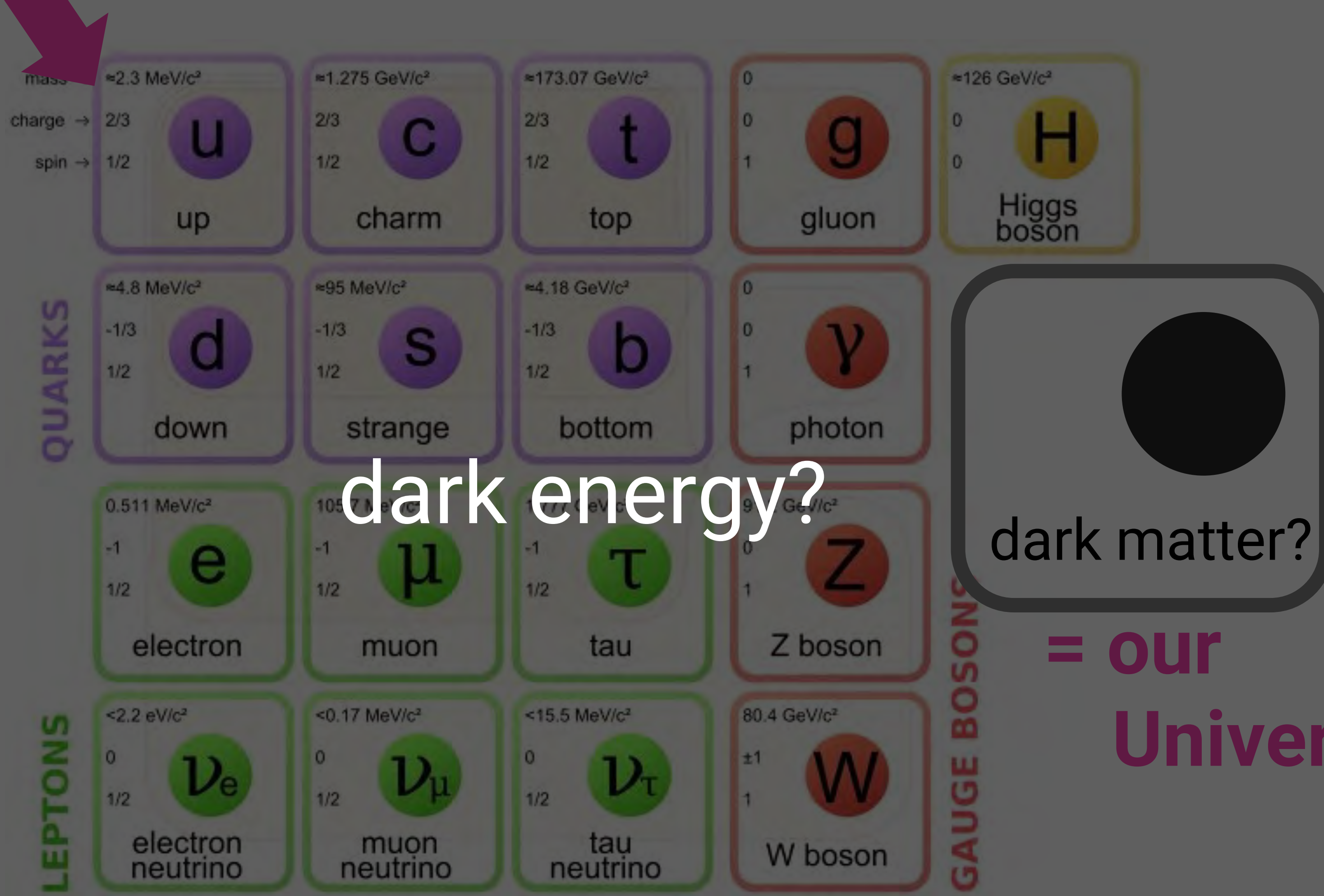
BSM ?





= our Universe

BSM ?



= our Universe

BSM ?

Many hints of BSM

- ✓ Dark matter
- ✓ Dark energy
- ✓ Neutrino mass
- ✓ Gauge coupling unification
- ✓ Higgs mass (“naturalness”)
- ✓ Muon “$g-2$”
- ✓ …

BSM ?

- SUSY
- composite Higgs
- composite DM
- extra dimensions
- extended Higgs
- …

Many hints of BSM

✓ Dark matter

✓ Dark energy

✓ Neutrino mass

✓ Gauge coupling unification

✓ Higgs mass (“naturalness”)

✓ Muon “g−2”

✓ …

BSM at Colliders?

- SUSY
- composite Higgs
- composite DM
- extra dimensions
- extended Higgs
- …

- LHC
- future pp collider
- future ee collider

BSM at Colliders?

- SUSY
- composite Higgs
- composite DM
- extra dimensions
- extended Higgs
- ...

- LHC
- fu [illegible] lider
- future ee collider

BSM at Colliders?

- SUSY
- composite Higgs
- composite DM
- extra dimensions
- extended Higgs
- …

- LHC
- fu… lider
- future ee collider

“strange” signature

BSM at Colliders?

- SUSY
- composite Higgs
- composite DM
- extra dimensions
- extended Higgs
- …

- LHC

- fu lider
- future ee collider

"strange" signature ??

- new heavy particles
  - stable & neutral → $\not{E}$
  - stable & charged
    → exotic tracks (LLCP)
    [long-lived charged/colored particle]
  - unstable
    → decay products
    - resonance
    - "more exotic" signatures

high energy

- LHC
- future pp collider
- future ee collider

high precision

- deviation in known parameters
  - Higgs-, top-, and EW-sectors.

- new heavy particles
  - stable & neutral → $\not{E}$
  - stable & charged
    → exotic tracks (LLCP)
    [long-lived charged/colored particle]
  - unstable
    → decay products
    - resonance
    - “more exotic” signatures

high energy

- LHC
- future pp collider
- future ee collider

high precision

- deviation in known parameters
  - Higgs-, top-, and EW-sectors.

- ✓ Dark matter
- ✓ Dark energy
- ✓ Neutrino mass
- ✓ Gauge coupling unification
- ✓ Higgs mass (“naturalness”)
- ✓ Muon “g−2”
- ✓ …

- SUSY
- composite Higgs
- composite DM
- extra dimensions
- extended Higgs
- …

- ➢ $\not{E}$
- ➢ resonances
- ➢ LLCP
- ➢ “more exotic”

LHC

FCC-pp

hep-ph

- ✓ Dark matter
- ✓ Dark energy
- ✓ Neutrino mass
- ✓ Gauge coupling unification
- ✓ Higgs mass (“naturalness”)
- ✓ Muon “g−2”
- ✓ …

- SUSY
- composite Higgs
- composite DM
- extra dimensions
- extended Higgs
- …

hep-ex

- $\not{E}$
- resonances
- LLCP
- “more exotic”

LHC

FCC-pp

- ✓ Dark matter
- ✓ Dark energy
- ✓ Neutrino mass
- ✓ Gauge coupling unification
- ✓ Higgs mass (“naturalness”)
- ✓ Muon “g−2”
- ✓ …

- ■ SUSY
- ■ composite Higgs
- ■ composite DM
- ■ extra dimensions
- ■ extended Higgs
- ■ …

- ➢ $\not{E}$
- ➢ resonances
- ➢ LLCP
- ➢ “more exotic”

LHC

FCC-pp

1) $\not{E}_T$

2) LLCP

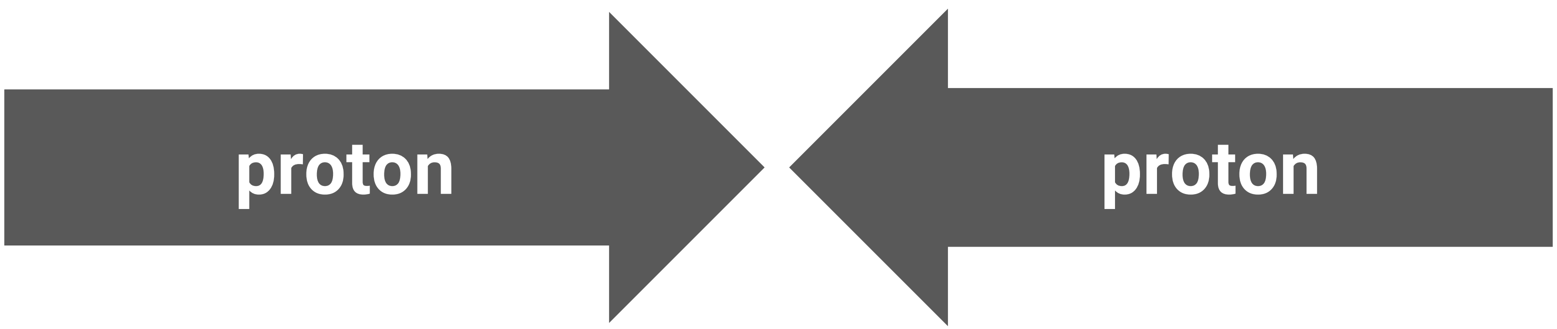
3) more exotic

- $\not{E}$: primary search target @ LHC

✓ Dark matter

…neutral

& (almost) **stable**

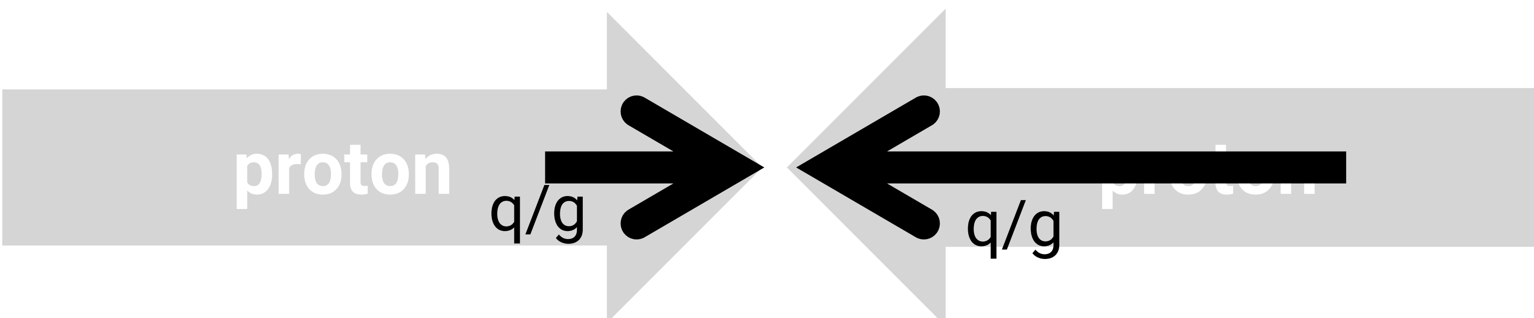


- $\not{E}$: primary search target @ LHC

✓ Dark matter

…**neutral**

& (almost) **stable**

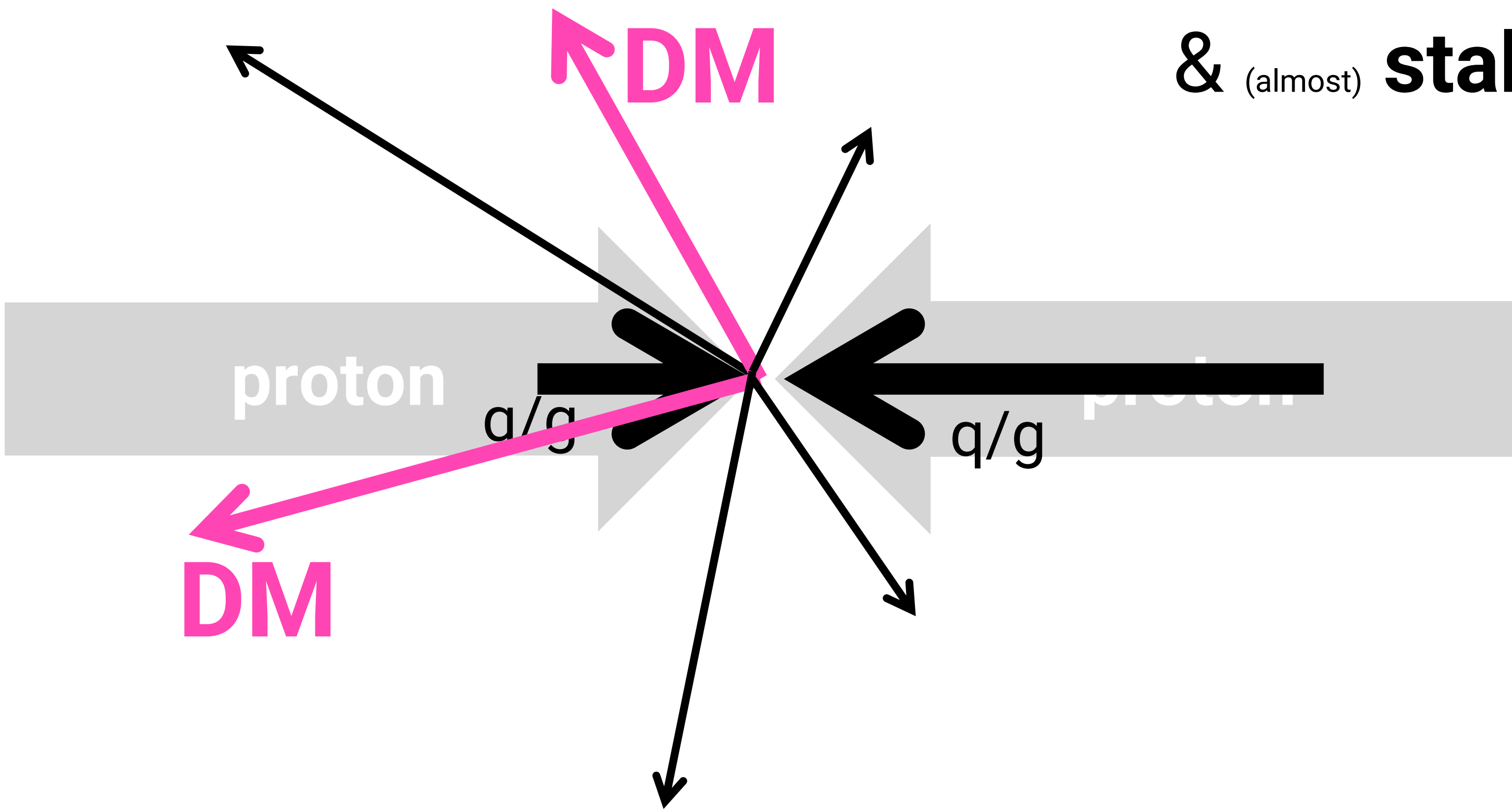


- $\not{E}$: primary search target @ LHC

✓ Dark matter

...neutral

& (almost) **stable**

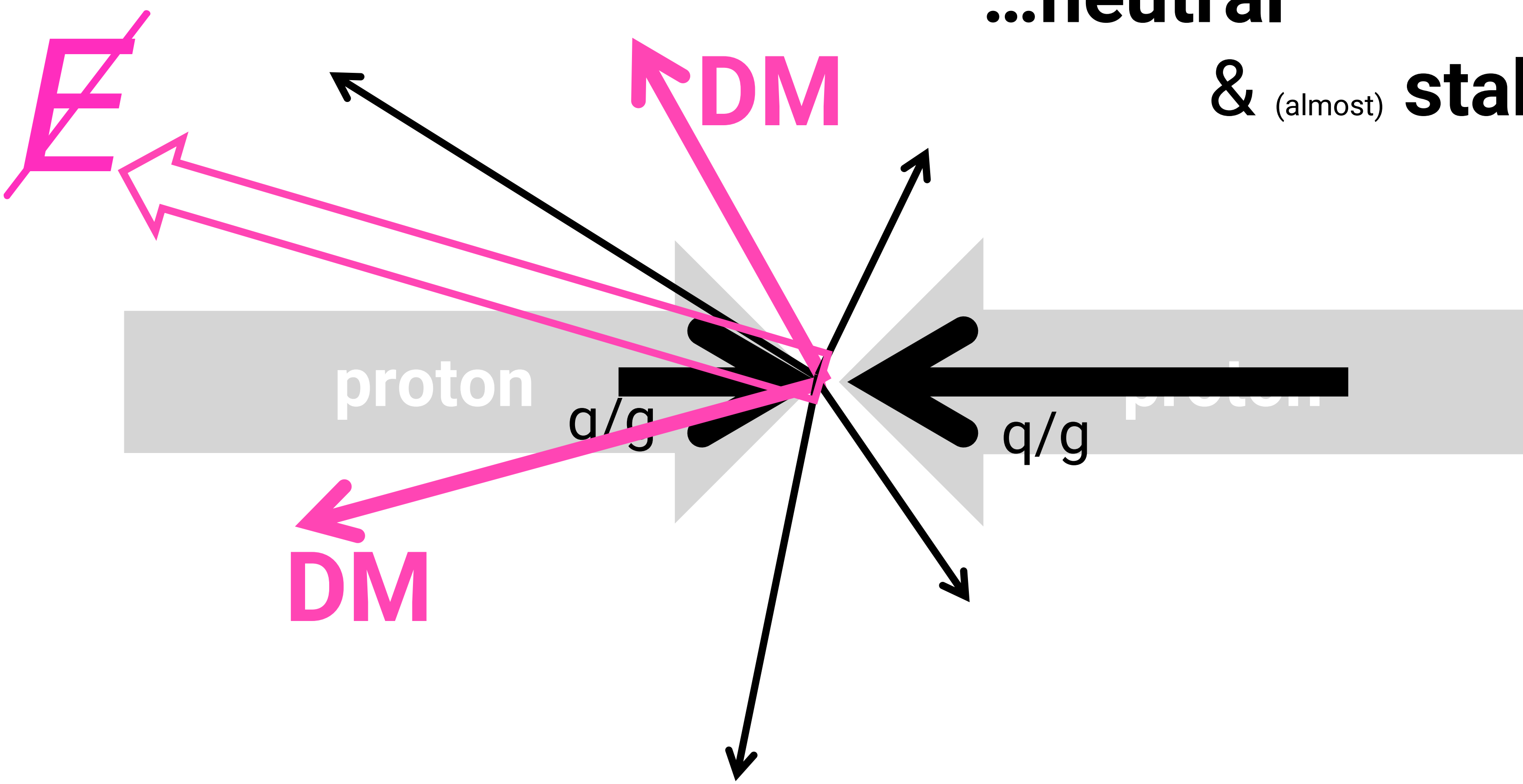


- $\not{E}$: primary search target @ LHC

✓ Dark matter

…neutral

& (almost) **stable**

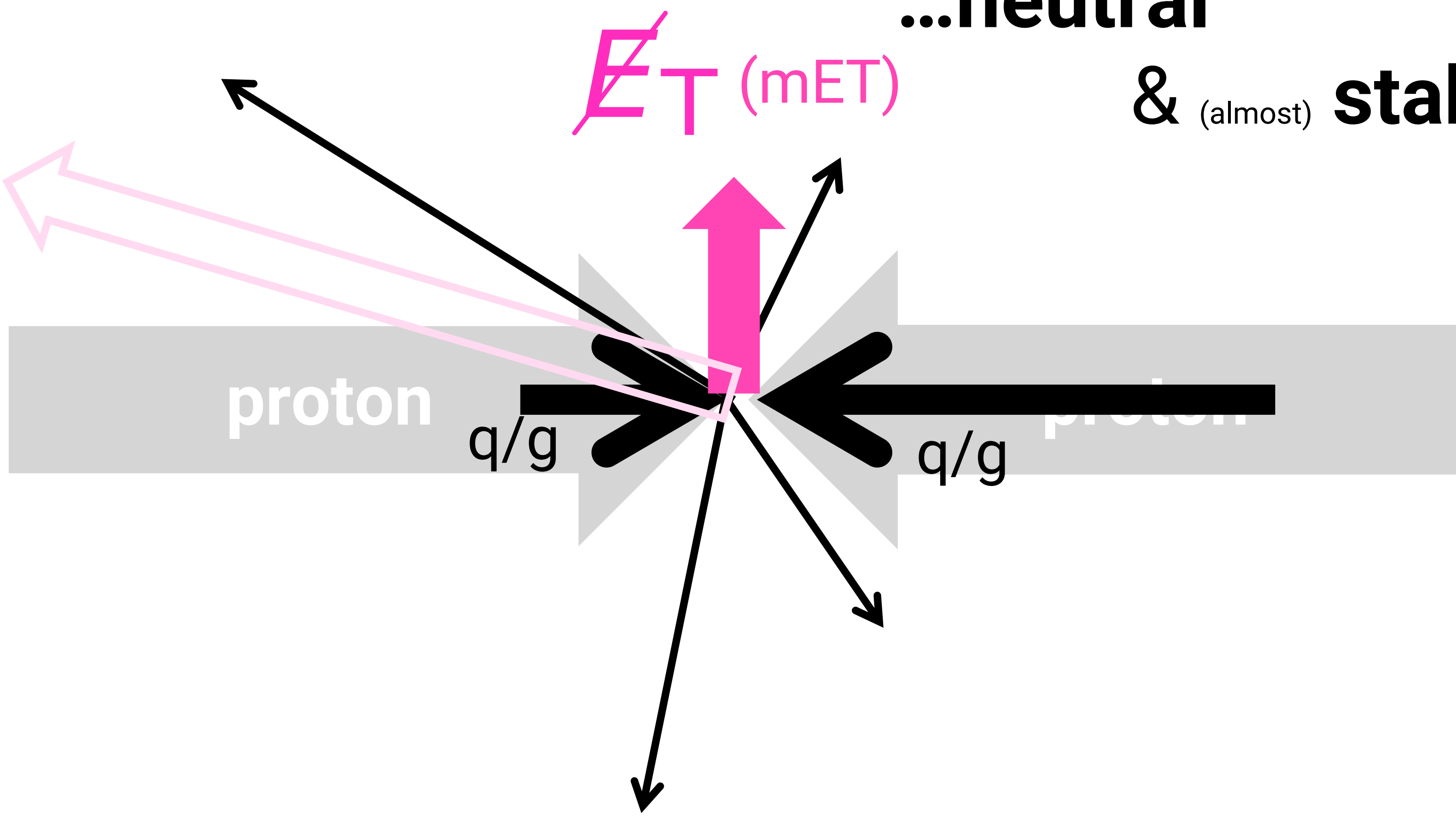


- mET : primary search target @ LHC

✓ Dark matter

…neutral

& (almost) **stable**



- mET : primary search target @ LHC

  We cannot “see” mET.

  → mET + **something**

  - from ISR: “mono-jet” “mono-photon” etc.

    → **DM searches at LHC (Shih-Chieh Hsu’s talk)**

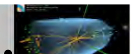
  - from cascade decay: “SUSY” searches

- "SUSY" searches : **something + mET**

the list of "something"

Compact Muon Solenoid
LHC, CERN

Visit us: CMS Public Website, CMS Ph



Recent Supersymmetry Preliminary Results

CMS-PAS-SUS-15-009	Search for natural supersymmetry in events with top quark pairs and photons in pp collisions at $\sqrt{s}$ = 8 TeV
CMS-PAS-SUS-16-025	Search for new physics in the compressed mass spectra scenario using events with two soft opposite-sign leptons and missing transverse momentum at 13 TeV
CMS-PAS-SUS-16-028	Search for direct top squark pair production in the single lepton final state at $\sqrt{s}$ = 13 TeV
CMS-PAS-SUS-16-021	Search for new physics in final states with two opposite-sign, same-flavor leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV
CMS-PAS-SUS-16-029	Search for direct top squark pair production in the fully hadronic final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 12.9 fb^{-1}
CMS-PAS-SUS-16-026	Search for electroweak production of charginos and neutralinos in the WH final state at 13 TeV
CMS-PAS-SUS-16-024	Search for electroweak SUSY production in multilepton final states in 12.9 fb^{-1} of pp collision data at $\sqrt{s}$ = 13 TeV
CMS-PAS-SUS-16-022	Search for supersymmetry with multileptons in 13 TeV data
CMS-PAS-SUS-16-016	An inclusive search for new phenomena in final states with one or more jets and missing transverse momentum at $\sqrt{s}$ = 13 TeV with the α_T variable
CMS-PAS-SUS-16-015	Search for new physics in the all-hadronic final state with the M_{T2} variable
CMS-PAS-SUS-16-014	Search for supersymmetry in events with jets and missing transverse momentum in proton-proton collisions at 13 TeV
CMS-PAS-SUS-16-012	Search for supersymmetry in events with a Higgs decaying to two photons using the razor variables
CMS-PAS-SUS-16-013	Search for R-parity-violating SUSY in final states with zero or one lepton and large multiplicity of jets and b-tagged jets
CMS-PAS-SUS-16-019	Search for supersymmetry in events with one lepton and multiple jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV in 2016
CMS-PAS-SUS-16-030	Search for supersymmetry in the all-hadronic final state using top quark tagging in pp collisions at $\sqrt{s}$ = 13 TeV
CMS-PAS-SUS-16-020	Search for SUSY in same-sign dilepton events with 12.9 fb^{-1} of pp collision data at 13 TeV
CMS-PAS-SUS-16-023	Search for supersymmetry in final states with at least one photon and E_T^{miss} in pp collisions at $\sqrt{s}$ = 13 TeV

papers

Short Title of Paper	Date	$\sqrt{s}$ (TeV)	L (fb^{-1})	Document	Plots+Aux. Material	Journal
1-2 taus + Etmiss	07/2016	13	3.2	1607.05979	Link (+data)	Submitted to EPJC
di-photon + MET	6/2016	13	3.2	1606.09150	Link	Accepted by EPJC
2b + MET	6/2016	13	3.2	1606.08772	Link (+data)	EPJC, (2016) 76:547
LLP (pixel+Tile)	6/2016	13	3.2	1606.05129	Link (+data)	Physics Letters B (2016), pp. 647-665
1L stop	6/2016	13	3.2	1606.03903	Link (+data)	Phys. Rev. D 94 (2016) 052009
multi b-jets	5/2016	13	3.2	1605.09318	Link (+data)	Phys. Rev. D 94 032003
1L 2-6 jets	5/2016	13	3.2	1605.04285	Link (+data)	Accepted by EPJC
0L 2-6 jets	5/2016	13	3.2	1605.03814	Link (+data)	Eur. Phys. J. C (2016) 76: 392
monojet (compressed squarks) NEW	4/2016	13	3.2	1604.07773	Link	Phys. Rev. D 94 (2016) 032005
LLP with pixel dE/dx	4/2016	13	3.2	1604.04520	Link (+data)	Phys. Rev. D 93, 112015 (2016)
2 same sign or 3 leptons	2/2016	13	3.2	1602.09058	Link (+data)	EPJ C, 76(5), 1-26
0L 7-10 jets	2/2016	13	3.2	1602.06194	Link (+data)	Phys. Lett. B 757 (2016) 334

conference notes

Short Title of preliminary conference note/paper	Date	$\sqrt{s}$ (TeV)	L (fb^{-1})	Document	Plots
2L+jets+MET (Z/edge)	9/2016	13	14.7	ATLAS-CONF-2016-098	Link
EWK 2/3L	9/2016	13	14.8	ATLAS-CONF-2016-096	Link
EWK di-tau	9/2016	13	14.8	ATLAS-CONF-2016-093	Link
0L 8-10 jets (RPC gluinos)	9/2016	13	18.2	ATLAS-CONF-2016-095	Link
RPV 1L+jets	9/2016	13	14.8	ATLAS-CONF-2016-094	Link
0L 2-6 jets (squark/gluinos)	8/2016	13	13.3	ATLAS-CONF-2016-078	Link
1L 2-6 jets (squark/gluinos)	8/2016	13	14.8	ATLAS-CONF-2016-054	Link
SS/3L + jets (squarks/gluinos)	8/2016	13	13.2	ATLAS-CONF-2016-037	Link
0/1L + 3b jets (squarks/gluinos)	8/2016	13	14.8	ATLAS-CONF-2016-052	Link
photon + jets	8/2016	13	13.3	ATLAS-CONF-2016-066	Link
stop 0L	8/2016	13	13.3	ATLAS-CONF-2016-077	Link
stop 1L	8/2016	13	13.3	ATLAS-CONF-2016-050	Link
stop 2L	8/2016	13	13.3	ATLAS-CONF-2016-076	Link
stop2 (3L)	8/2016	13	13.3	ATLAS-CONF-2016-038	Link
stop stau	8/2016	13	13.3	ATLAS-CONF-2016-048	Link
4 lepton (RPV EWK)	8/2016	13	13.3	ATLAS-CONF-2016-075	Link
multijet (RPV)	8/2016	13	14.8	ATLAS-CONF-2016-057	Link
Stop to bs (RPV)	8/2016	13	15.6	ATLAS-CONF-2016-084	Link

- “SUSY” searches : **something + mET**

… What is “something”?

hep-ex people: We will look at **anything** we can see!

... if we had infinite time.

“what should we see **at first**?”

hep-ex → hep-ph

→ hep-ph people will answer

based on their theory

- A theory : SUSY (supersymmetry)

$$\textbf{SM} \xrightarrow{+\text{SUSY}} \textbf{MSSM}$$

Boson — Fermion

$h \Leftrightarrow \tilde{H}$ [Higgsino]

$\tilde{q}$ [squark] $\Leftrightarrow q$

$\tilde{\mu}$ [smu] $\Leftrightarrow \mu$

[Standard Model]

- SM =

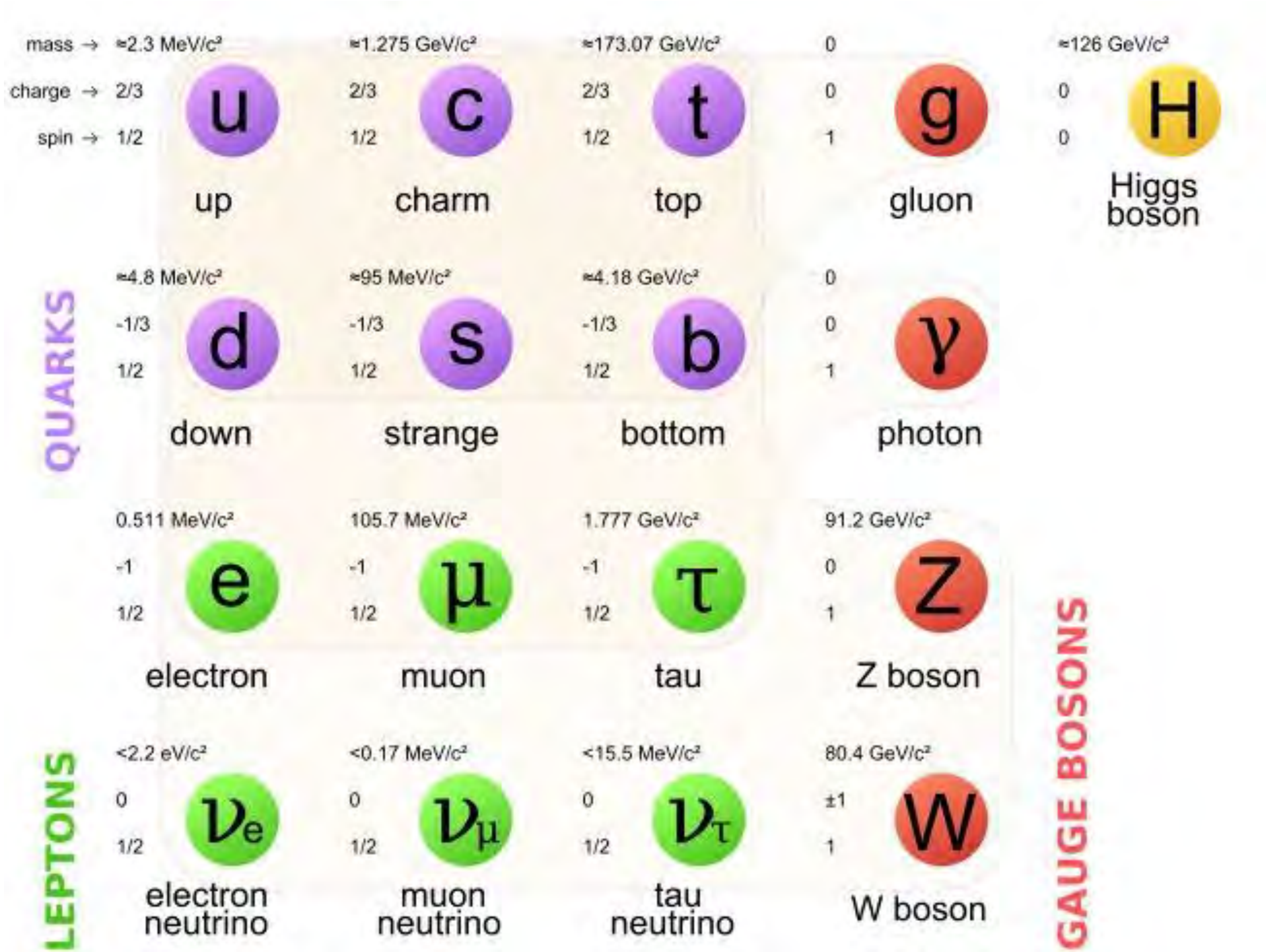
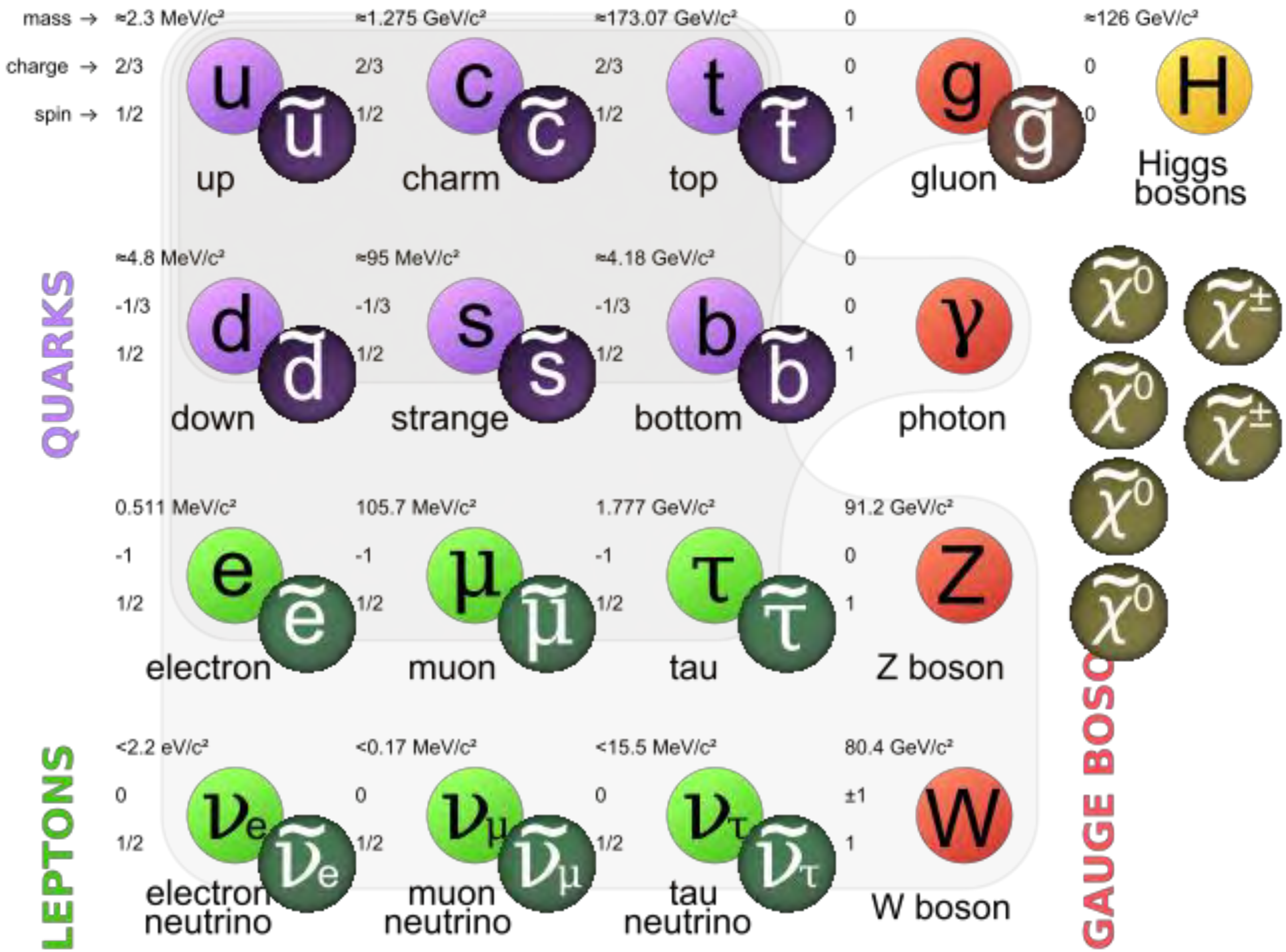


Image by MissBJ [CC BY 3.0], via Wikimedia Commons
(changes were made by S.I.)

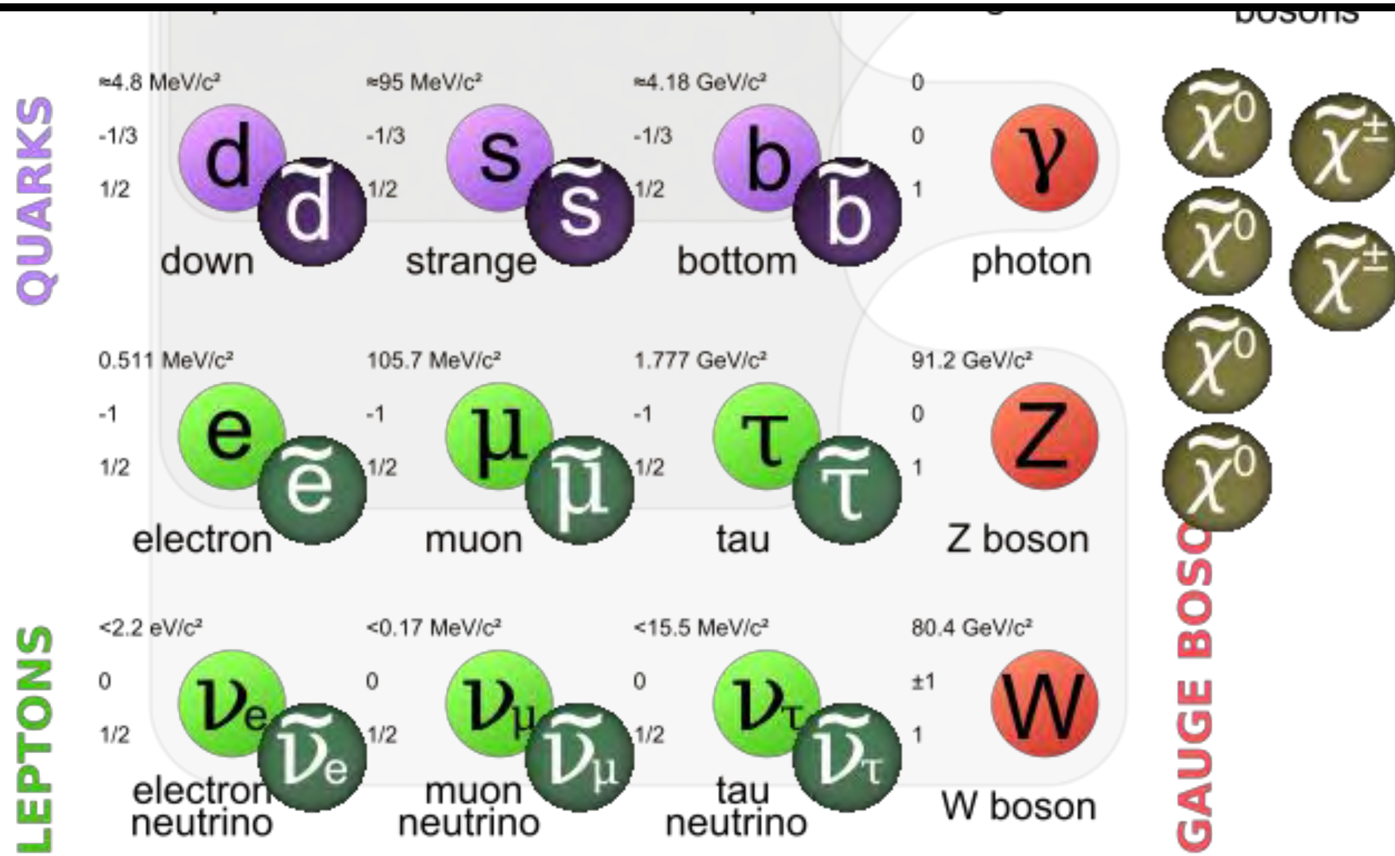
- MSSM =

[Minimal Supersymmetric Standard Model]



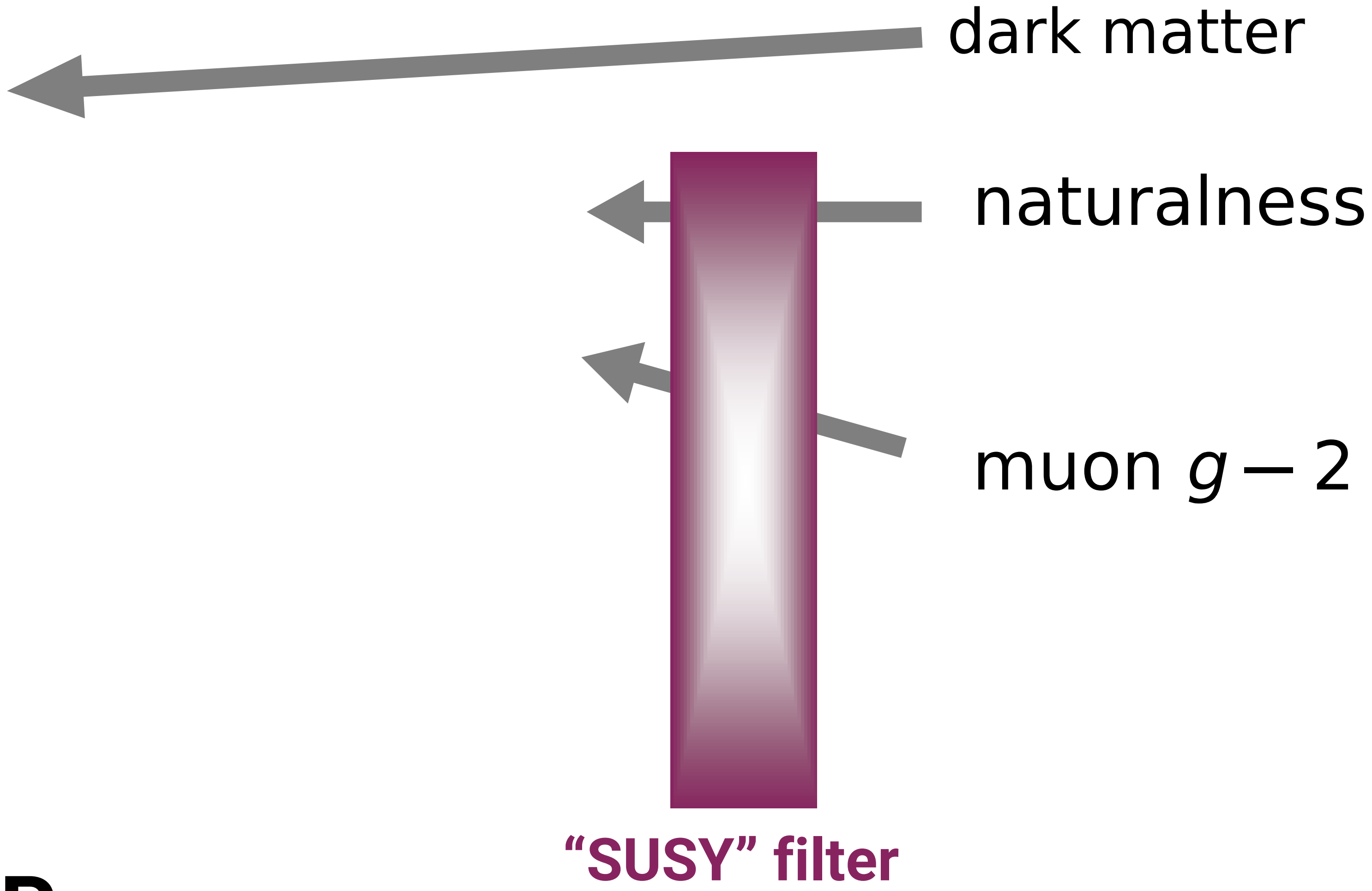
$$\tilde{\chi}^0_{1,2,3,4}\ \text{(neutralino)} = \tilde{B} \oplus \widetilde{W}^3 \oplus \tilde{H}_\mathrm{d} \oplus \tilde{H}_\mathrm{u}$$

$$\tilde{\chi}^{\pm}_{1,2}\ \text{(chargino)} = \widetilde{W}^{\pm} \oplus \tilde{H}^{\pm}$$



- Why SUSY?
  - ✓ **Dark matter**
  - ~~✓ Dark energy~~
  - ✓(Neutrino mass)
  - ✓ **Gauge coupling unification**
  - ✓ Higgs mass “naturalness”
  - ✓ Muon “g−2”
  - ✓ …

1) $\not{E}_T$



2) LLCP

3) more exotic

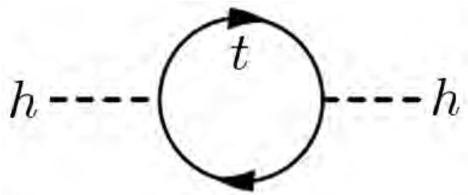
$$m_h^2 \sim m_{\text{bare}}^2 + \Delta m_h^2$$

10^4 GeV^2

cut-off (Planck or GUT scale)

$$\text{SM} : \Delta m_\text{h}^2 \sim -\frac{3|\lambda|^2}{8\pi^2}\Lambda^2 + \text{finite}$$

unnatural



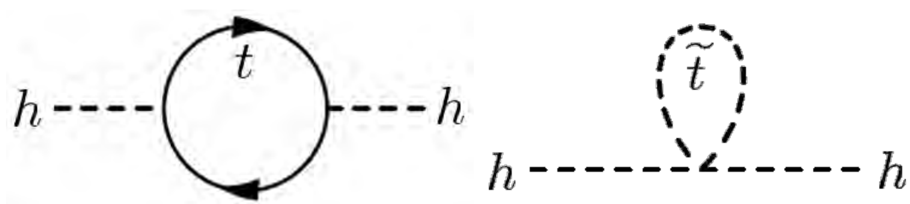
$$\mathrm{O}\left(10^{30}\right) - \mathrm{O}\left(10^{30}\right) \rightsquigarrow 10^4$$

$$m_h^2 \sim m_{\text{bare}}^2 + \Delta m_h^2$$

10^4 GeV^2

cut-off (Planck or GUT scale)

$$\text{SM} : \Delta m_\text{h}^2 \sim -\frac{3|\lambda|^2}{8\pi^2}\Lambda^2 + \text{finite}$$



cancel

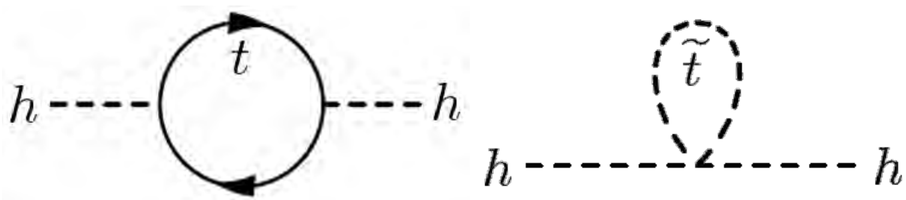
$$\text{MSSM} : \Delta m_h^2 \sim -\frac{3|\lambda|^2}{8\pi^2}\Lambda^2 + \left(2 \times \frac{3|\lambda|^2}{16\pi^2}\Lambda^2\right) + \mathrm{O}(\log \Lambda)$$

$$m_h^2 \sim m_{\text{bare}}^2 + \Delta m_h^2$$

10^4 GeV^2

cut-off (Planck or GUT scale)

$$\text{SM} : \Delta m_{\text{h}}^2 \sim -\frac{3|\lambda|^2}{8\pi^2}\Lambda^2 + \text{finite}$$



$$\text{MSSM} : \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda}{m_{\tilde{t}}}$$

"natural" if $m_{\tilde{t}} \sim m_h$

Kitano, Nomura [hep-ph/0602096]

MSSM condition for EWSB:

$$\frac{m_Z^2}{2} = -\mu^2 + \frac{m_{H_\mathrm{d}}^2 - m_{H_\mathrm{u}}^2 \tan^2\beta}{\tan^2\beta - 1}$$

Higgsino mass

"natural" if $\mu \sim m_Z$

$$\text{MSSM}: \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda}{m_{\tilde{t}}}$$

"natural" if $m_{\tilde{t}} \sim m_h$

Kitano, Nomura [hep-ph/0602096]

"Natural SUSY"

$$\left(\alpha := A_t/m_{\tilde{t}}\right)$$

$$|\mu| \lesssim 200\,\mathrm{GeV}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

$$\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim 600\,\mathrm{GeV}\,\frac{\sin\beta}{\sqrt{1+\alpha^2}}\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

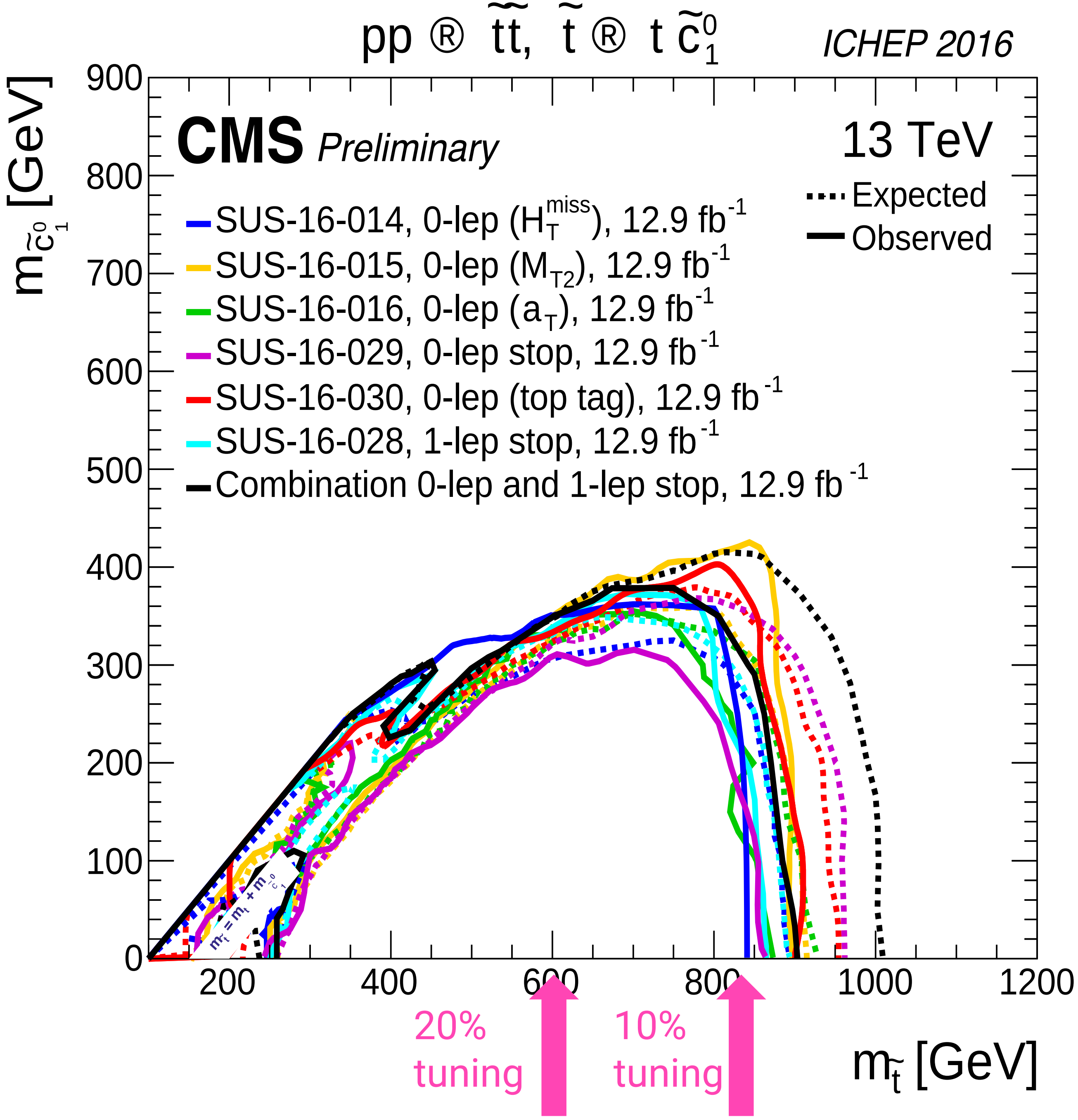
$$m_{\tilde{g}} \lesssim 900\,\mathrm{GeV}\cdot\sin\beta\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

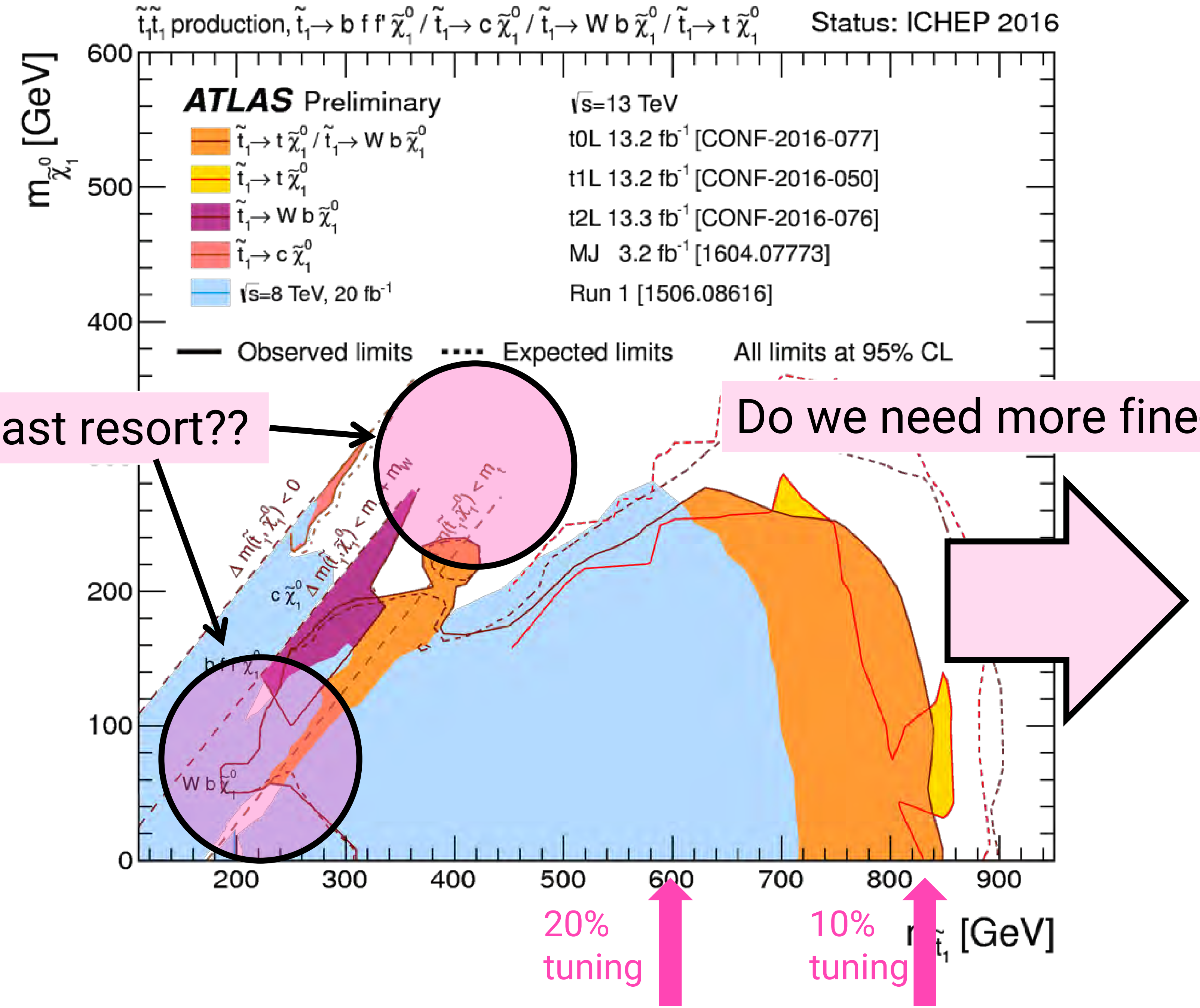
Papucci, Ruderman, Weiler [1110.6926]

interesting channel: "stop search" $\tilde{t}\tilde{t}^* \longrightarrow t\bar{t} + \mathrm{mET}$

(and squark/gluon search

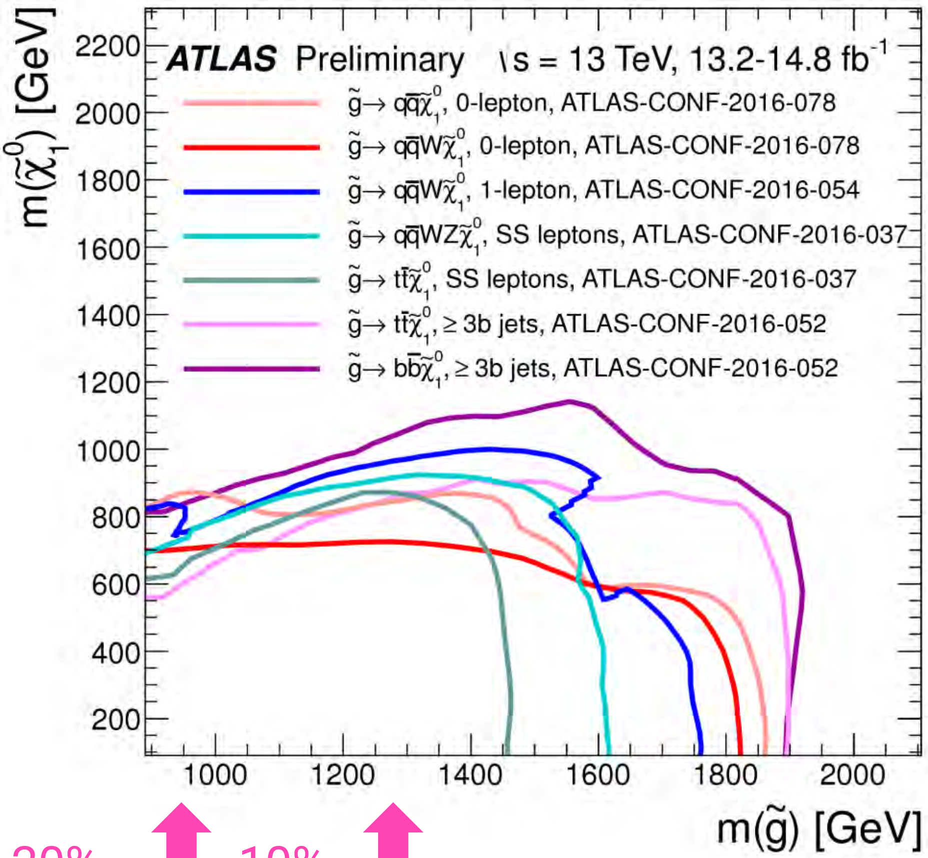
$(\tilde{q}\tilde{q}^*, \tilde{g}\tilde{q}, \tilde{g}\tilde{g}) \longrightarrow \mathrm{jets} + \mathrm{mET}$)

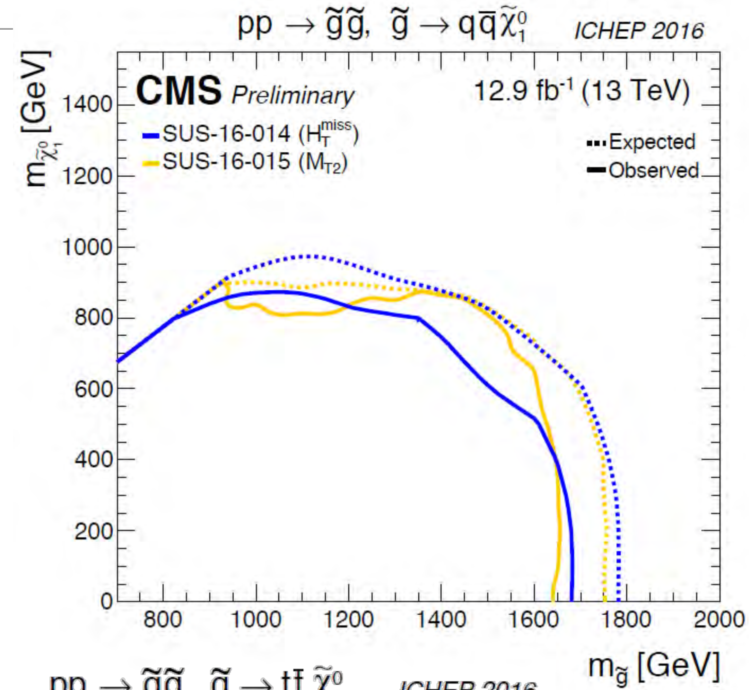

pp ® t̃t̃, t̃ ® t χ̃⁰₁
ICHEP 2016
CMS Preliminary
13 TeV
Expected
Observed
SUS-16-014, 0-lep (H_T^{miss}), 12.9 fb^{-1}
SUS-16-015, 0-lep (M_{T2}), 12.9 fb^{-1}
SUS-16-016, 0-lep (a_T), 12.9 fb^{-1}
SUS-16-029, 0-lep stop, 12.9 fb^{-1}
SUS-16-030, 0-lep (top tag), 12.9 fb^{-1}
SUS-16-028, 1-lep stop, 12.9 fb^{-1}
Combination 0-lep and 1-lep stop, 12.9 fb^{-1}
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}}$ [GeV]
20% tuning
10% tuning



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to b f f' \tilde{\chi}^0_1$ / $\tilde{t}_1 \to c \tilde{\chi}^0_1$ / $\tilde{t}_1 \to W b \tilde{\chi}^0_1$ / $\tilde{t}_1 \to t \tilde{\chi}^0_1$
Status: ICHEP 2016
ATLAS Preliminary
$\sqrt{s}$=13 TeV
$\tilde{t}_1 \to t \tilde{\chi}^0_1$ / $\tilde{t}_1 \to W b \tilde{\chi}^0_1$
t0L 13.2 fb^{-1} [CONF-2016-077]
$\tilde{t}_1 \to t \tilde{\chi}^0_1$
t1L 13.2 fb^{-1} [CONF-2016-050]
$\tilde{t}_1 \to W b \tilde{\chi}^0_1$
t2L 13.3 fb^{-1} [CONF-2016-076]
$\tilde{t}_1 \to c \tilde{\chi}^0_1$
MJ 3.2 fb^{-1} [1604.07773]
$\sqrt{s}$=8 TeV, 20 fb^{-1}
Run 1 [1506.08616]
Observed limits
Expected limits
All limits at 95% CL
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
last resort??
Do we need more fine-tune?
20% tuning
10% tuning

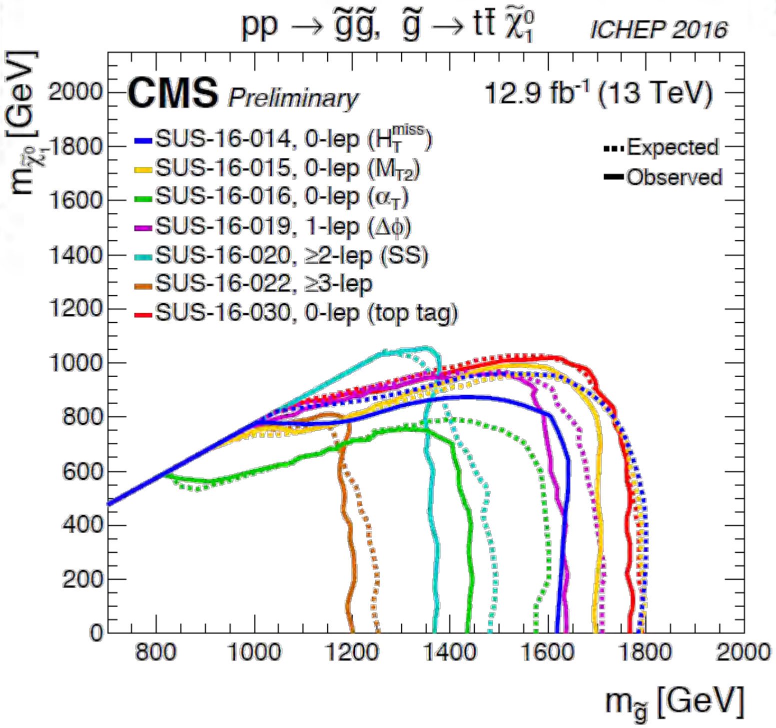
Cf. gluon searches





20% tuning

10% tuning



LHC: $m_h \sim 125\,\mathrm{GeV}$

$$m_h^2(\mathrm{MSSM}) \approx \underbrace{m_Z^2}_{\text{tree}} + \overbrace{\frac{3g_W^2 m_t^4}{8\pi^2 m_W^2}\left(\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{12\alpha^2 - \alpha^4}{12}\right)}^{\Delta\left(m_h^2\right)^{\text{loop}}}$$

$$\left(\alpha := A_t/m_{\tilde{t}}, \quad m_{\tilde{t}}^2 := \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{2}\right)$$

- stop left-right mixing α is Large ($A_t \sim \sqrt{6} m_{\tilde{t}}$)

  and/or
- (at least one) heavy stop

LHC: $m_h \sim 125\,\mathrm{GeV}$

$\Delta\left(m_h^2\right)^{\text{loop}}$

$$m_h^2(\mathrm{MSSM}) \approx m_Z^2 + \frac{3g_W^2 m_t^4}{8\pi^2 m_W^2}\left(\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{12\alpha^2 - \alpha^4}{12}\right)$$

↑ tree

$$\left(\alpha := A_t/m_{\tilde{t}}, \quad m_{\tilde{t}}^2 := \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{2}\right)$$

- stop left-right mixing α is Large ($A_t \sim \sqrt{6} m_{\tilde{t}}$)

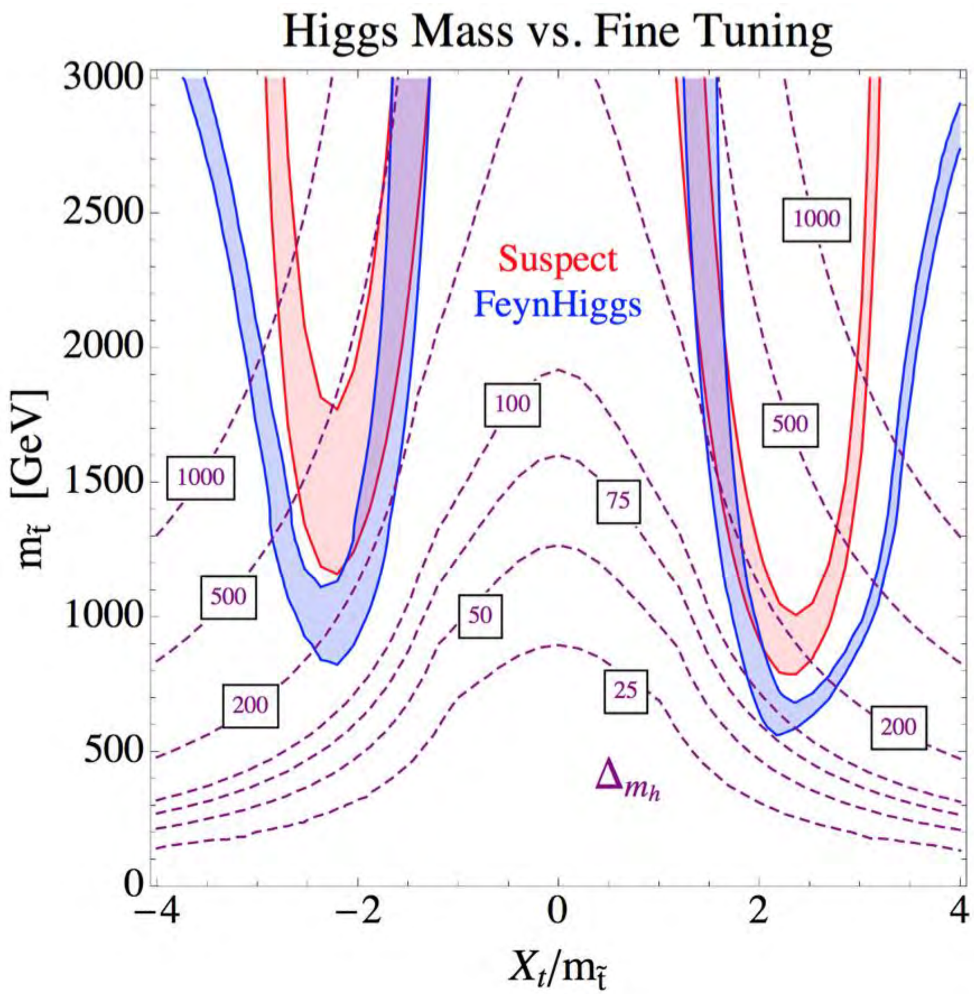
  and/or

- (at least one) heavy stop

→ **disfavors "natural"**

A canonical illustration:

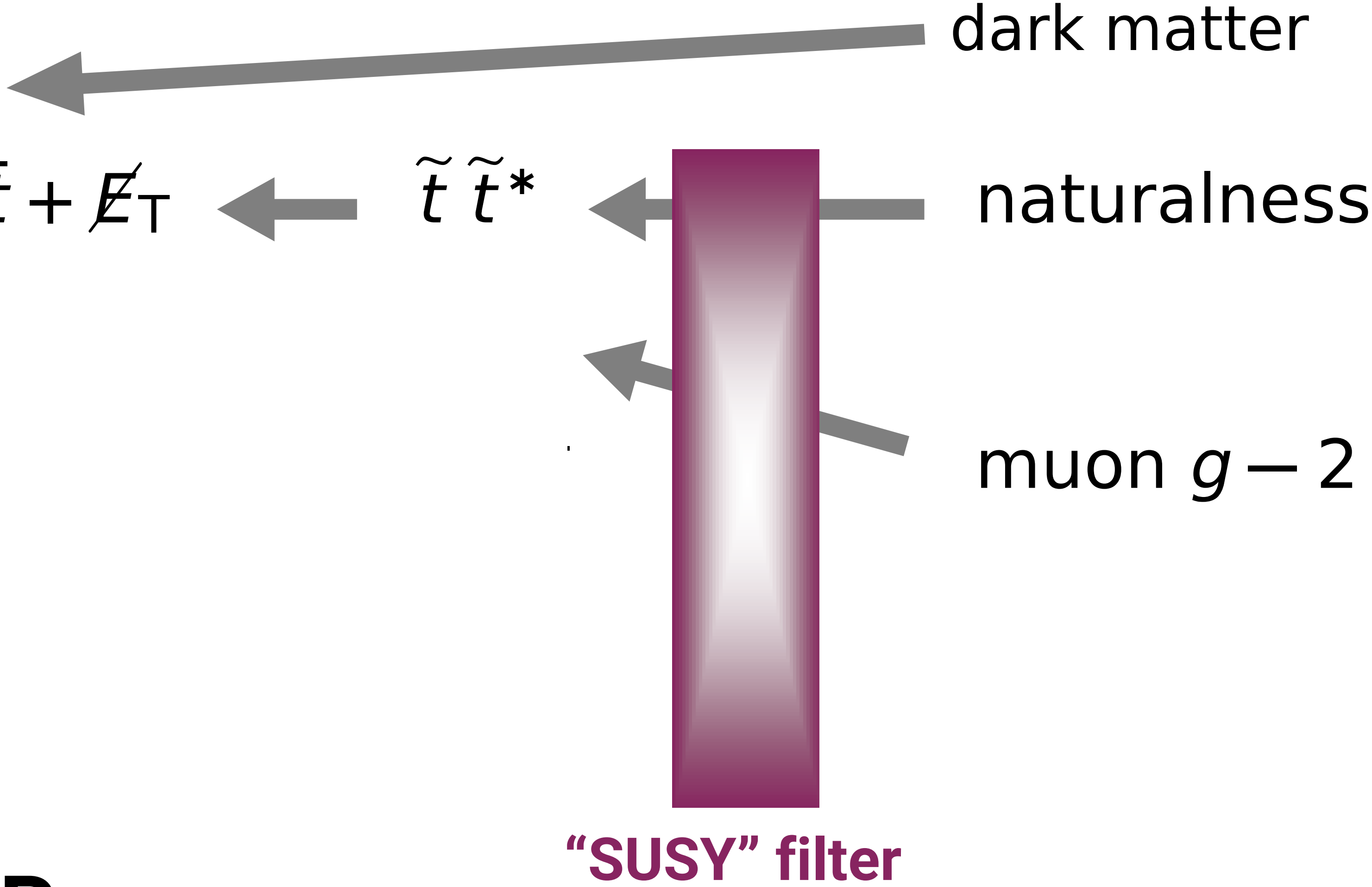
Hall, Pinner, Ruderman [1112.2703]



$(m_{\widetilde{Q}_3} = m_{\widetilde{u}_3^c}$ and $\tan\beta = 20$; bands show 124–126 GeV)

1) $\not{E}_{\mathrm{T}}$

- $t\bar{t} + \not{E}_{\mathrm{T}}$



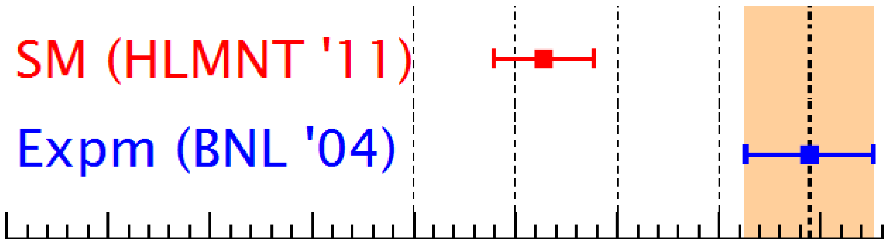
2) LLCP

3) more exotic

$$\left(a_\mu := \frac{g_\mu - 2}{2}\right)$$

Muon g−2

[anomalous magnetic moment]



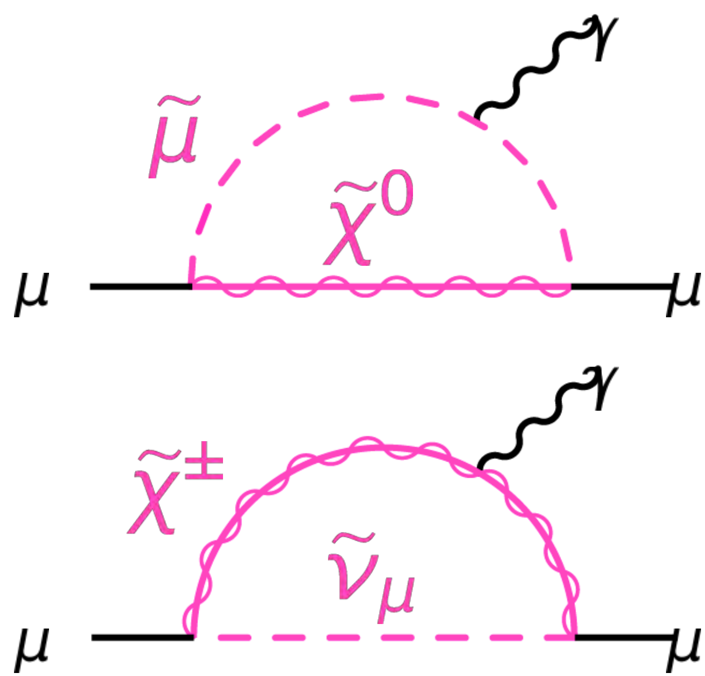
Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149]

$$a_\mu^{\mathrm{SM}} = (116\,591\,828 \pm 49) \times 10^{-11}$$

$$a_\mu^{\mathrm{exp}} = (116\,592\,089 \pm 63) \times 10^{-11}$$

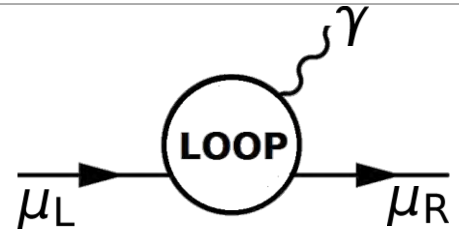
…3.3σ

extra contribution? MSSM!



Muon $g-2$ SM expectation : discrepancy!

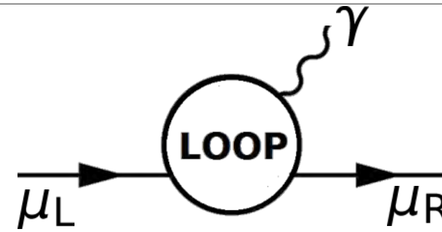
$$a_\mu = \frac{(g-2)_\mu}{2} =$$



QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

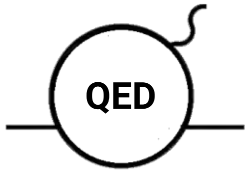
See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

$$a_\mu = \frac{(g-2)_\mu}{2} =$$



(5-loop) (2⁺-loop)

$$a_\mu^{\mathrm{SM}} \simeq$$



$+$

$+$

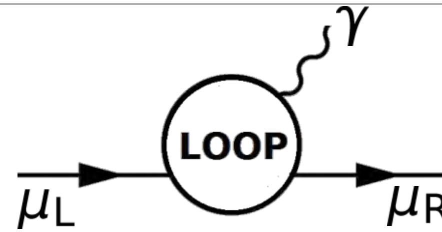
$$a_\mu(\mathrm{QED}) = (11\,658\,471.8951 \pm 0.0080) \times 10^{-10},$$

$$a_\mu(\mathrm{EW}) = (15.36 \pm 0.1) \times 10^{-10},$$

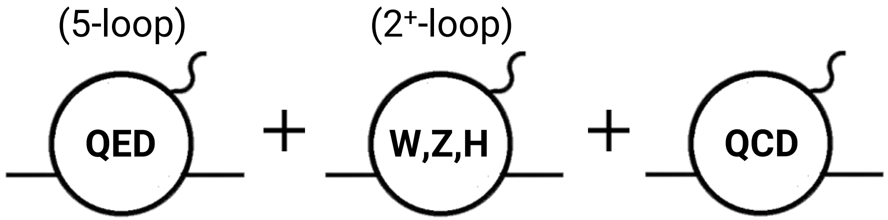
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

$$a_\mu = \frac{(g-2)_\mu}{2} =$$



$$a_\mu^{SM} \simeq$$

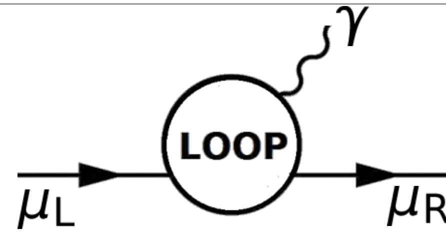


$$a_\mu(\text{QED}) = (11\,658\,471.8951 \pm 0.0080) \times 10^{-10},$$
$$a_\mu(\text{EW}) = (15.36 \pm 0.1) \times 10^{-10},$$

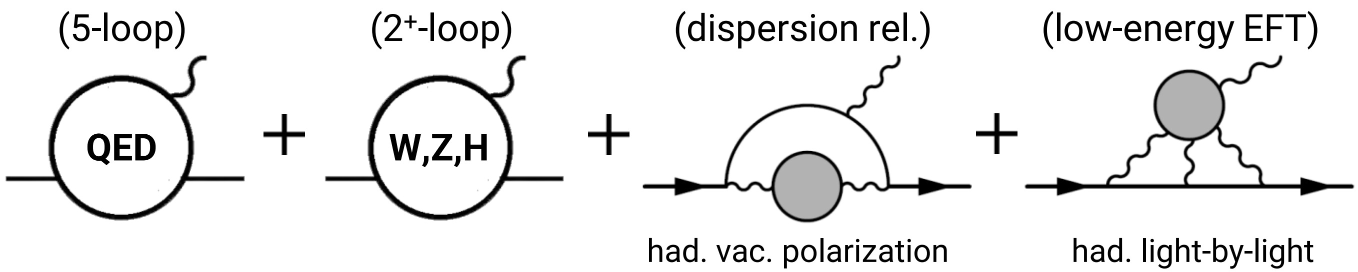
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

$$a_\mu = \frac{(g-2)_\mu}{2} =$$



$$a_\mu^{SM} \simeq$$



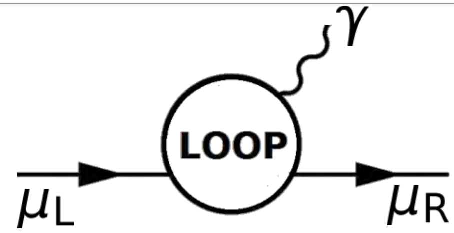
$$
\begin{aligned}
a_\mu(\text{QED}) &= (11\,658\,471.8951 \pm 0.0080) \times 10^{-10},\\
a_\mu(\text{EW}) &= (15.36 \pm 0.1) \times 10^{-10},\\
a_\mu(\text{HVP-LO}) &= (694.91 \pm 4.27) \times 10^{-10},\\
a_\mu(\text{HVP-HO}) &= -(9.84 \pm 0.07) \times 10^{-10},\\
a_\mu(\text{HLbL}) &= (10.5 \pm 2.6) \times 10^{-10}.
\end{aligned}
$$

QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

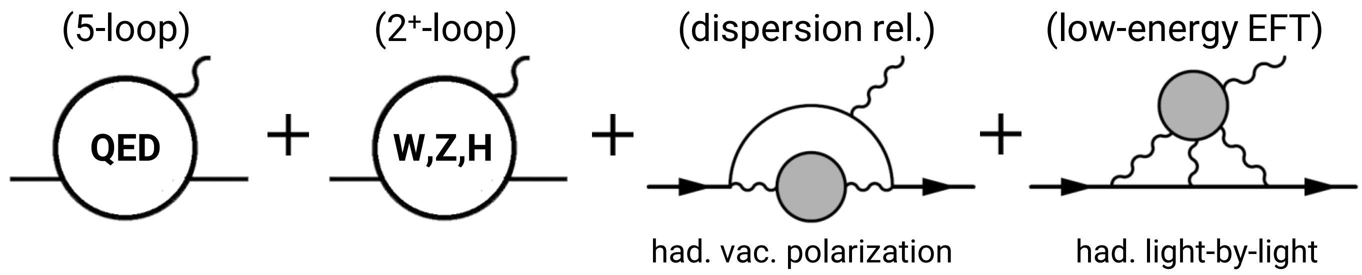
See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

Muon $g-2$ SM expectation : discrepancy!

$$a_\mu = \frac{(g-2)_\mu}{2} =$$



$$a_\mu^{SM} \simeq$$



$$\begin{aligned}
a_\mu(\text{QED}) &= (11\,658\,471.8951 \pm 0.0080) \times 10^{-10},\\
a_\mu(\text{EW}) &= (15.36 \pm 0.1) \times 10^{-10},\\
a_\mu(\text{HVP-LO}) &= (694.91 \pm 4.27) \times 10^{-10},\\
a_\mu(\text{HVP-HO}) &= -(9.84 \pm 0.07) \times 10^{-10},\\
a_\mu(\text{HLbL}) &= (10.5 \pm 2.6) \times 10^{-10}.
\end{aligned}$$

+)

$$a_\mu^{SM} = (11\,659\,182.8 \pm 5.0) \times 10^{-10}$$

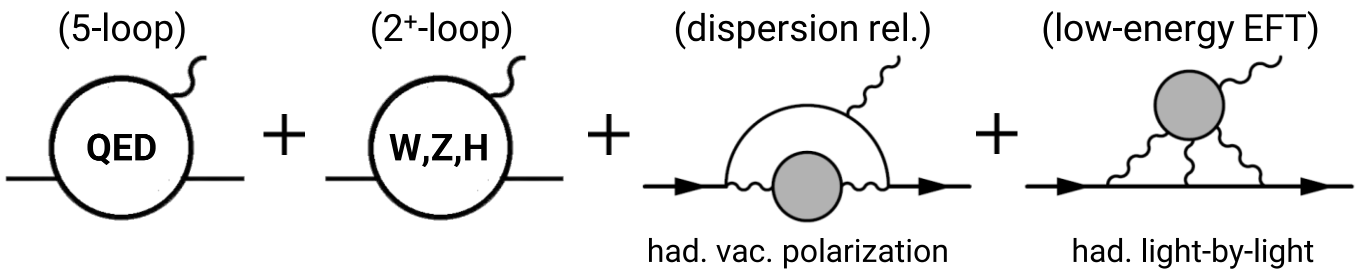
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

$$\Delta a_\mu = (26.4 \pm 8.0) \times 10^{-10}$$ ···**3.3σ** anomaly

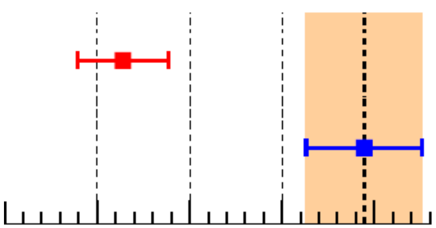
μ_L μ_R

$$a_\mu^{SM} \simeq$$



$$a_\mu(\text{QED}) = (11\,658\,471.8951 \pm 0.0080) \times 10^{-10},$$
$$a_\mu(\text{EW}) = (15.36 \pm 0.1) \times 10^{-10},$$
$$a_\mu(\text{HVP-LO}) = (694.91 \pm 4.27) \times 10^{-10},$$
$$a_\mu(\text{HVP-HO}) = -(9.84 \pm 0.07) \times 10^{-10},$$
$$a_\mu(\text{HLbL}) = (10.5 \pm 2.6) \times 10^{-10}.$$

+)



$$a_\mu^{SM} = (11\,659\,182.8 \pm 5.0) \times 10^{-10}$$

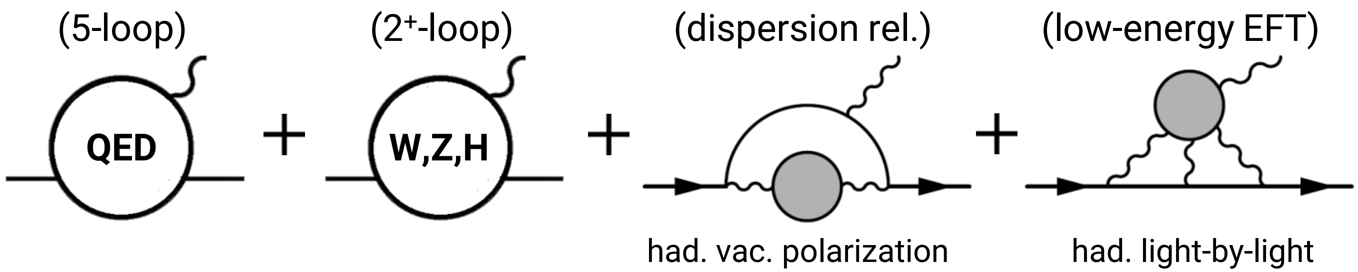
$$a_\mu^{exp} = (11\,659\,209.2 \pm 6.3) \times 10^{-10}$$ (BNL '04 +CODATA '14) [future: ±1.6]

QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

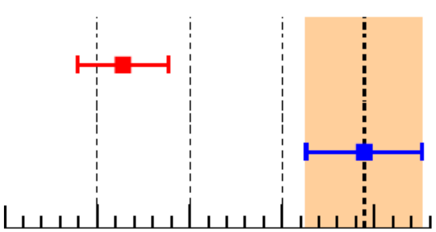
$$\Delta a_\mu = (26.4 \pm 8.0) \times 10^{-10}$$ ⋯**3.3σ** anomaly

$$a_\mu^{SM} \simeq$$



$$a_\mu(\text{QED}) = (11\,658\,471.8951 \pm 0.0080) \times 10^{-10},$$
$$a_\mu(\text{EW}) = (15.36 \pm 0.1) \times 10^{-10},$$
$$a_\mu(\text{HVP-LO}) = (694.91 \pm 4.27) \times 10^{-10},$$
$$a_\mu(\text{HVP-HO}) = -(9.84 \pm 0.07) \times 10^{-10},$$
$$a_\mu(\text{HLbL}) = (10.5 \pm 2.6) \times 10^{-10}.$$

$$+)\quad a_\mu(\text{NP})? \quad \ldots \quad 10 \times 10^{-10} \quad \sim a_\mu(\text{EW})$$



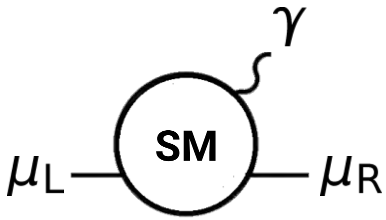
$$a_\mu^{SM} = (11\,659\,182.8 \pm 5.0) \times 10^{-10}$$

$$a_\mu^{exp} = (11\,659\,209.2 \pm 6.3) \times 10^{-10}$$ (BNL '04 +CODATA '14)
[future: ± 1.6]

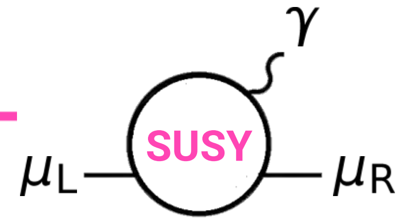
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

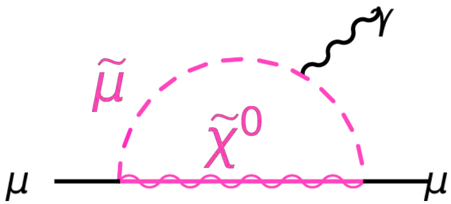
$$a_\mu = \frac{(g-2)_\mu}{2} =$$



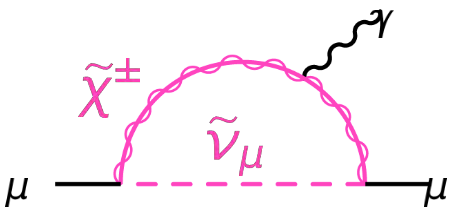
+



?



$$a_\mu^{\rm SUSY}\left(\widetilde{\chi}^0, \widetilde{\mu}\right) \approx \frac{g_Y^2}{(4\pi)^2}\frac{m_\mu^2}{m_{\rm soft}^2}\,{\rm sgn}(\mu)\tan\beta + \cdots,$$

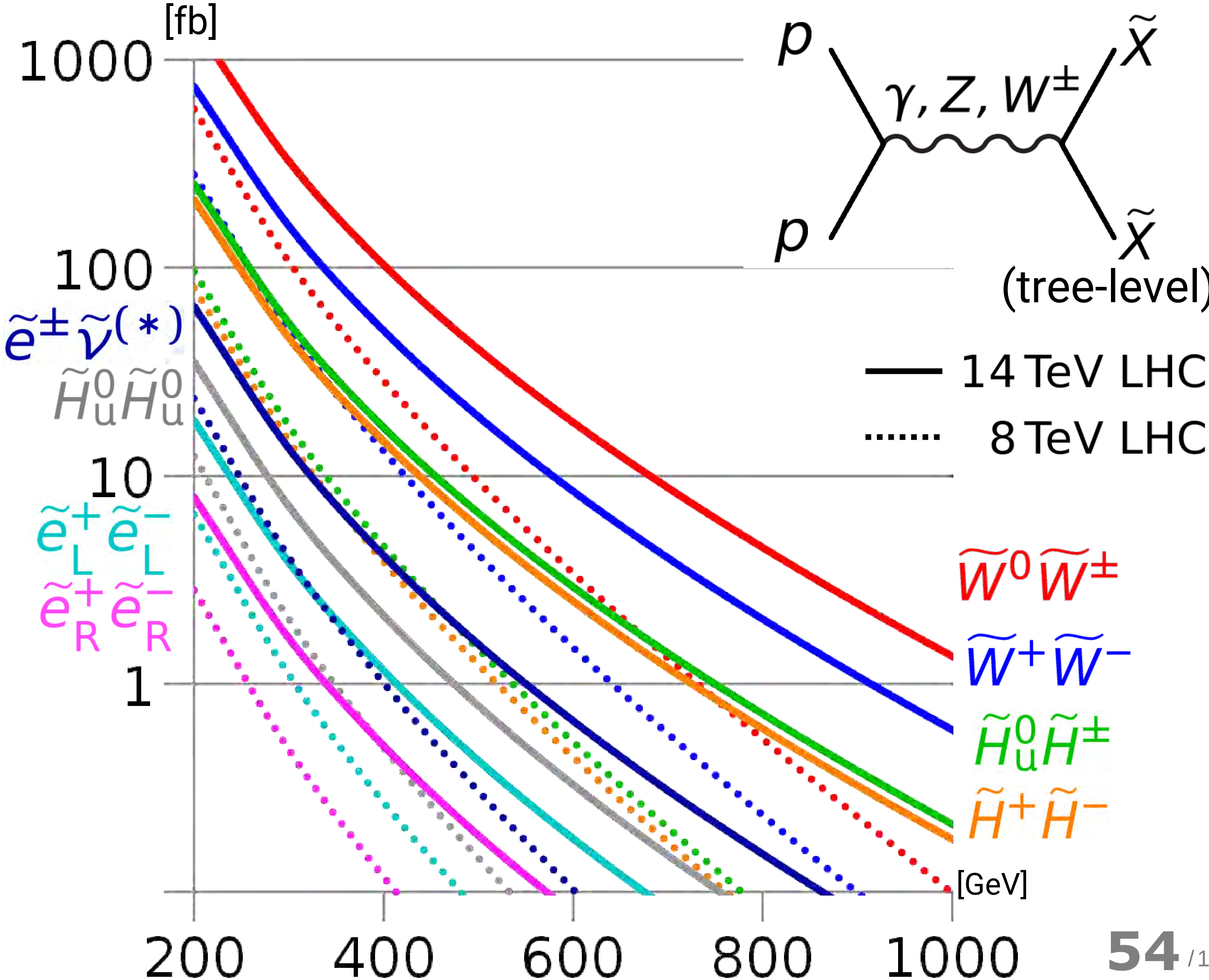


$$a_\mu^{\rm SUSY}\left(\widetilde{\chi}^\pm, \widetilde{\nu}_\mu\right) \approx \frac{g_2^2}{(4\pi)^2}\frac{m_\mu^2}{m_{\rm soft}^2}\,{\rm sgn}(\mu)\tan\beta.$$

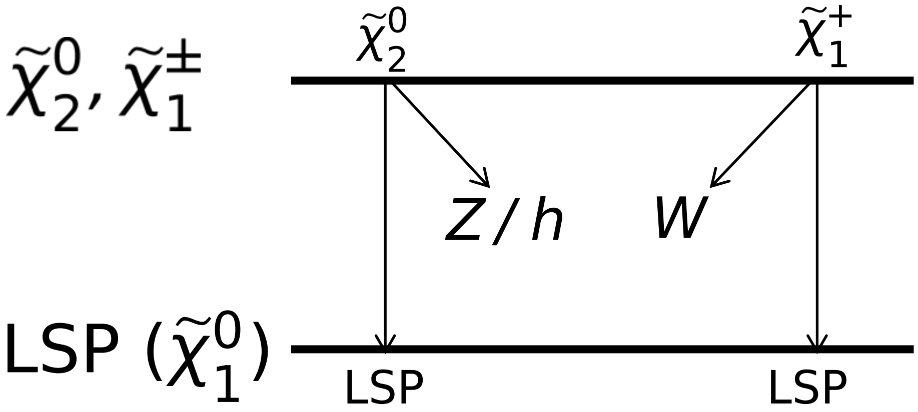
$$\Longrightarrow m\left(\widetilde{\mu}, \widetilde{\nu}_\mu, \widetilde{\chi}^0, \widetilde{\chi}^\pm\right) \lesssim 1\,\text{TeV} \quad !?$$

Lopez, Nanopoulos, Wang [ph/9308336]
Chattopadhyay, Nath [ph/9507386]
Moroi [ph/9512396]

$W \ni \mu H_{\rm u} H_{\rm d}$ (higgsino mass term), $\tan\beta = \langle H_{\rm u}\rangle / \langle H_{\rm d}\rangle$,
$m_{\rm soft}$: SUSY-particle mass-scale, g_i : gauge couplings.


[fb]
1000
100
10
1
200
400
600
800
1000
[GeV]
p
p
γ, Z, W±
χ̃
χ̃
(tree-level)
14 TeV LHC
8 TeV LHC
ẽ±ν̃(*)
H̃u0H̃u0
ẽL+ẽL−
ẽR+ẽR−
W̃0W̃±
W̃+W̃−
H̃u0H̃±
H̃+H̃−

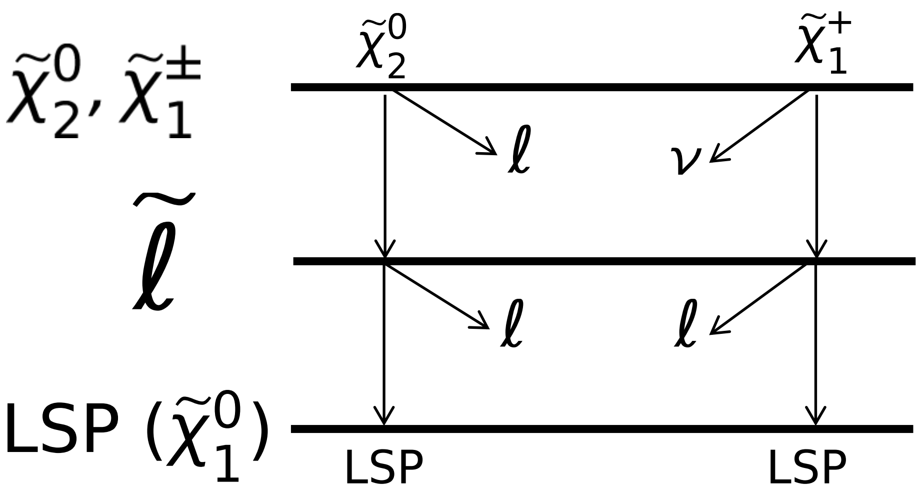
$pp \to \tilde{\chi}^0 \tilde{\chi}^+ \quad (\widetilde{W}^0 \widetilde{W}^+$ or $\widetilde{H}^0 \widetilde{H}^+)$; then?



$\tilde{\chi}^0_2 \tilde{\chi}^+_1 \to ZW / hW + \text{mET}$

$(\to 3\ell + \text{mET})$

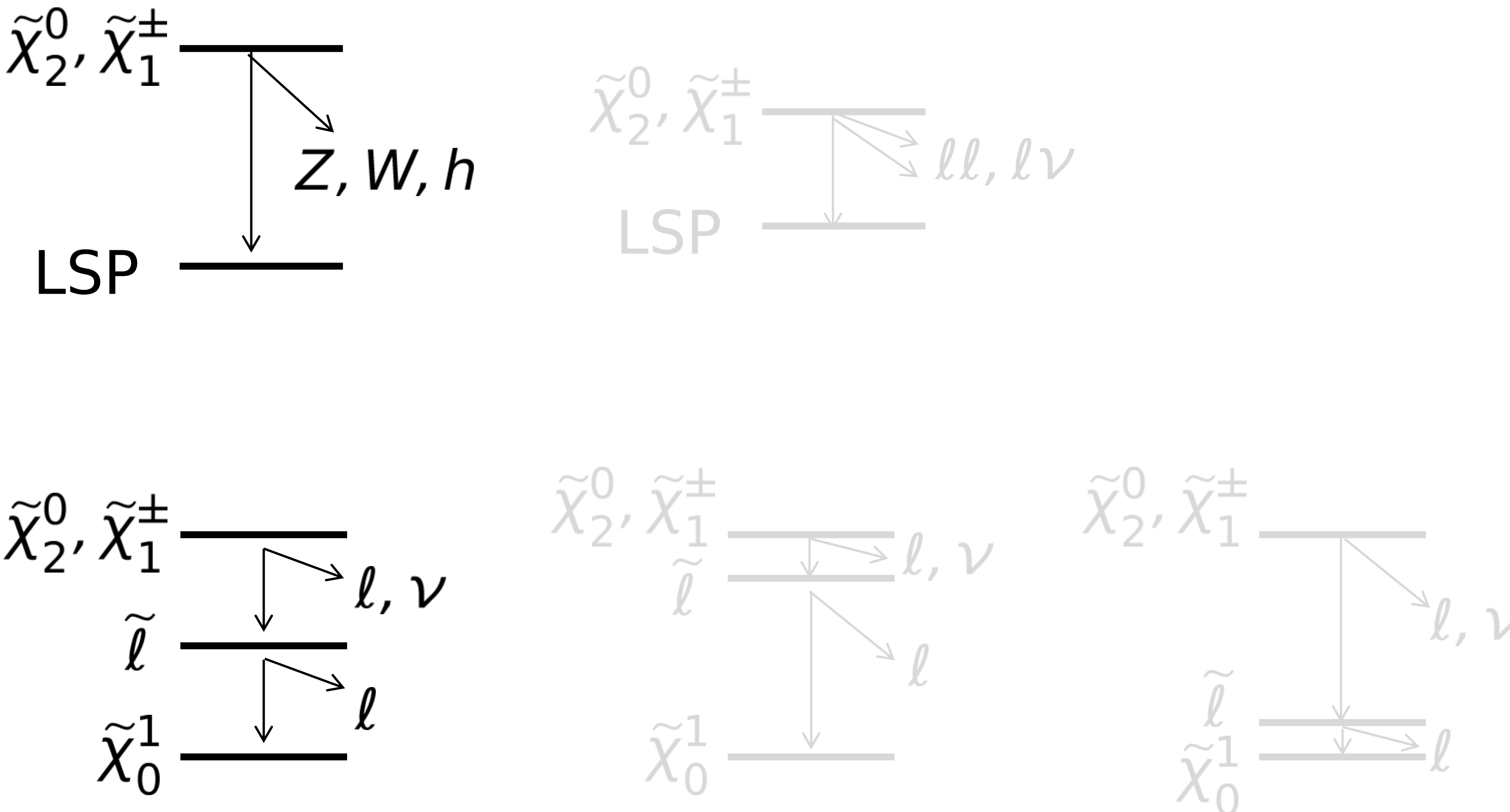
but Z-like leptons



$\tilde{\chi}^0_2 \tilde{\chi}^+_1 \to 3\ell + \text{mET}$

***Z*-unlike**

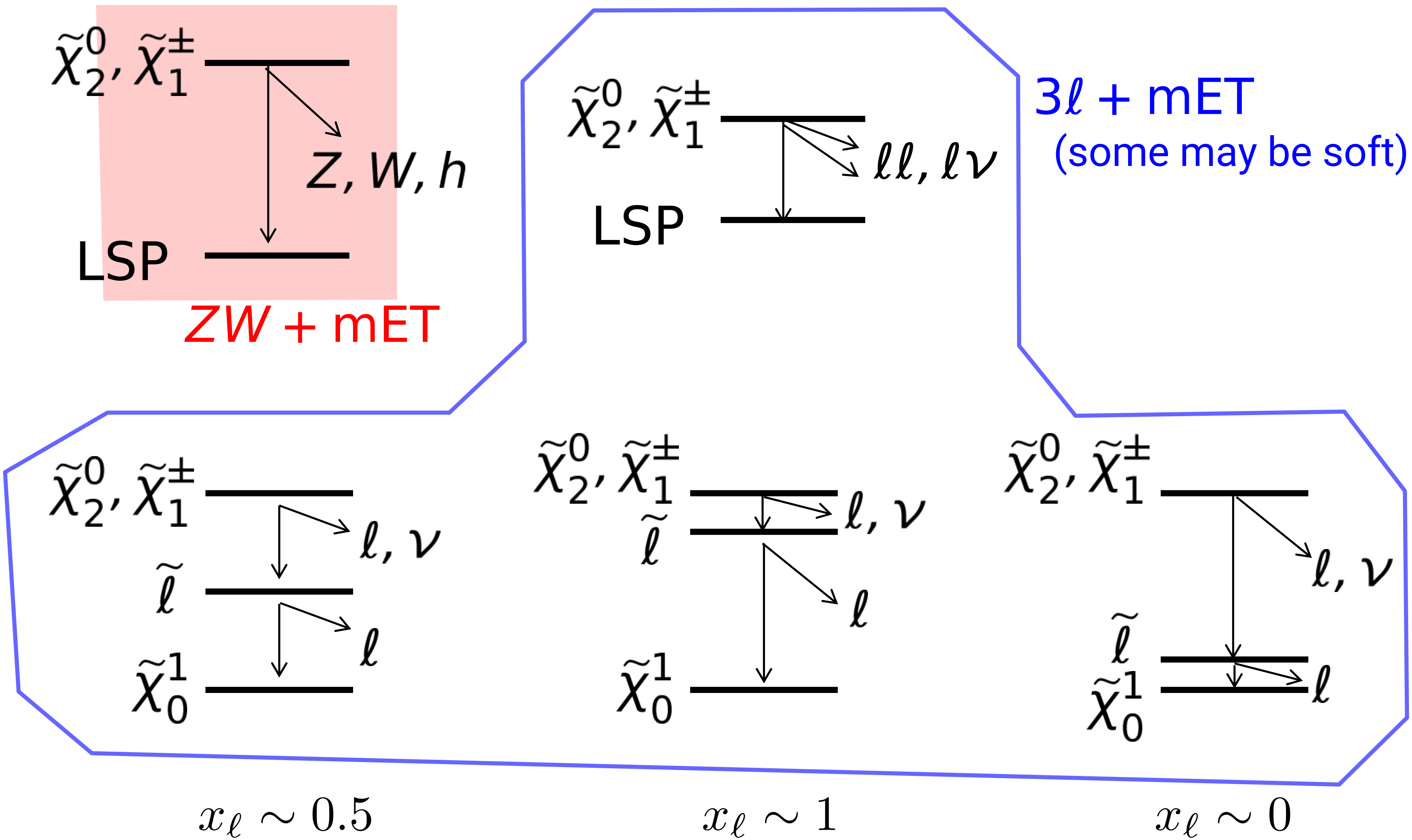
$pp \to \tilde{\chi}^0 \tilde{\chi}^+$ ($\widetilde{W}^0 \widetilde{W}^+$ or $\widetilde{H}^0 \widetilde{H}^+$); then?



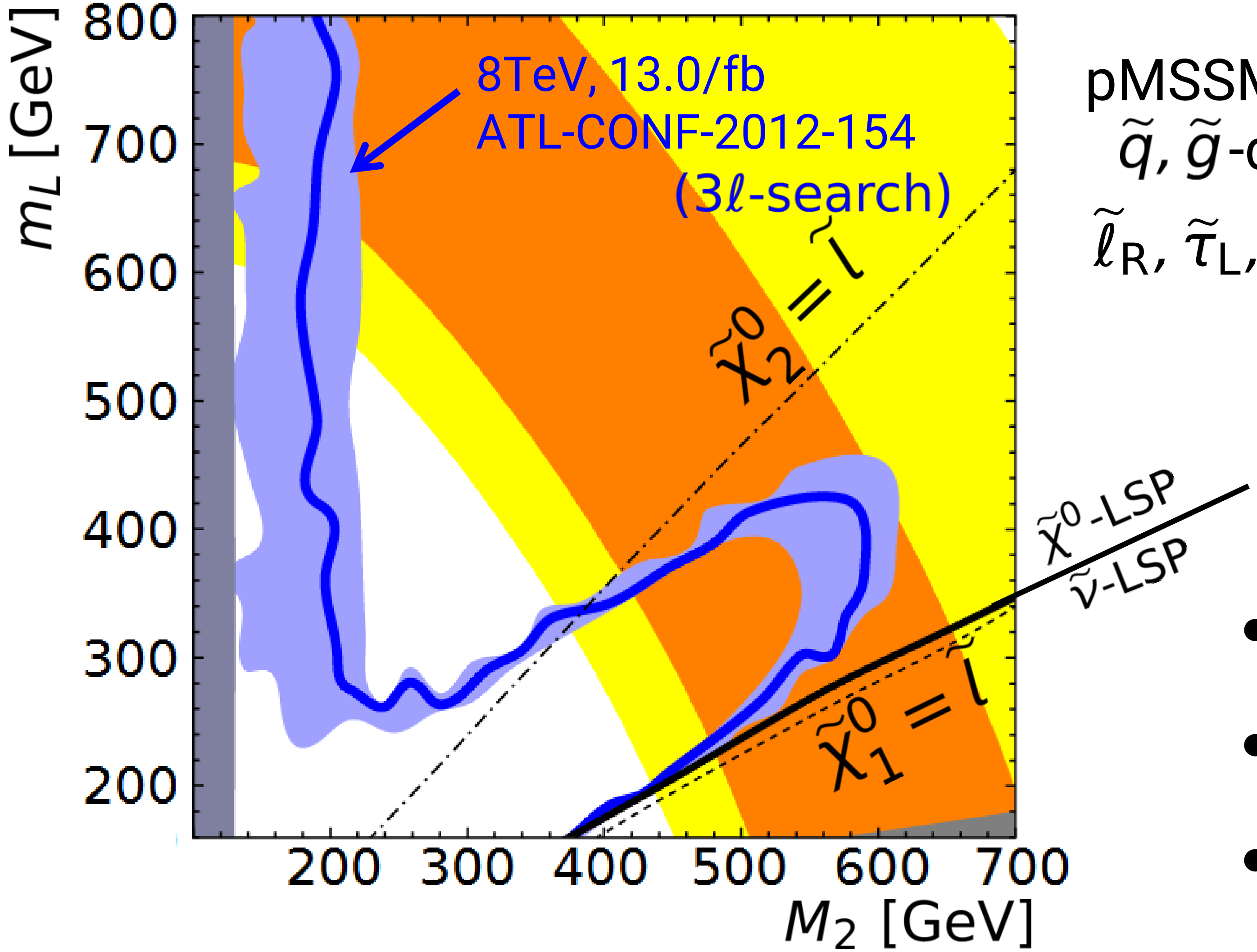
$x_\ell \sim 0.5$ $x_\ell \sim 1$ $x_\ell \sim 0$

Five types of signatures from Neutralino-Chargino production

$$pp \to \tilde{\chi}^0 \tilde{\chi}^+ \quad (\widetilde{W}^0 \widetilde{W}^+ \text{ or } \widetilde{H}^0 \widetilde{H}^+);\ \text{then?}$$

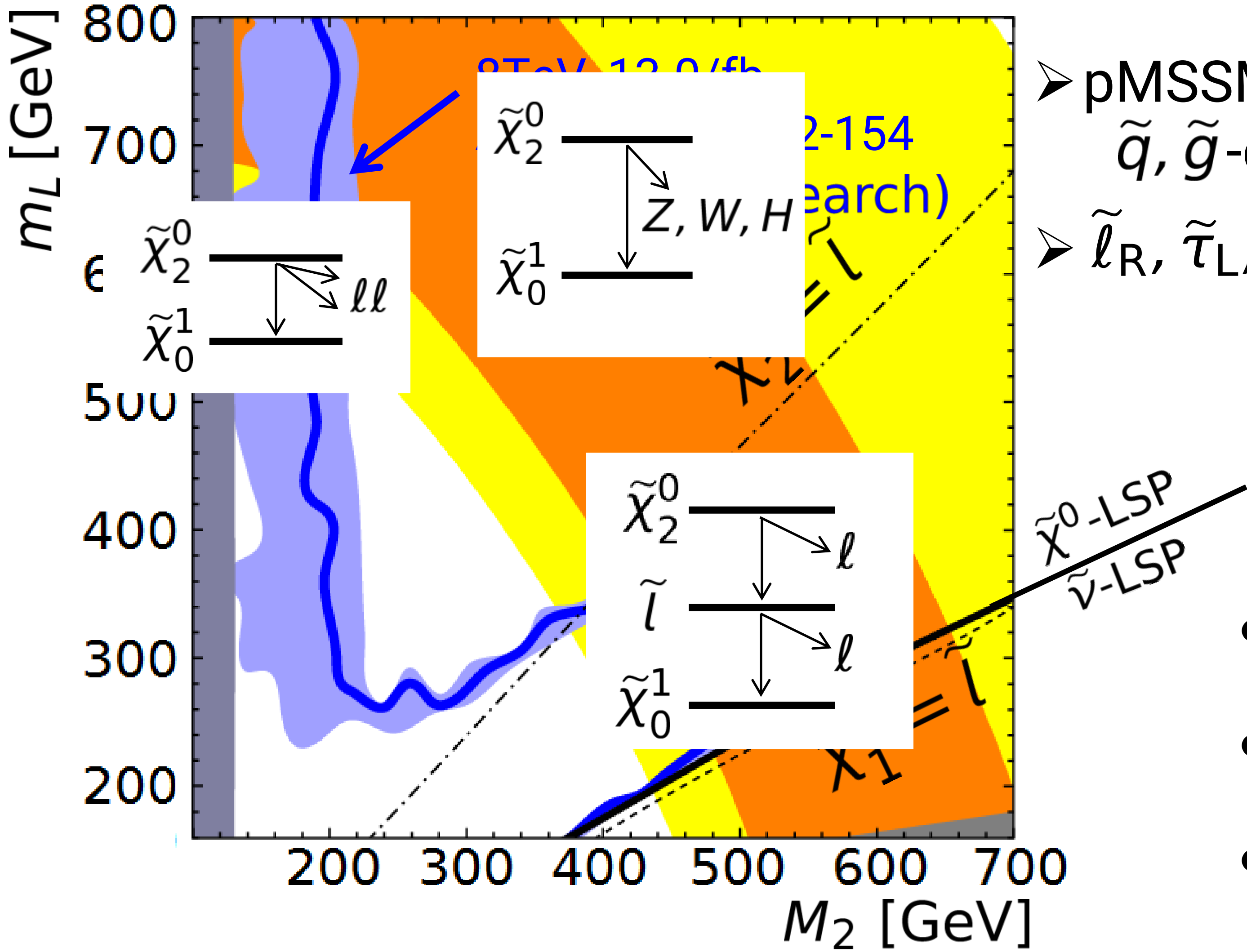


Endo, Hamaguchi, SI, Yoshinaga [1303.4256]



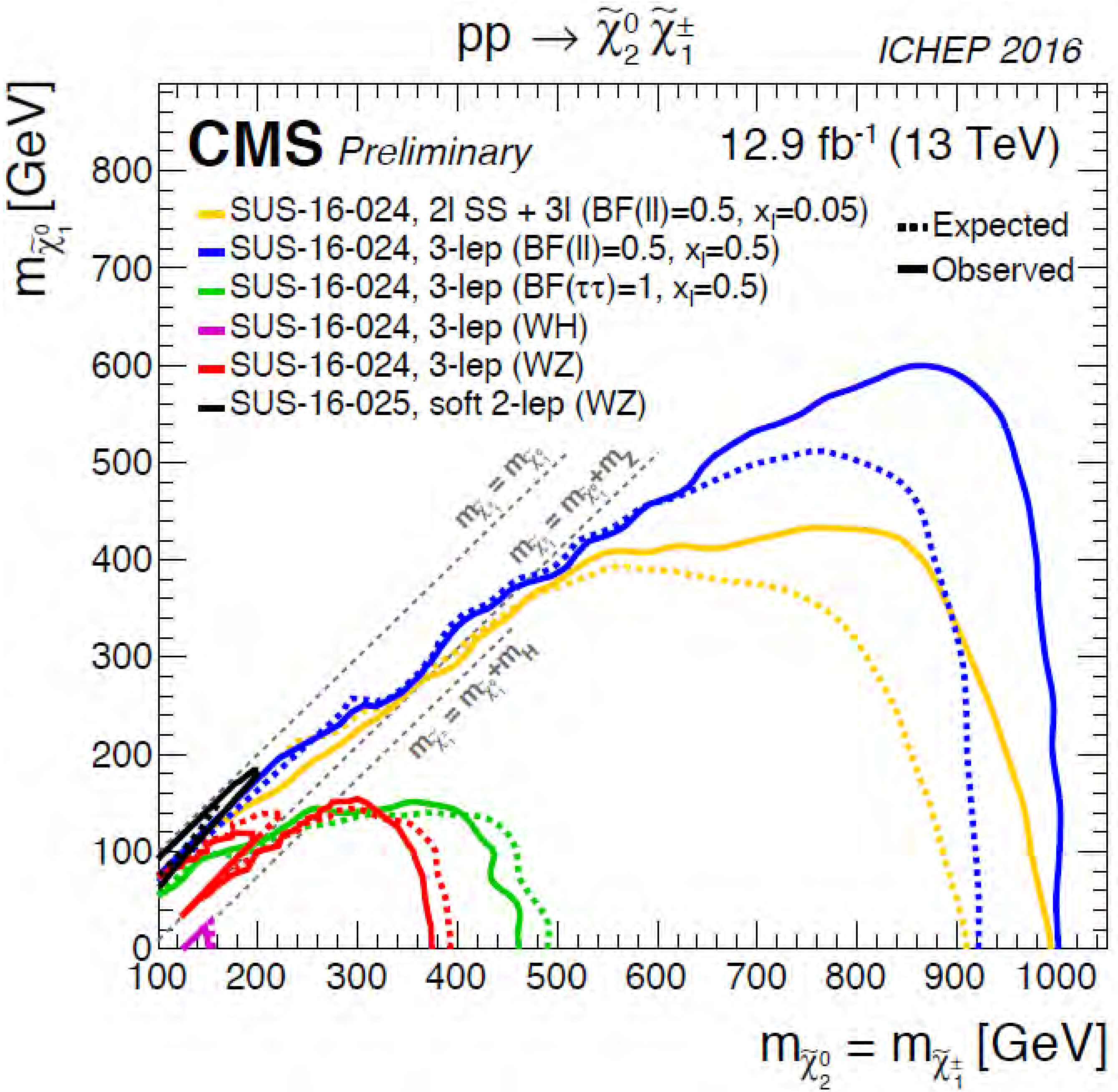
pMSSM w.
$\tilde{q}, \tilde{g}$-decoupled.
$\tilde{\ell}_R, \tilde{\tau}_L, \tilde{\tau}_R$ also decoupled.

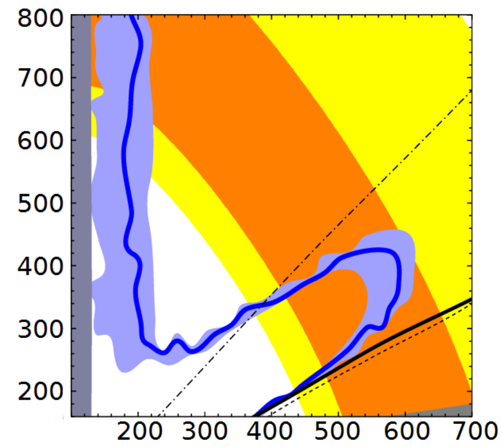
- $\tan\beta = 40$
- $M_1 = M_2/2$
- $\mu = M_2$



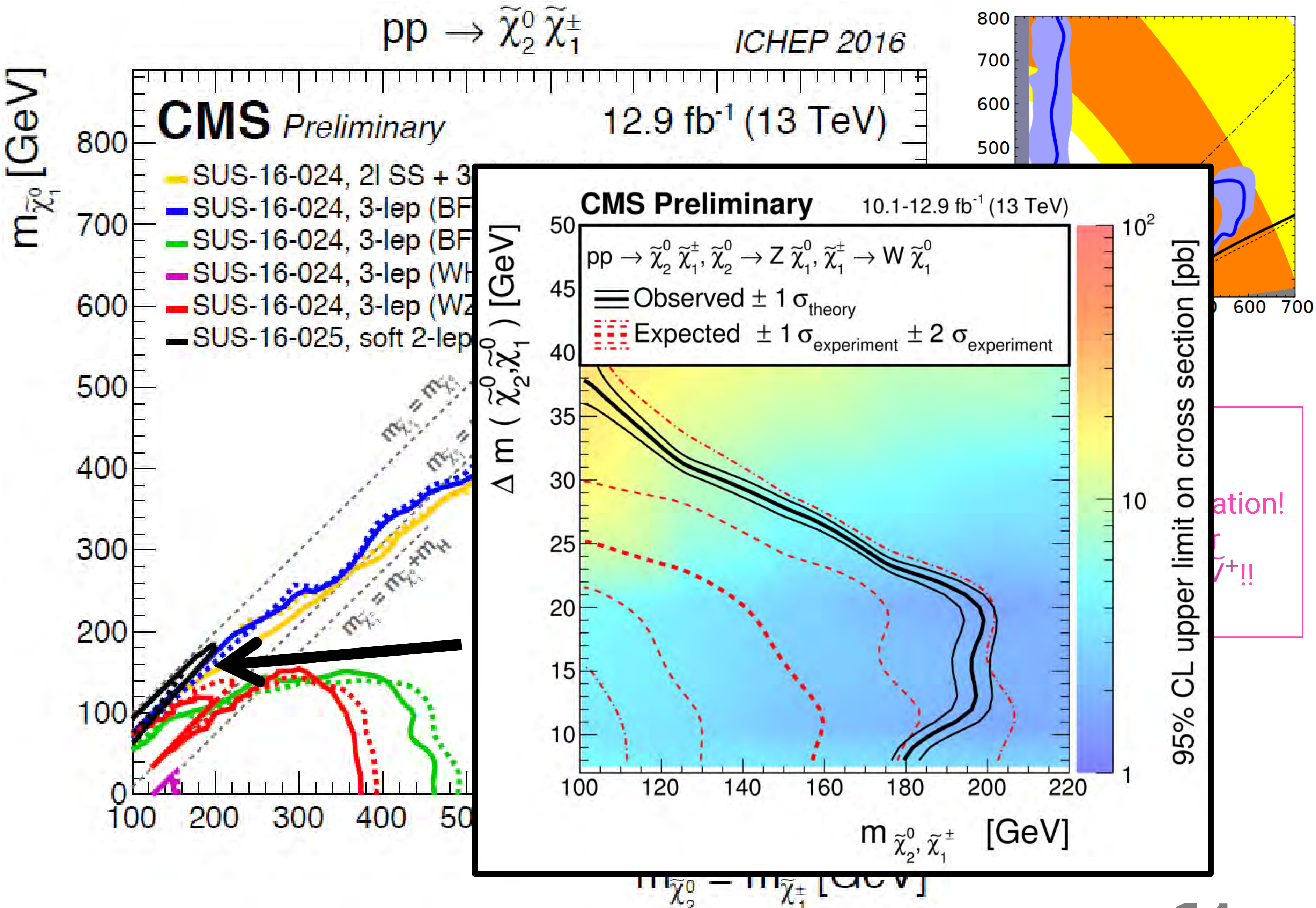
- pMSSM w. $\tilde{q}, \tilde{g}$-decoupled.
- $\tilde{\ell}_R, \tilde{\tau}_L, \tilde{\tau}_R$ also decoupled.

- $\tan\beta = 40$
- $M_1 = M_2/2$
- $\mu = M_2$

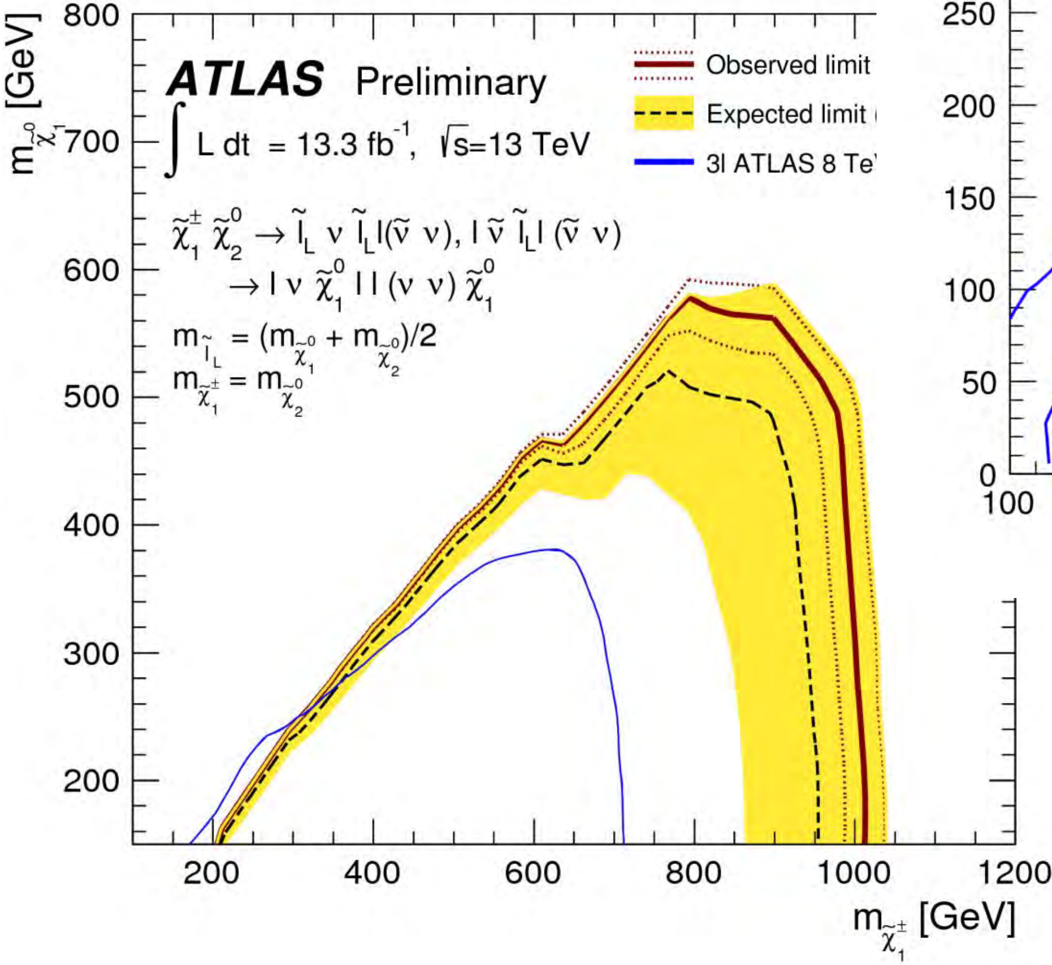


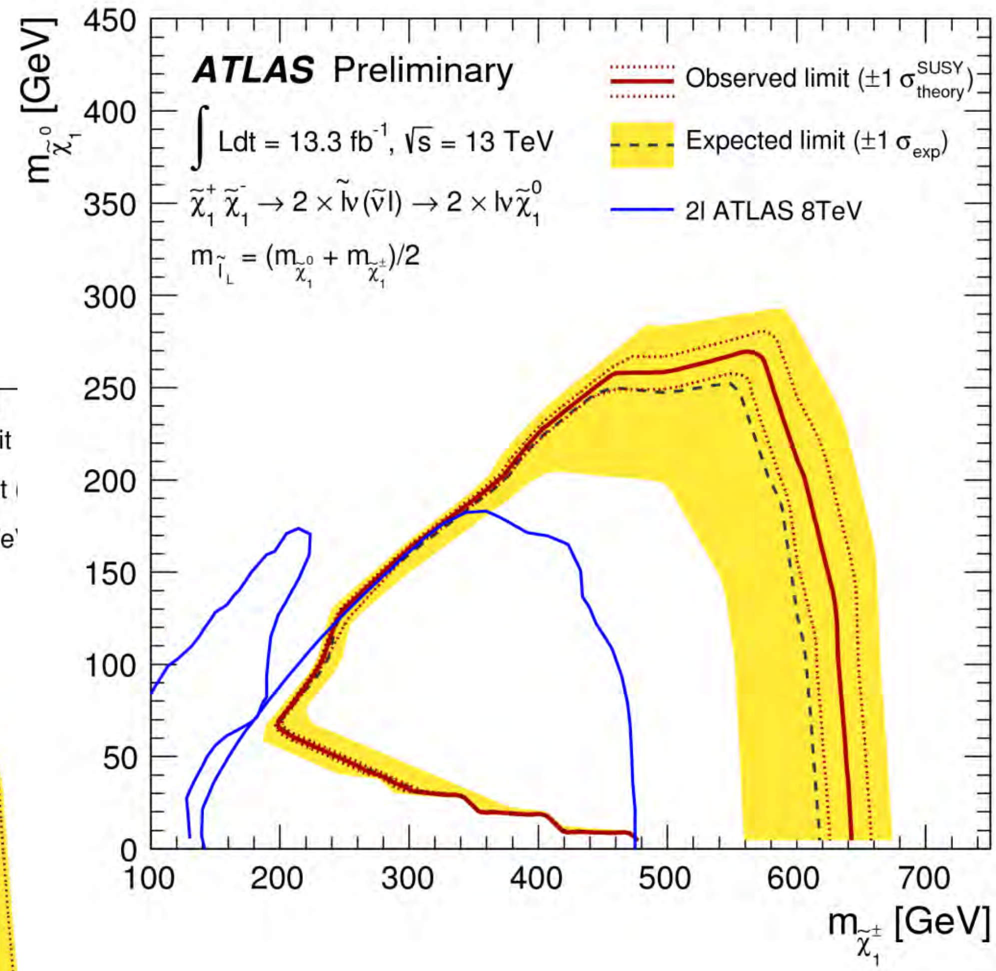


Warning
Assumptions for model simplification!
Crosssection is for $pp \to \widetilde{W}^0\widetilde{W}^+$!!
Read the papers!



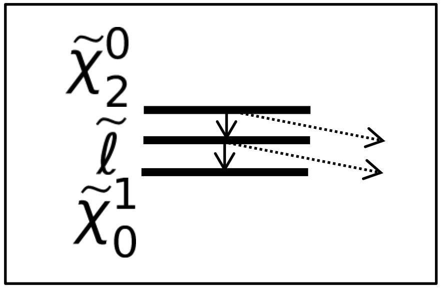
pp → $\tilde{\chi}^0_2 \tilde{\chi}^\pm_1$
ICHEP 2016
CMS Preliminary
12.9 fb^{-1} (13 TeV)
SUS-16-024, 2l SS + 3
SUS-16-024, 3-lep (BF
SUS-16-024, 3-lep (BF
SUS-16-024, 3-lep (WH
SUS-16-024, 3-lep (WZ
SUS-16-025, soft 2-lep
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^\pm_1}$ [GeV]
CMS Preliminary
10.1-12.9 fb^{-1} (13 TeV)
pp → $\tilde{\chi}^0_2 \tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2 \to Z \tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1 \to W \tilde{\chi}^0_1$
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$ ± 2 $\sigma_{experiment}$
$\Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1)$ [GeV]
$m_{\tilde{\chi}^0_2, \tilde{\chi}^\pm_1}$ [GeV]
95% CL upper limit on cross section [pb]

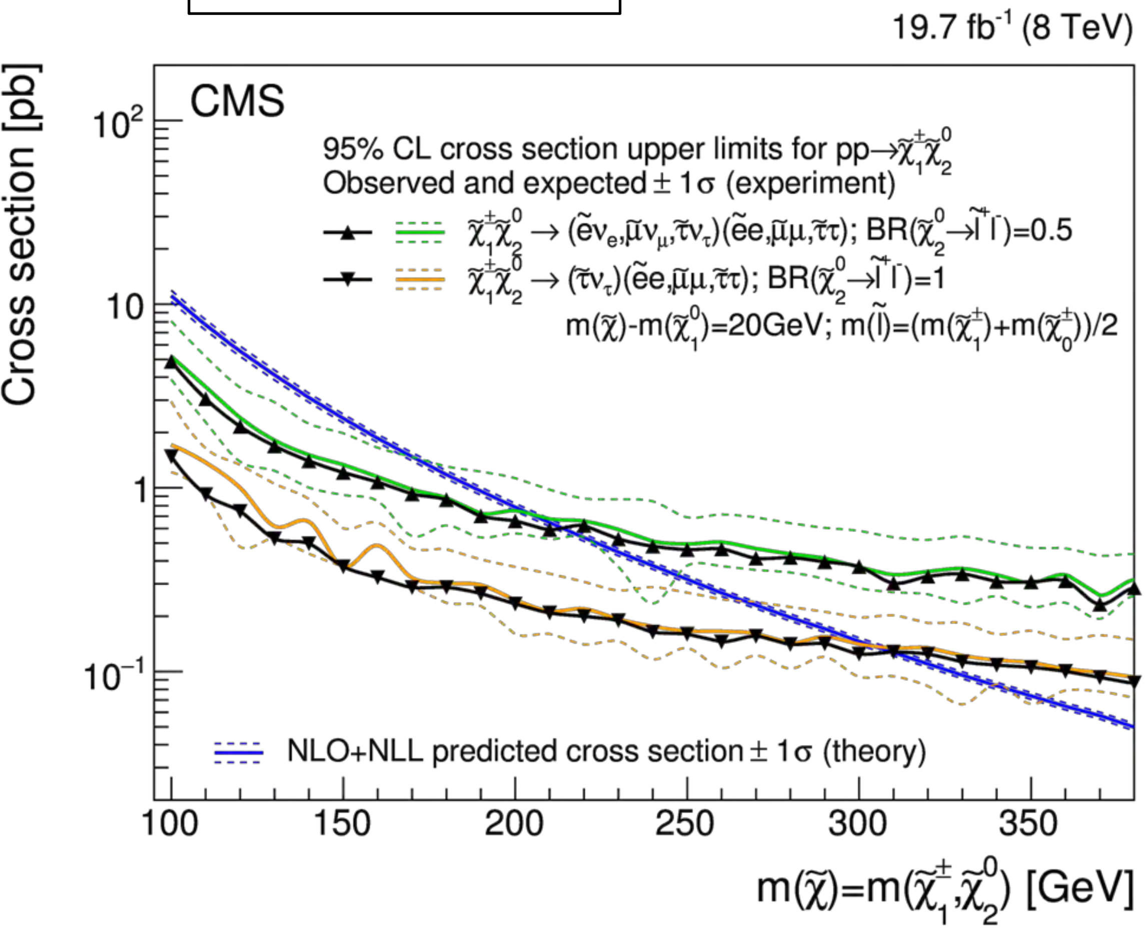




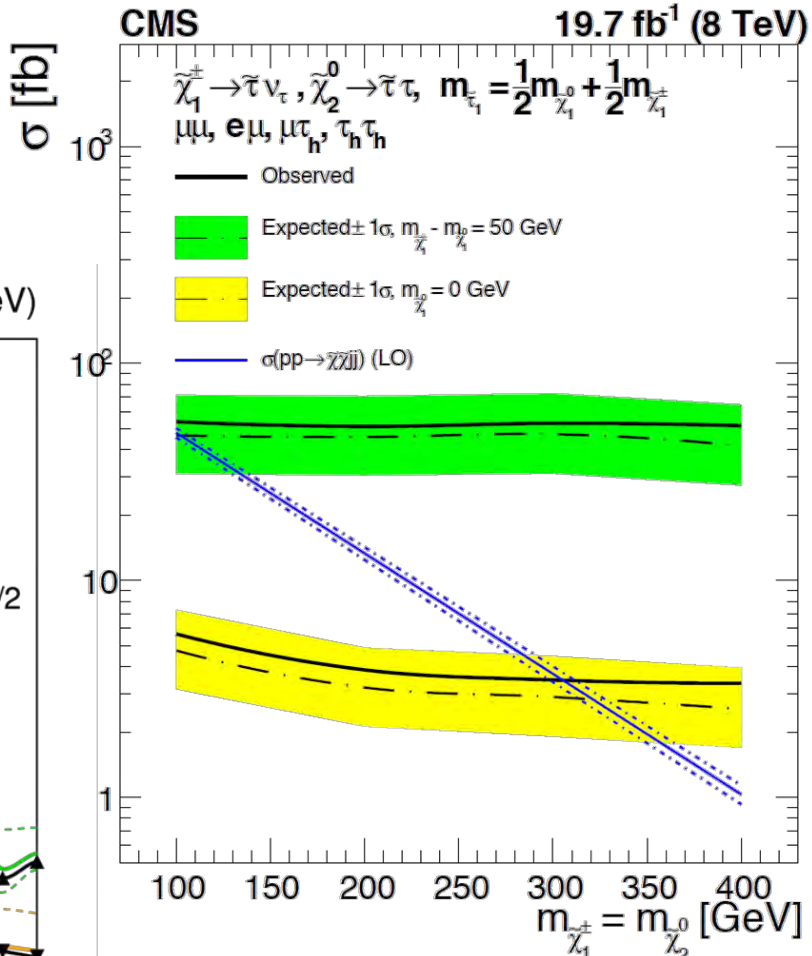
Warning
Assumptions for model simplification!
Crosssection is for $pp \to \widetilde{W}^0\widetilde{W}^+$!!
Read the papers!

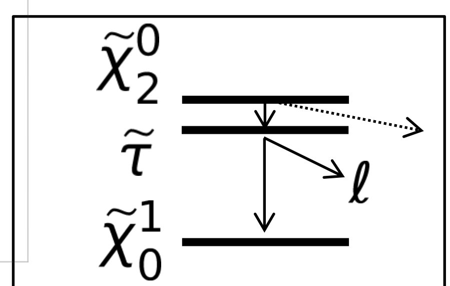
- ISR + 2-lepton [1512.08002]





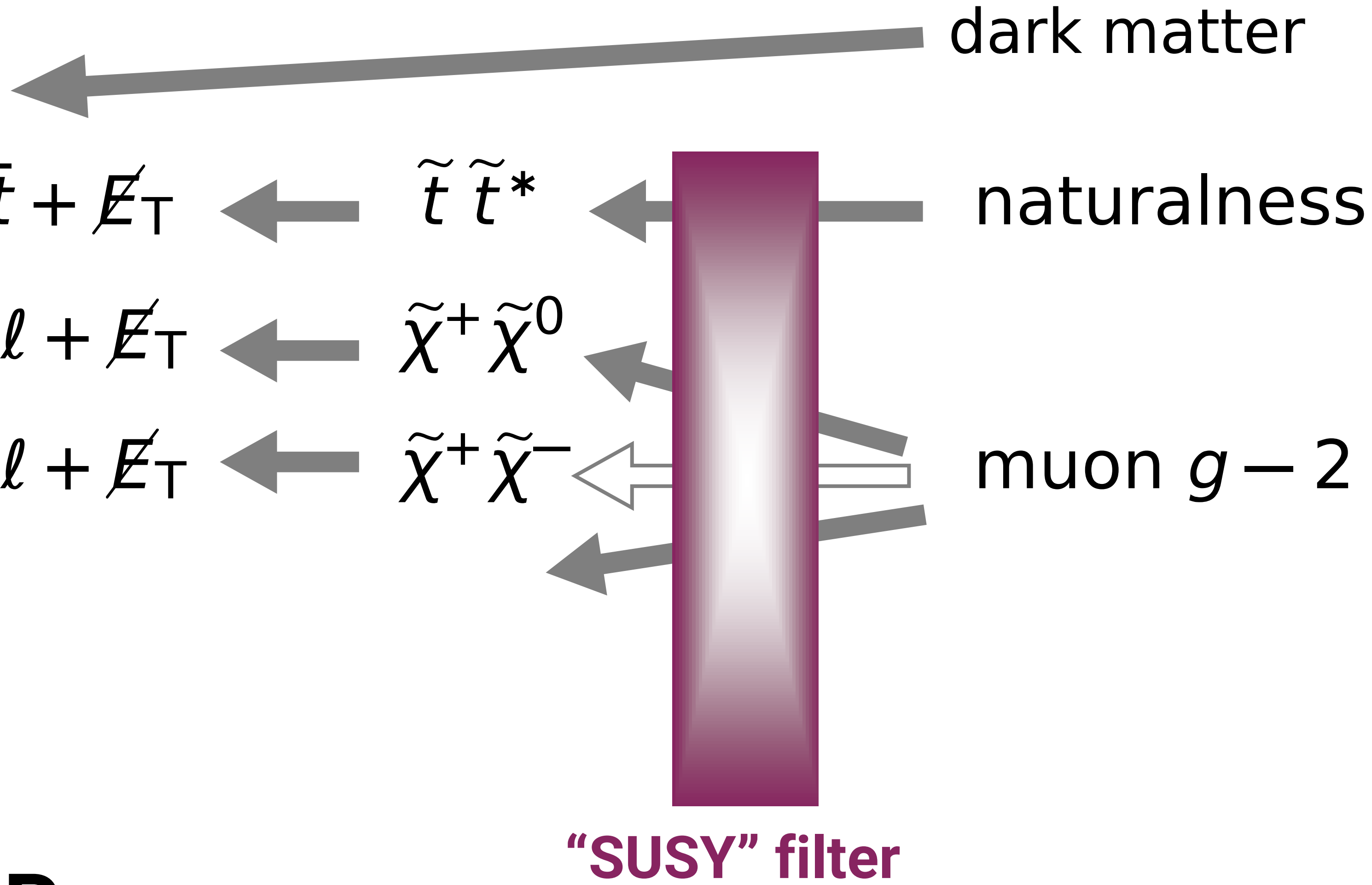
- VBF + 2-lepton [1508.07628]





1) $\not{E}_T$

- ▶ $t\bar{t} + \not{E}_T$
- ▶ $3\ell + \not{E}_T$
- ▶ $2\ell + \not{E}_T$



2) LLCP

3) more exotic

1) $\not\!\!E_T$

- $t\bar{t} + \not\!\!E_T$ ← $\tilde{t}\,\tilde{t}^*$
- $3\ell + \not\!\!E_T$ ← $\tilde{\chi}^+\tilde{\chi}^0$
- $2\ell + \not\!\!E_T$ ← $\tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\ell}\,\tilde{\ell}^*$

dark matter

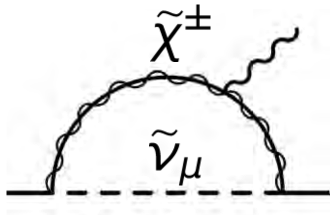
naturalness

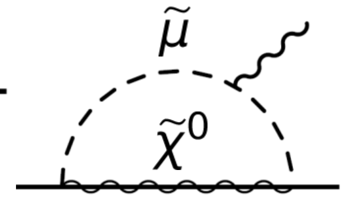
muon $g-2$

"SUSY" filter

2) LLCP

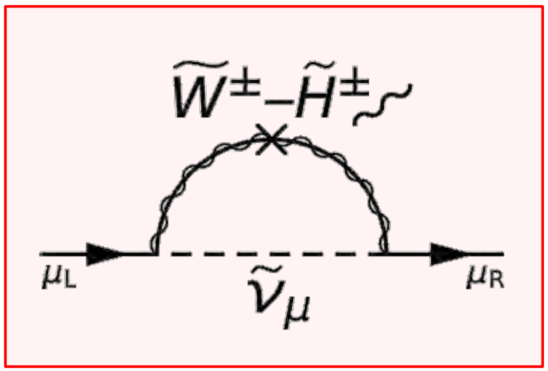
3) more exotic

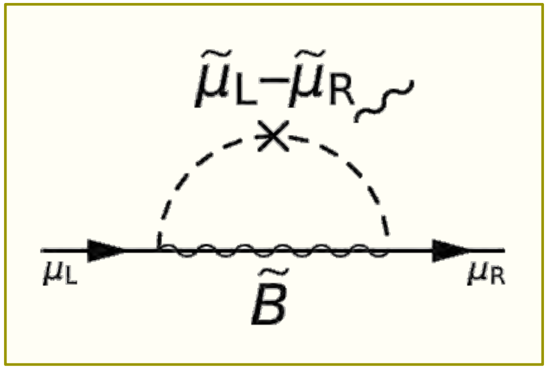
$a_\mu^{\mathrm{SUSY}} \simeq$ 

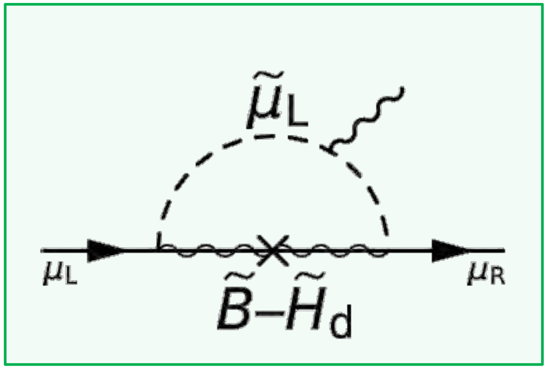
$+$ 

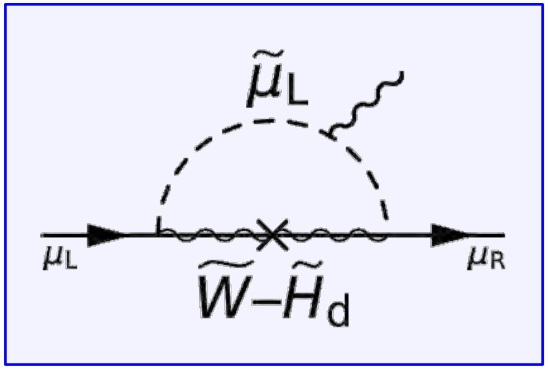
$$= a_\mu^{\mathrm{SUSY}}(M_1, M_2, \mu, m(\mu_\mathrm{L}), m(\mu_\mathrm{R}), \tan\beta, A_\mu)$$

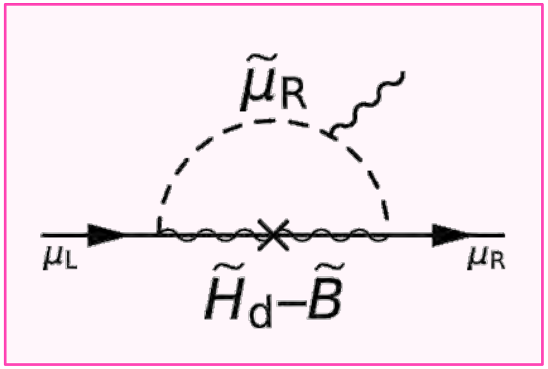
"mass insertion"



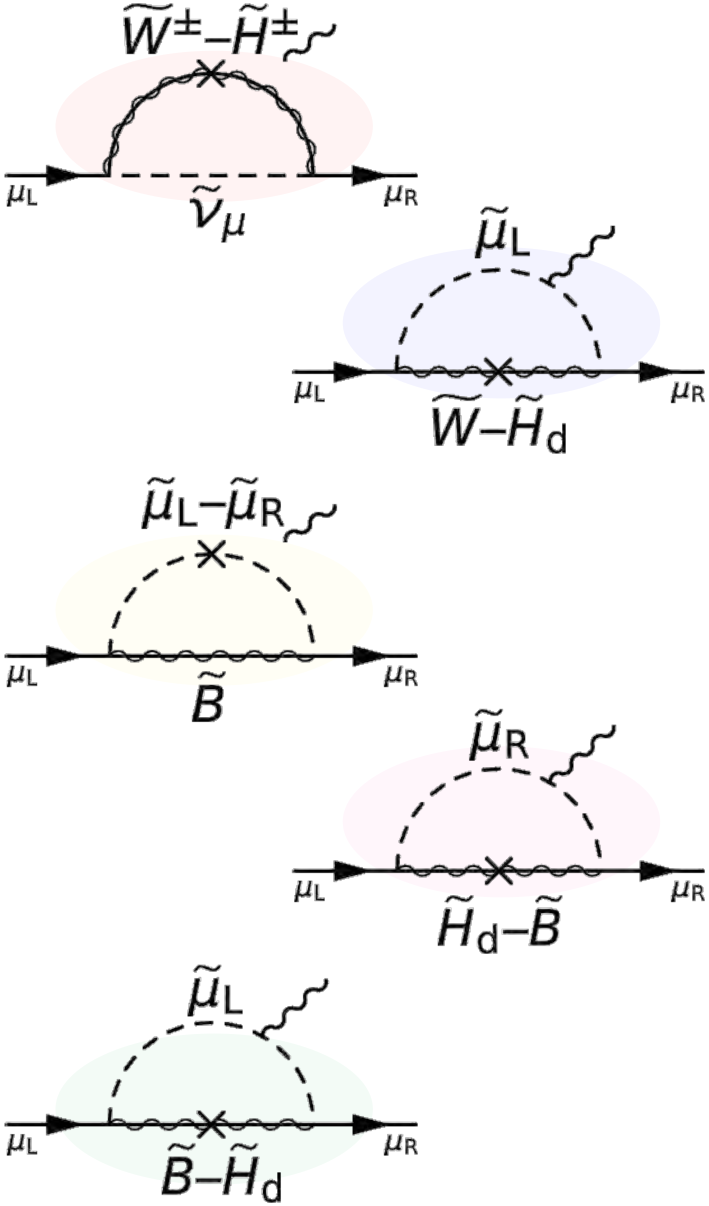








SUSY contribution to muon $g-2$: gauge basis



$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde\nu_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde\nu_\mu}},\frac{\mu}{m_{\tilde\nu_\mu}}\right)$$

$$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde\mu_L}^4}\cdot F_b\left(\frac{M_2}{m_{\tilde\mu_L}},\frac{\mu}{m_{\tilde\mu_L}}\right)$$

$$\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde\mu_L}}{M_1},\frac{m_{\tilde\mu_R}}{M_1}\right)$$

$$-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu\tan\beta}{m_{\tilde\mu_R}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde\mu_R}},\frac{\mu}{m_{\tilde\mu_R}}\right)$$

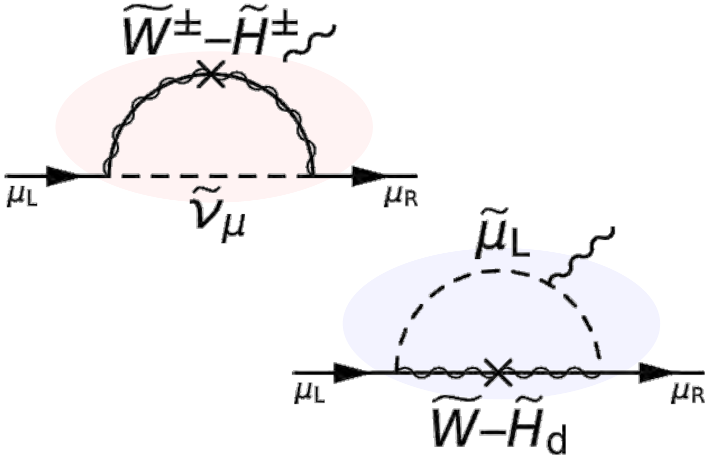
$$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m_{\tilde\mu_L}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde\mu_L}},\frac{\mu}{m_{\tilde\mu_L}}\right)$$

F_a, F_b are loop functions ($F > 0$):

$$F_a(x,y)=\frac{1}{2}\frac{C_1(x^2)-C_1(y^2)}{x^2-y^2},\qquad F_b(x,y)=-\frac{1}{2}\frac{N_2(x^2)-N_2(y^2)}{x^2-y^2};$$

$$C_1(x)=\frac{3-4x+x^2+2\log x}{(1-x)^3},\qquad N_2(x)=\frac{1-x^2+2x\log x}{(1-x)^3}.$$

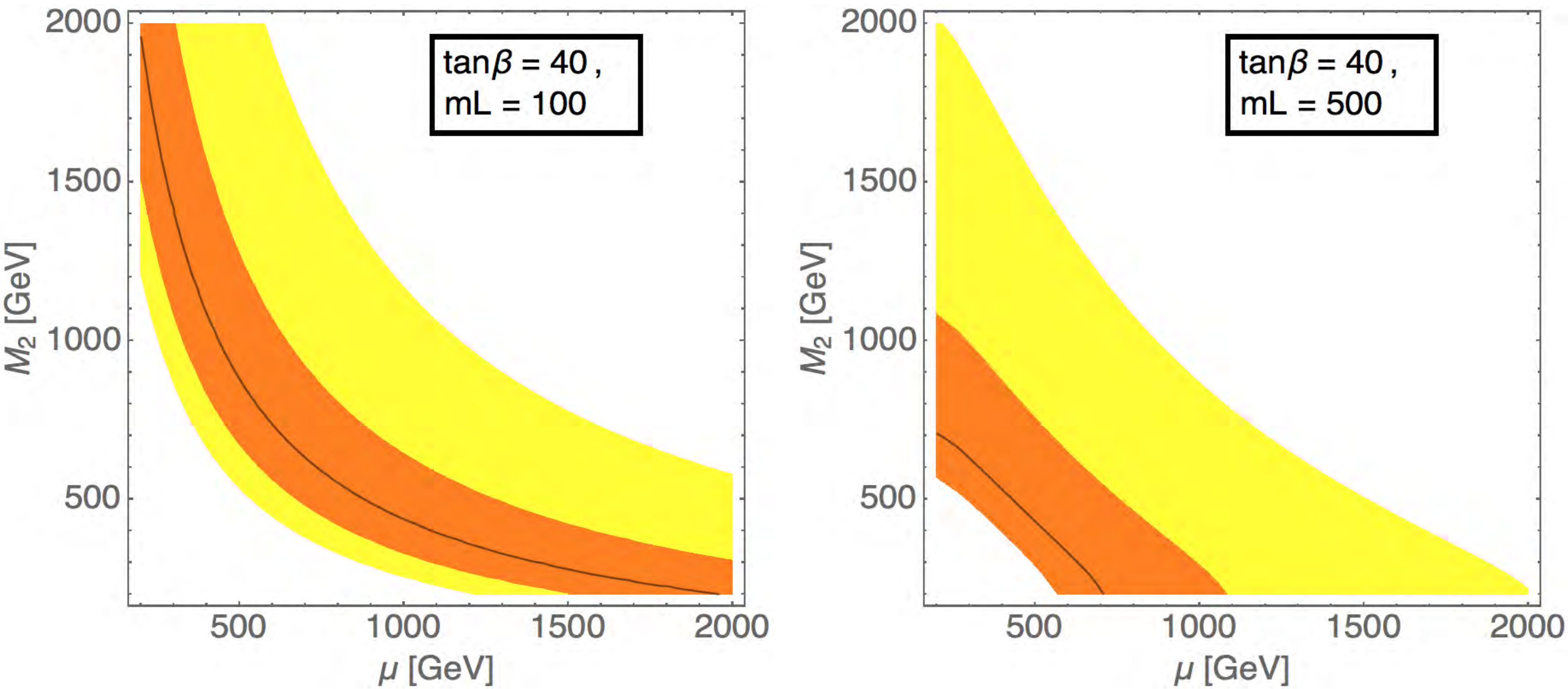
Muon $g-2$ vs LHC (1) 3-lepton signature coming from Wino-Higgsino contribution



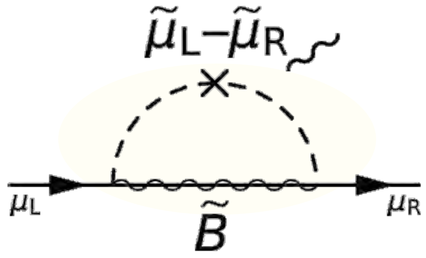
$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\widetilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\widetilde{\nu}_\mu}},\frac{\mu}{m_{\widetilde{\nu}_\mu}}\right)$$

$$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m_{\widetilde{\mu}_L}^4}\cdot F_b\left(\frac{M_2}{m_{\widetilde{\mu}_L}},\frac{\mu}{m_{\widetilde{\mu}_L}}\right)$$

Wino contributions [red+blue; tree; slep=sneu]

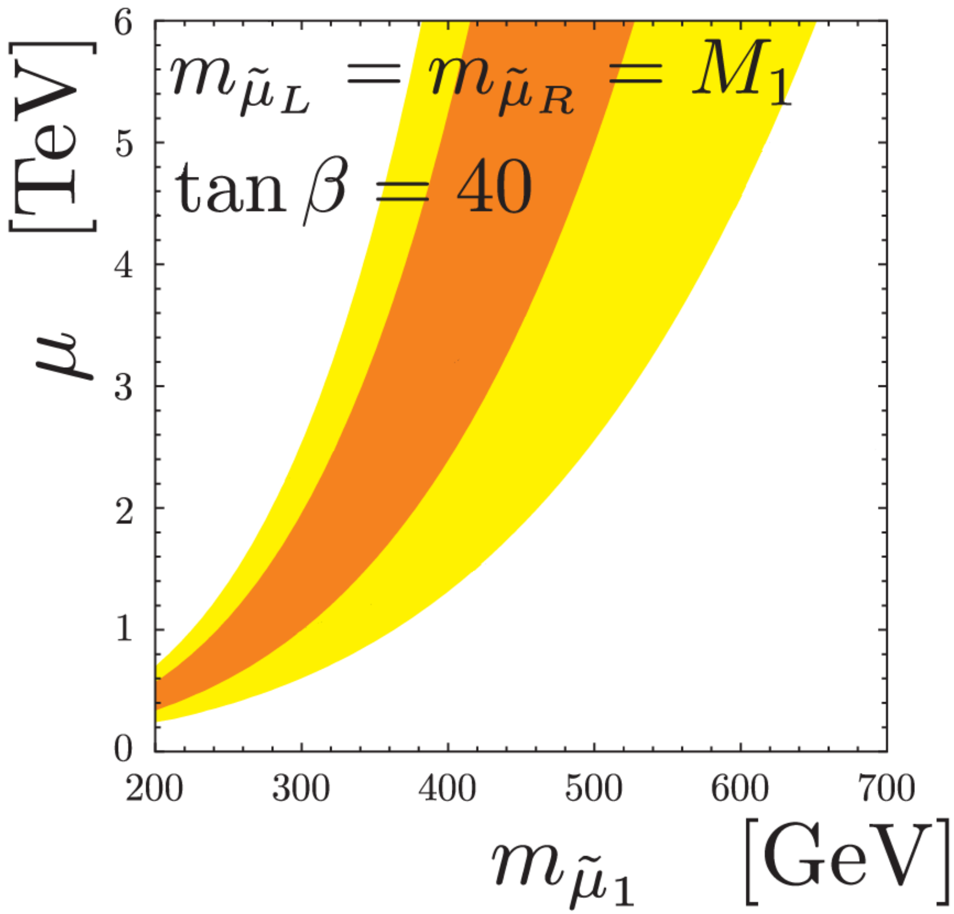


Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]



$$\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde{\mu}_{\rm L}}}{M_1},\frac{m_{\tilde{\mu}_{\rm R}}}{M_1}\right)$$

from $M^2_{\tilde{\mu}} = \begin{pmatrix} m(l_{\rm L})^2 & m_\mu(A^*_\mu - \mu\tan\beta) \\ m_\mu(A^*_\mu - \mu\tan\beta) & m(l_{\rm R})^2 \end{pmatrix}$



μ tanβ has upper bounds:

$$V_{\rm Higgs} \supset -\left(m_\tau\,\mu\tan\beta\cdot\tilde{\tau}^*_{\rm L}\tilde{\tau}_{\rm R}h + m_\mu\,\mu\tan\beta\cdot\tilde{\mu}^*_{\rm L}\tilde{\mu}_{\rm R}h\right)$$

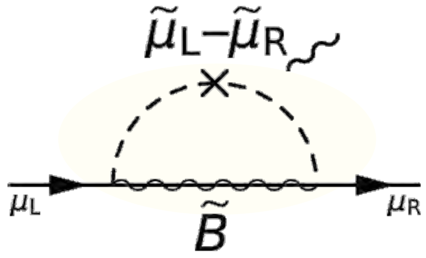
$m_{\tilde{\tau}}/m_{\tilde{\mu}}$

$= 1 \quad \Rightarrow m_{\tilde{\mu}} \lesssim 300(420)$ GeV

$= 2 \quad \Rightarrow \quad \lesssim 440(620)$ GeV

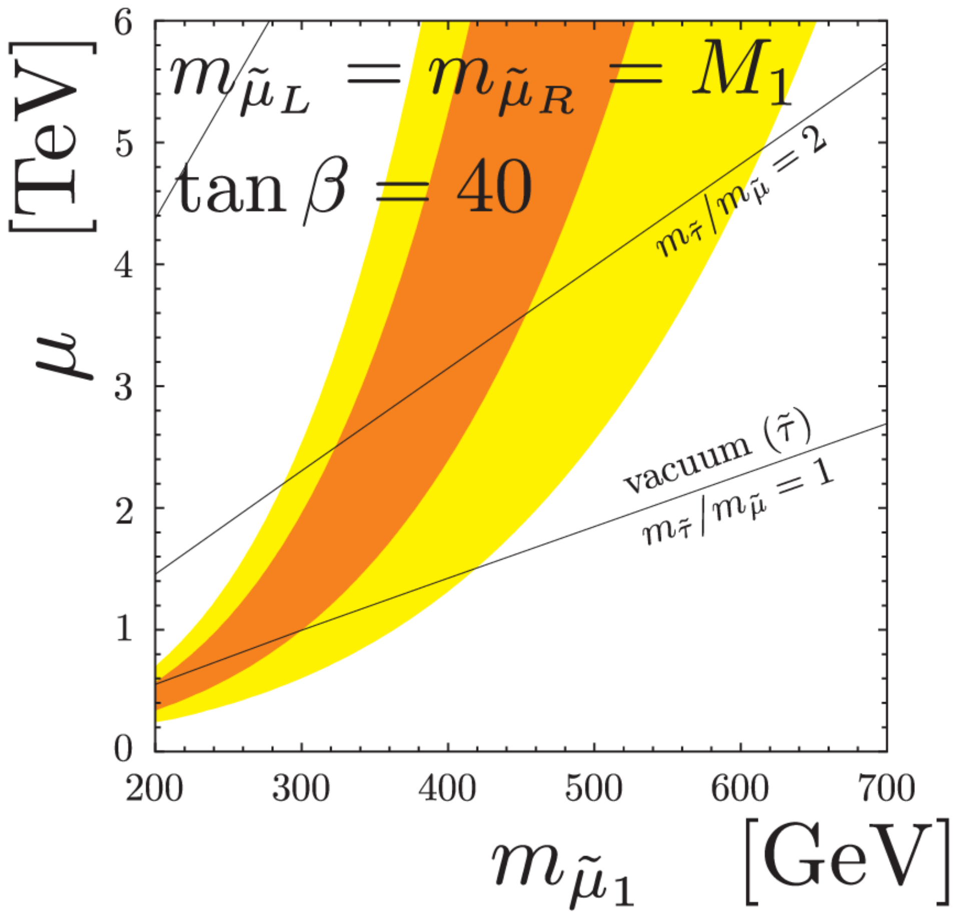
$= \infty \quad \Rightarrow \quad \lesssim 1.4(1.9)$ TeV

Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]



$$\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde\mu_L}}{M_1},\frac{m_{\tilde\mu_R}}{M_1}\right)$$

from $M_{\tilde\mu}^2 = \begin{pmatrix} m(l_L)^2 & m_\mu(A_\mu^* - \mu\tan\beta) \\ m_\mu(A_\mu^* - \mu\tan\beta) & m(l_R)^2 \end{pmatrix}$



μ tanβ has upper bounds:

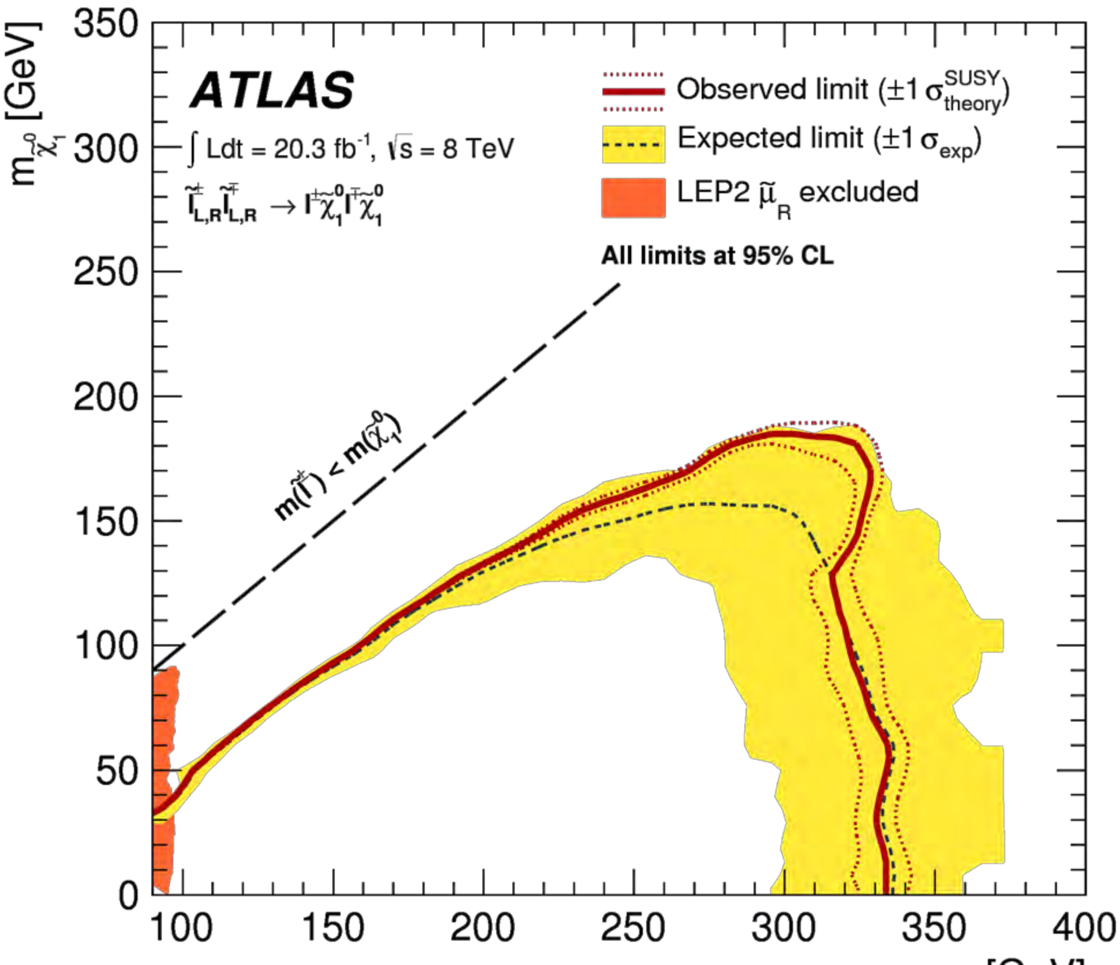
$$V_{\rm Higgs} \supset -\left(m_\tau\,\mu\tan\beta\cdot\tilde\tau_L^*\tilde\tau_R h + m_\mu\,\mu\tan\beta\cdot\tilde\mu_L^*\tilde\mu_R h\right)$$

$m_{\tilde\tau}/m_{\tilde\mu}$

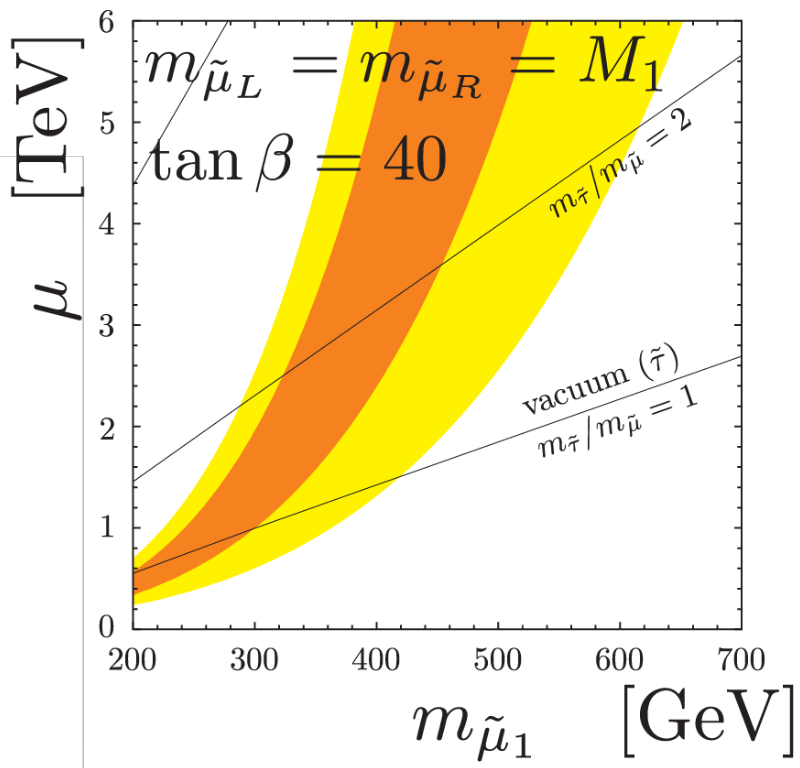
$= 1 \Rightarrow m_{\tilde\mu} \lesssim 300(420)$ GeV

$= 2 \Rightarrow \lesssim 440(620)$ GeV

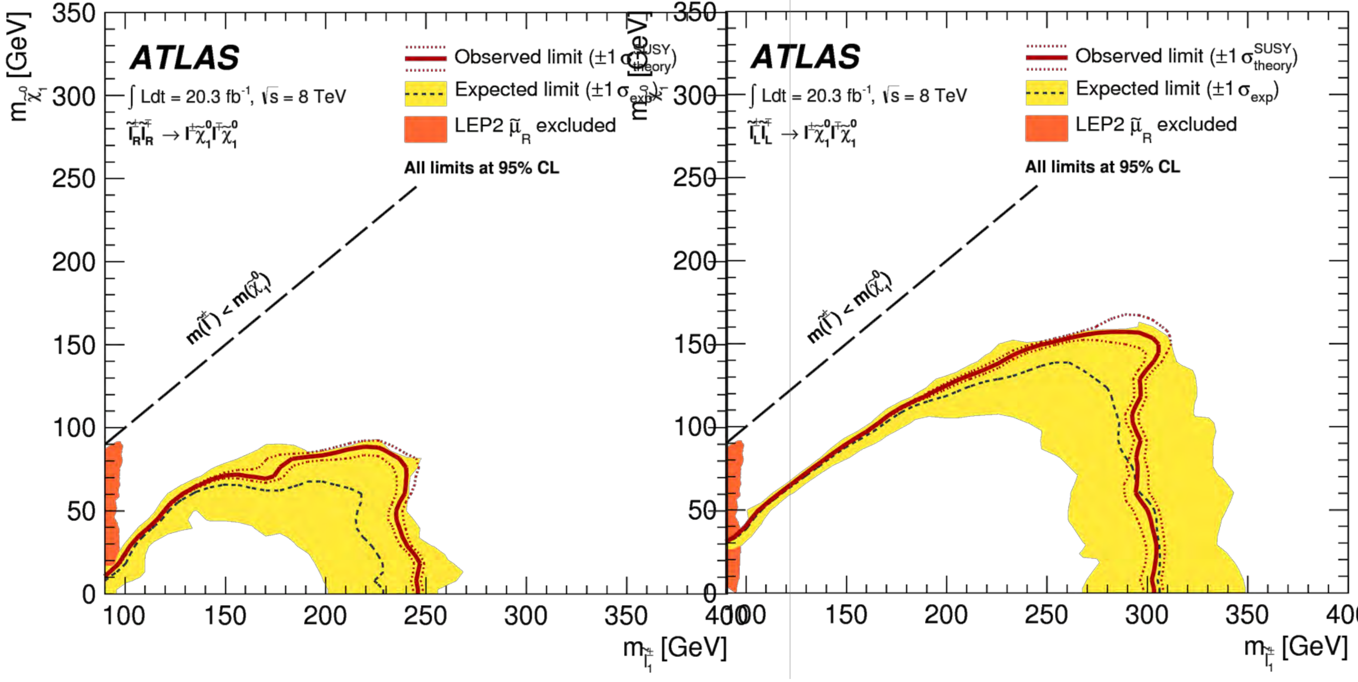
$= \infty \Rightarrow \lesssim 1.4(1.9)$ TeV

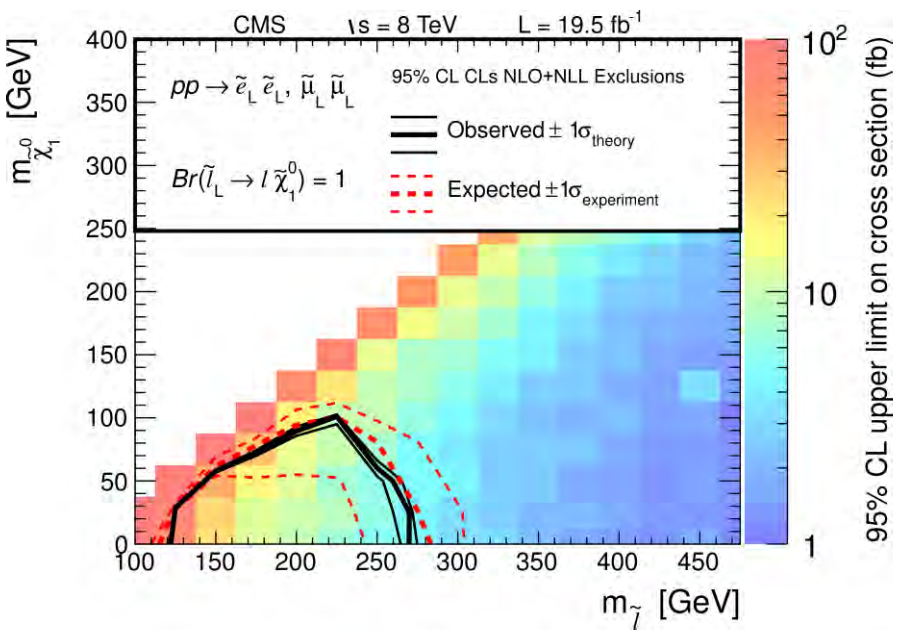

ATLAS
$\int$ Ldt = 20.3 fb^{-1}, $\sqrt{s}$ = 8 TeV
$\tilde{l}^{\pm}_{L,R}\tilde{l}^{\mp}_{L,R} \to l^{\pm}\tilde{\chi}^0_1 l^{\mp}\tilde{\chi}^0_1$
Observed limit ($\pm 1\,\sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
LEP2 $\tilde{\mu}_R$ excluded
All limits at 95% CL
$m(\tilde{l}^{\pm}) < m(\tilde{\chi}^0_1)$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{l}^{\pm}_1}$ [GeV]

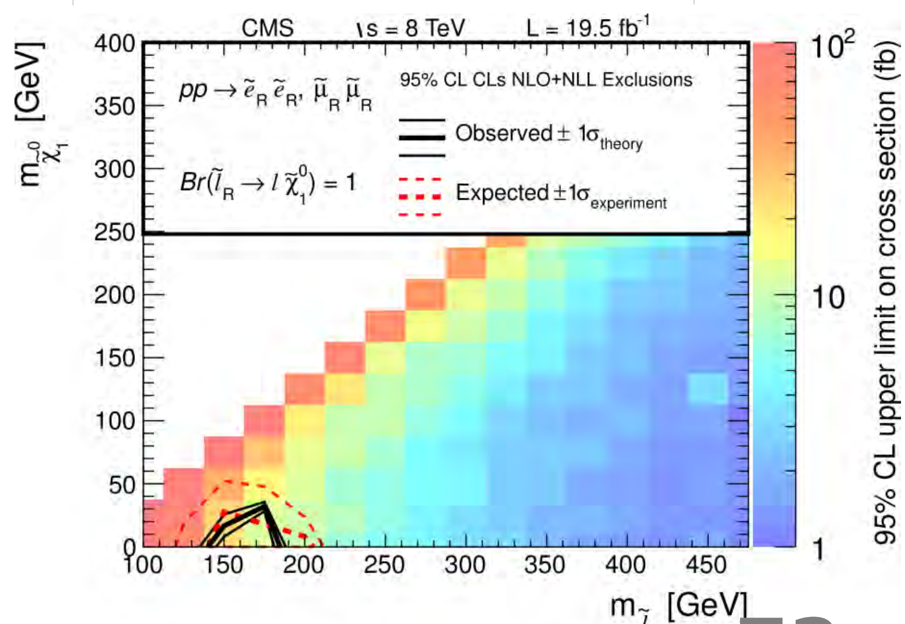
[1403.5294]


$m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R} = M_1$
$\tan\beta = 40$
$m_{\tilde{\tau}}/m_{\tilde{\mu}} = 2$
vacuum ($\tilde{\tau}$)
$m_{\tilde{\tau}}/m_{\tilde{\mu}} = 1$
μ [TeV]
$m_{\tilde{\mu}_1}$ [GeV]

Muon $g-2$ vs LHC (2) Pure-bino contribution results in slepton pair-production







1) $\not{E}_T$ ← dark matter

- $t\bar{t} + \not{E}_T$ ← $\tilde{t}\,\tilde{t}^*$ ← naturalness
- $3\ell + \not{E}_T$ ← $\tilde{\chi}^+\tilde{\chi}^0$ ← muon $g-2$
- $2\ell + \not{E}_T$ ← $\tilde{\chi}^+\tilde{\chi}^-$ ← muon $g-2$

$\tilde{\ell}\,\tilde{\ell}^*$ → $2\ell + \not{E}_T$; muon $g-2$ → $\tilde{\ell}\,\tilde{\ell}^*$

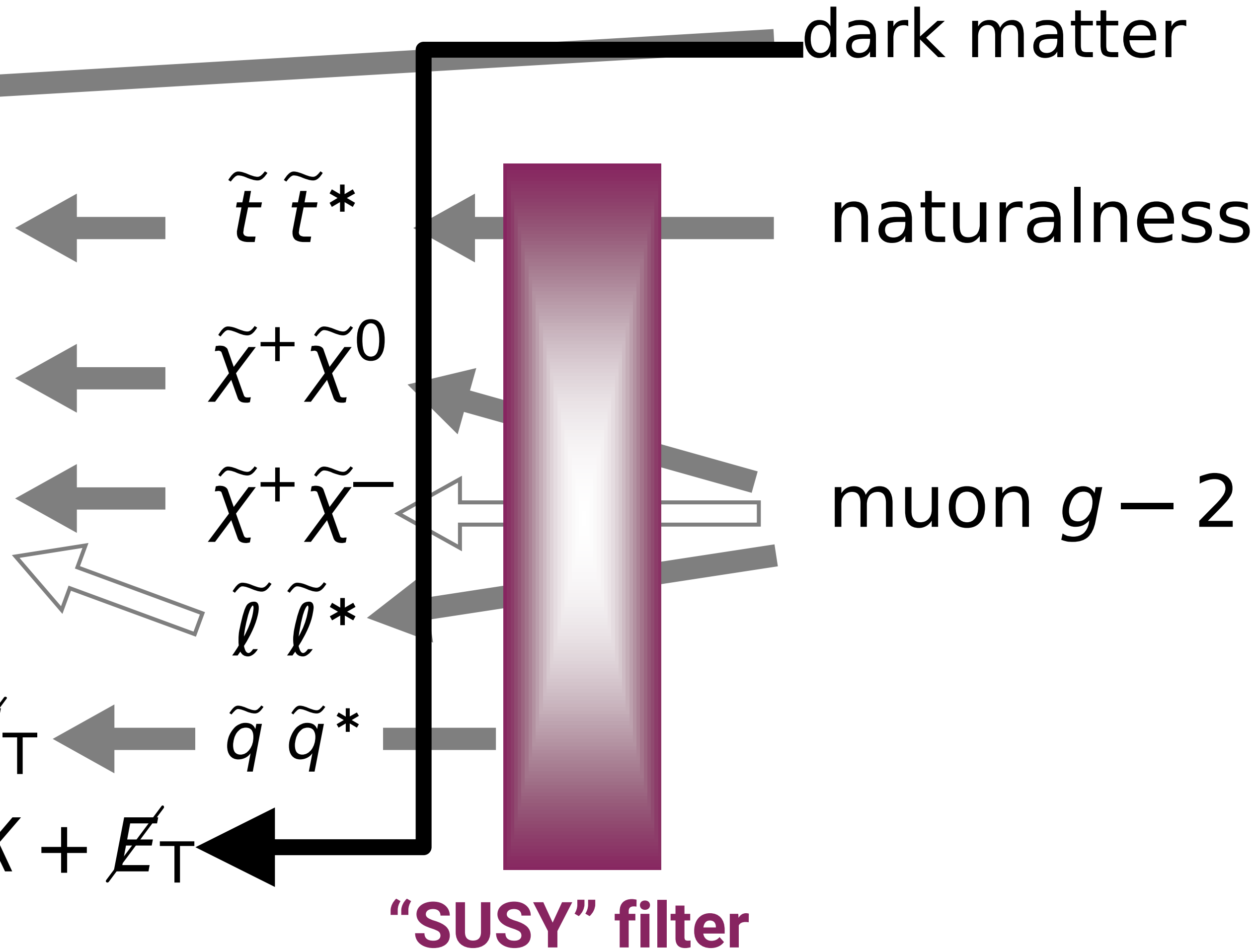
"SUSY" filter

2) LLCP

3) more exotic

1) $\not{E}_{\mathrm{T}}$

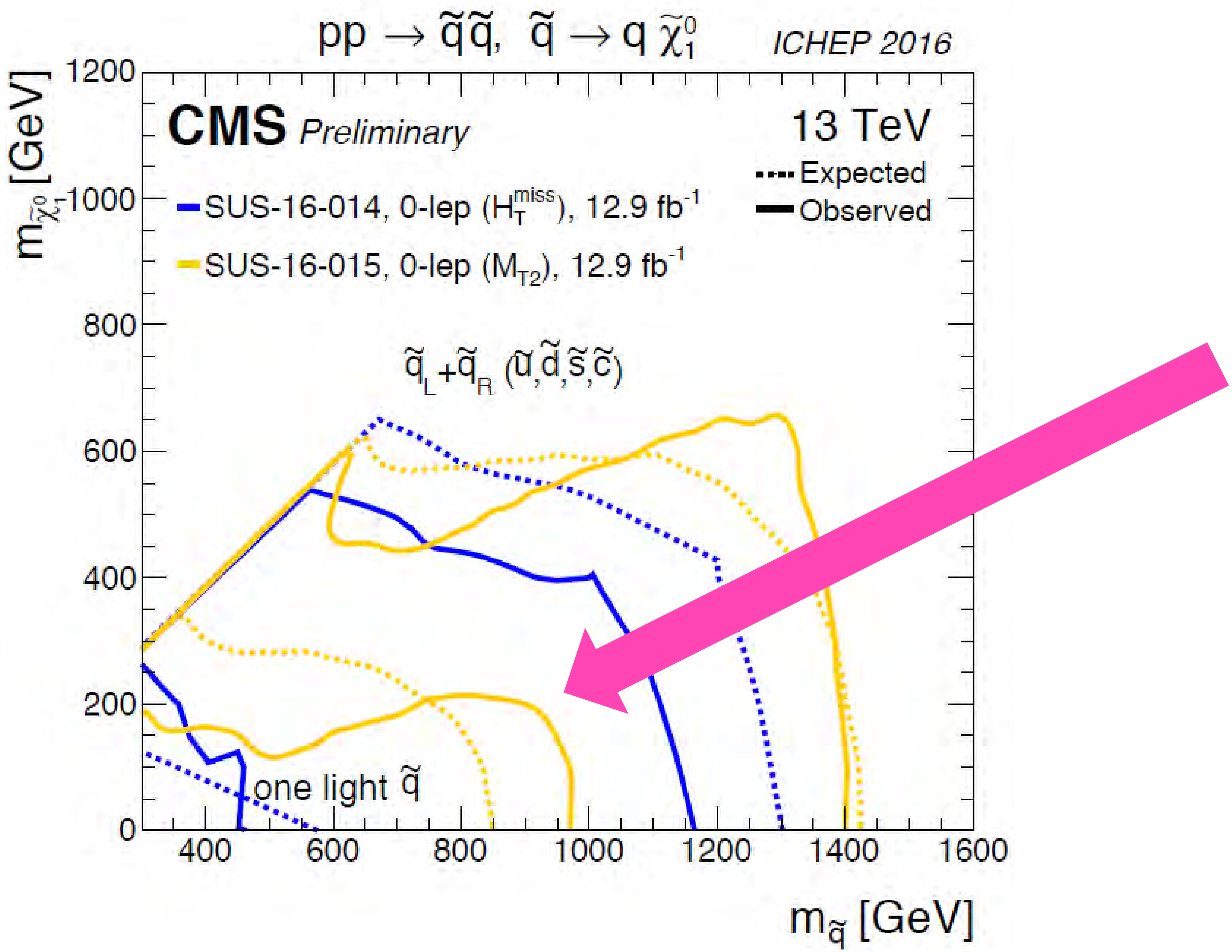
- ▶ $t\bar{t} + \not{E}_{\mathrm{T}}$
- ▶ $3\ell + \not{E}_{\mathrm{T}}$
- ▶ $2\ell + \not{E}_{\mathrm{T}}$
- ▶ jets $+ \not{E}_{\mathrm{T}}$
- ▶ mono-$X + \not{E}_{\mathrm{T}}$



2) **LLCP**

3) **more exotic**

- Ready for single-quark observation!



LLCP

1. Motivations
2. How to detect?
3. Current and future

LLCP signature ← charged (quasi-) stable particles

active in the early Universe
→ cosmological motivations

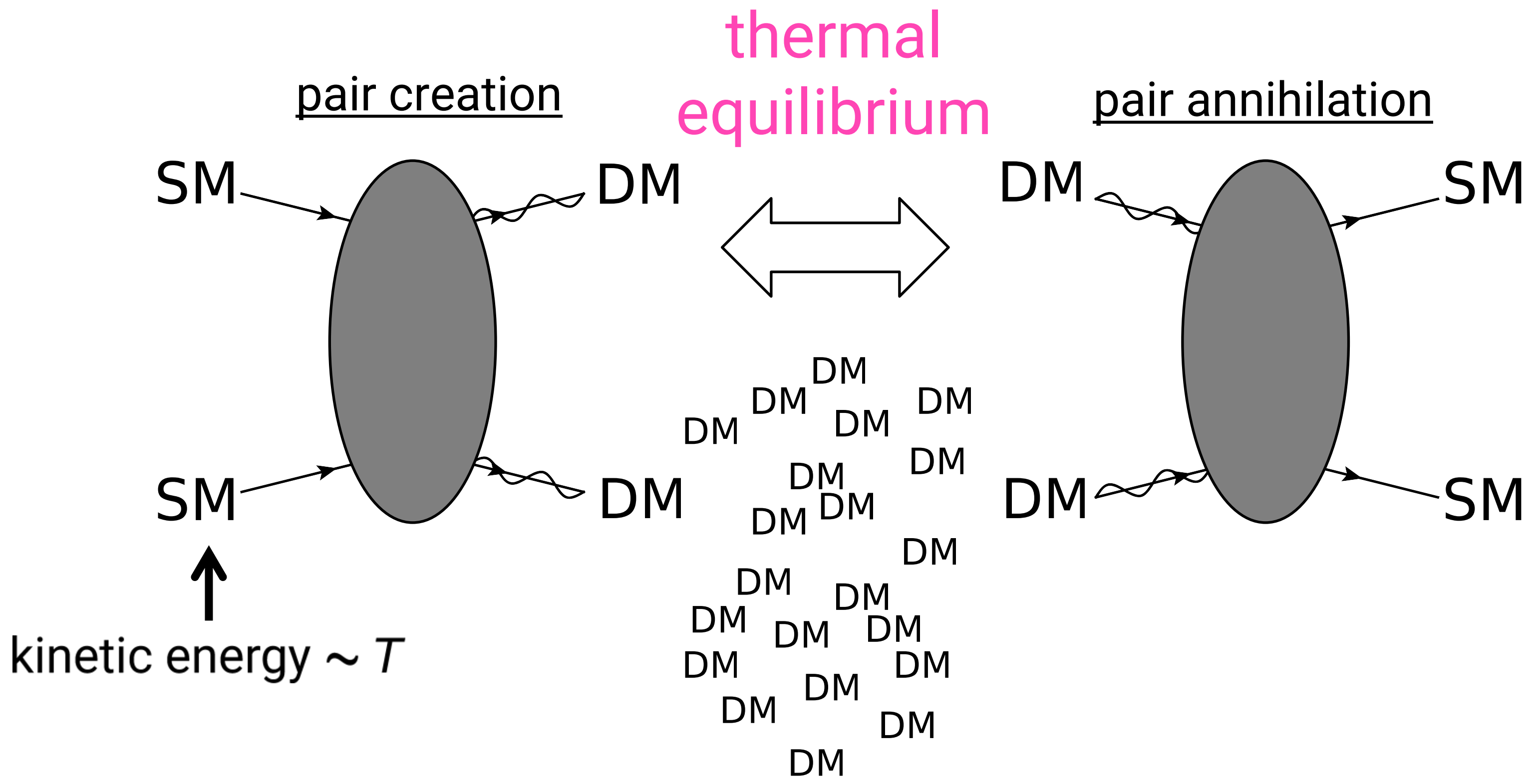
- DM relic abundance
(esp. to ameliorate DM over-abundance)
  - co-annihilation
  - super-WIMP scenario

  } → next slides
- Li problem
  - MSSM $\tilde{\tau}$ with $m_{\tilde{\tau}} \sim 400\,\mathrm{GeV}$

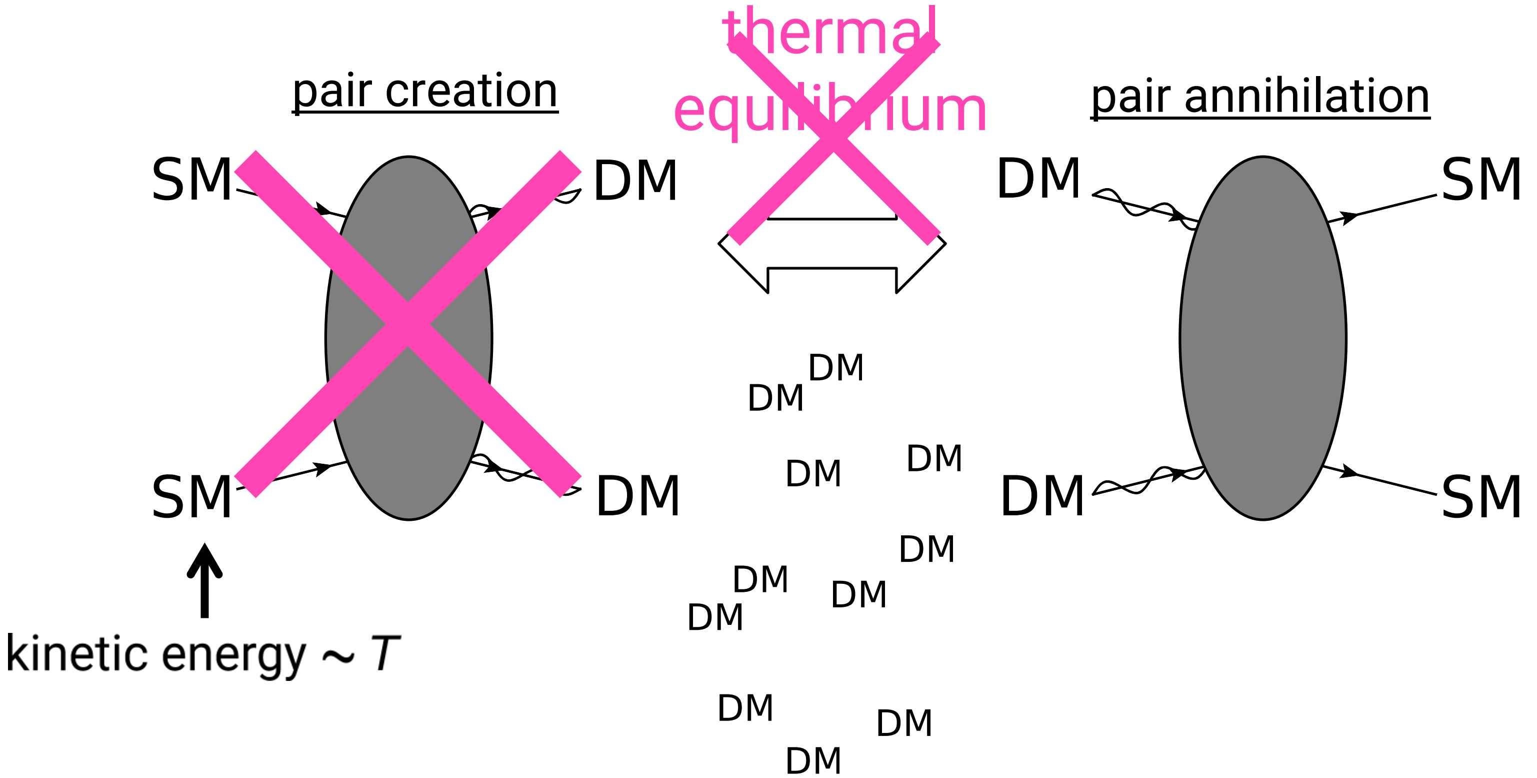
$$\Delta(m_{\tilde{\tau}} - m_{\text{LSP-DM}}) \sim 100\,\mathrm{MeV}$$

Sato, Shimomura, Yamanaka [1604.04769]

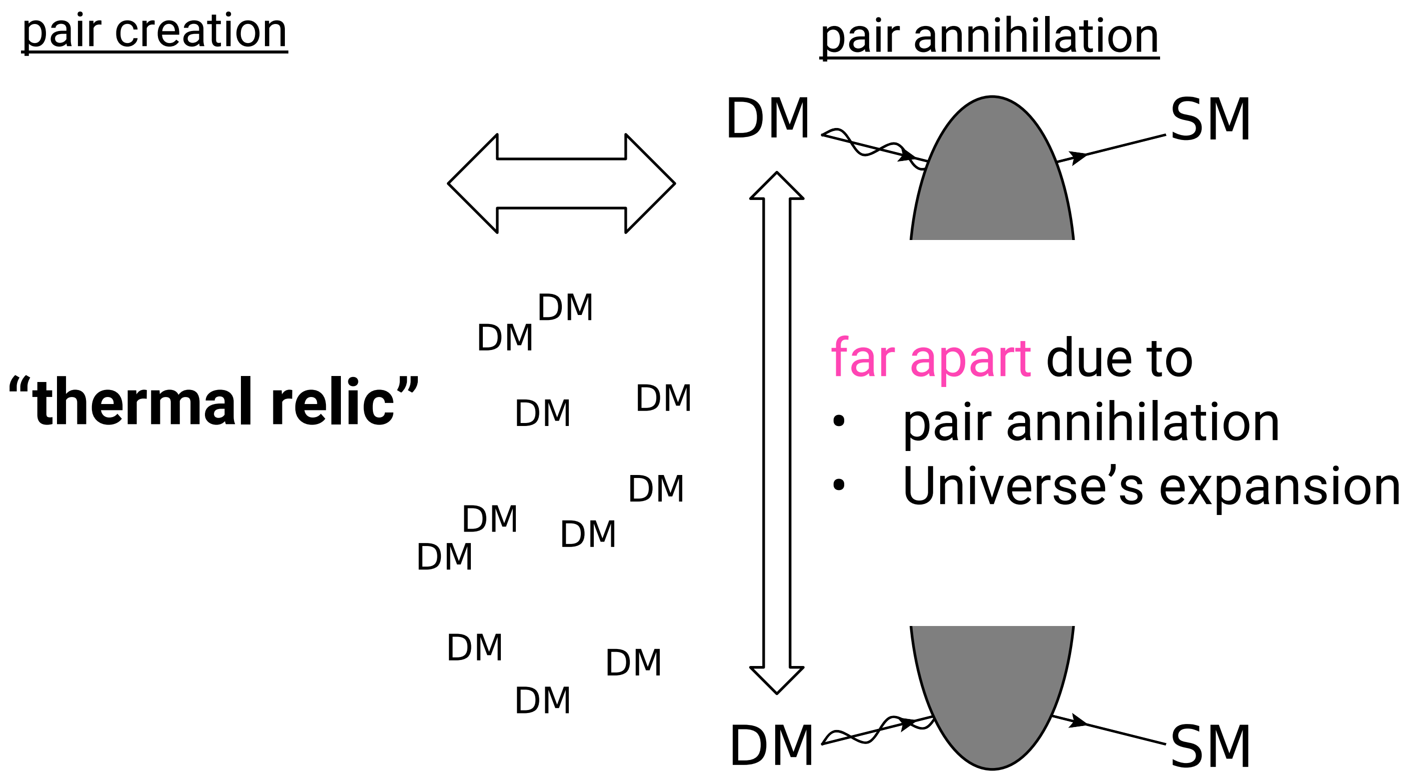
- Early Universe with $T > m_{\mathrm{DM}}$



- Early Universe with $T \lesssim m_{\mathrm{DM}}$

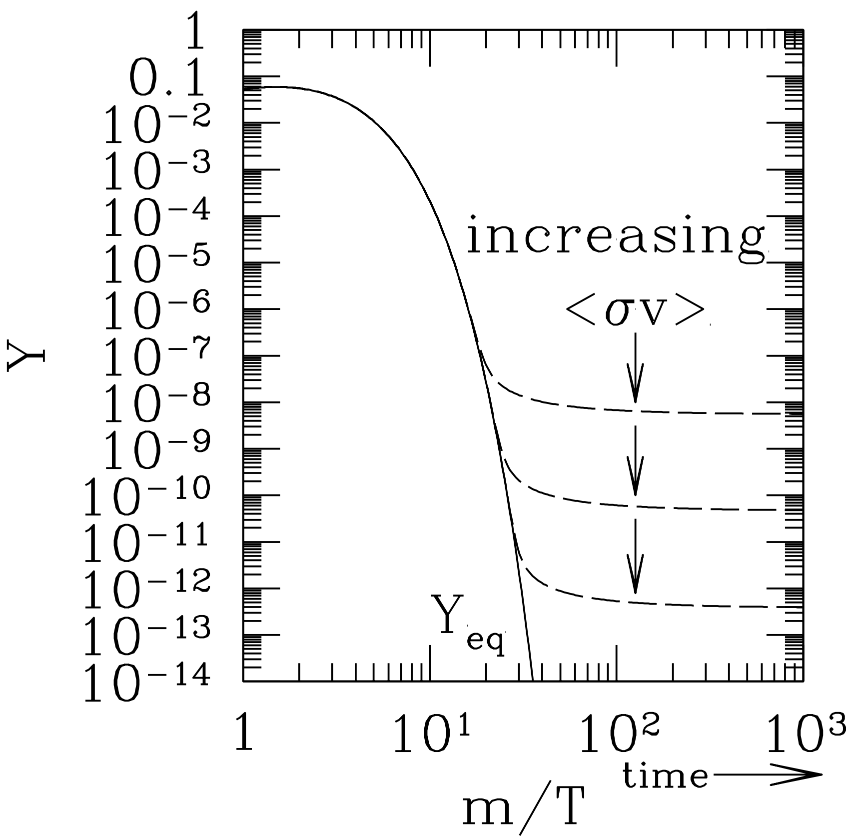


- Early Universe with $T \lesssim m_{\mathrm{DM}}/20$



- "observed" relic density Ωh^2

⇦ "proper" crosssection $\langle \sigma v \rangle$ of (DM)(DM)→SM



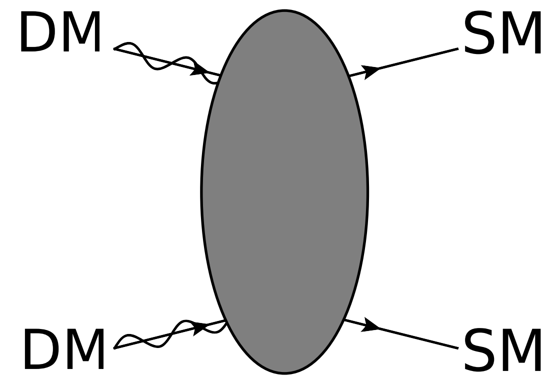


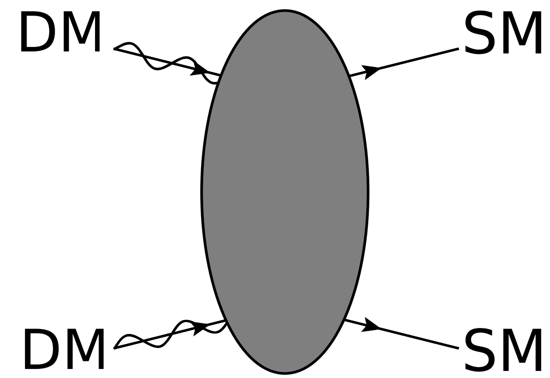
Figure from Gelmini and Gondolo, [1009.3690]

- "observed" relic density Ωh^2

  ⟸ "proper" crosssection $\langle \sigma v \rangle$ of (DM)(DM)→SM

- Sometimes overabundant : $\Omega h^2 > 0.12$
  - e.g. MSSM with $\widetilde{B}$-DM

    $m_{\widetilde{B}} \gtrsim 100$ GeV → overabundant

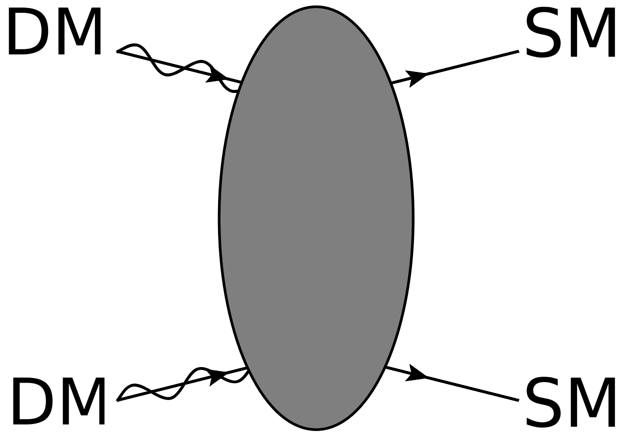


→ mechanisms for Ωh^2 down

- co-annihilation Binetruy, Girardi, Salati (1984), Griest, Seckel (1991)
- super-WIMP Feng, Rajaraman, Takayama [ph/0306024]
- MSSM4G Abdullah, Feng [1510.06089]

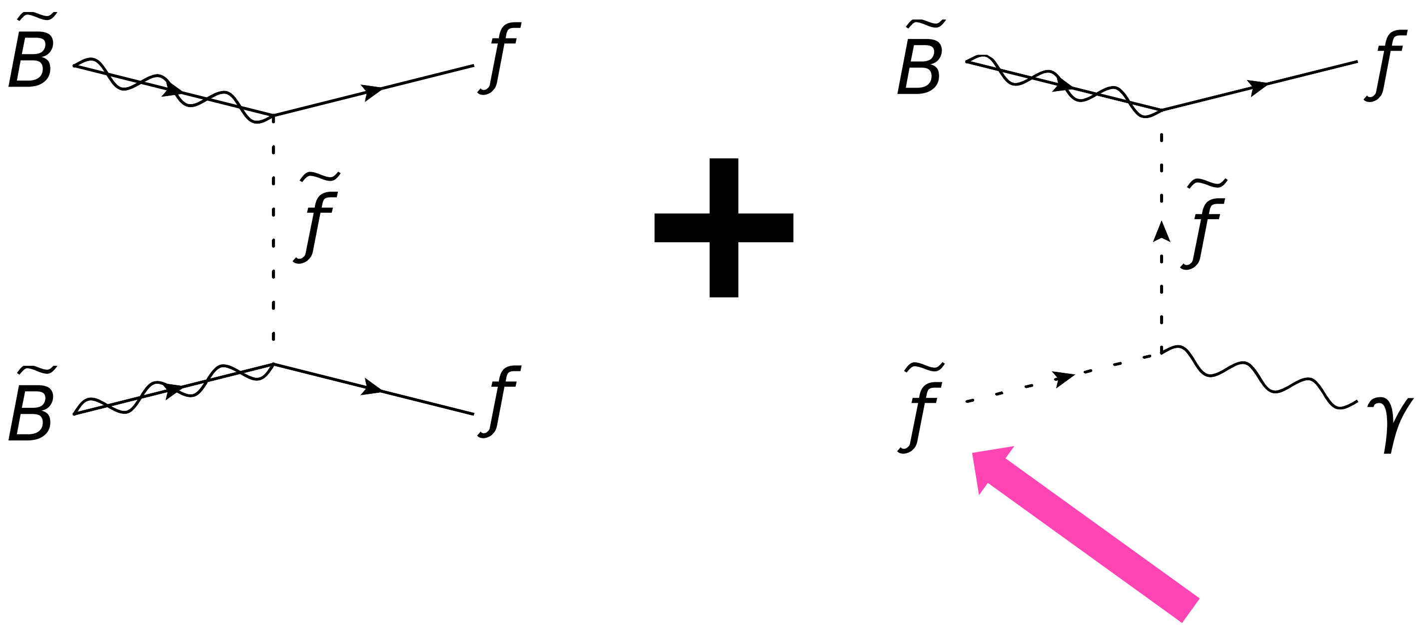
and a lot more…

- Co-annihilation



+ extra process

■ Co-annihilation



- Bino-stau → $m_{\tilde{B}} \lesssim$ 700 GeV
- Bino-Wino → 3 TeV
- Bino-gluino → 7-8 TeV
- Bino-stop → ~8 TeV

small mass splitting

$$\frac{m_{\tilde{f}} - m_{\tilde{B}}}{m_{\tilde{B}}} \ll 1$$

→ **LLCP**

cf. [1403.0715], [1404.5571], etc.

- Super-WIMP

NLSP

slepton $\tilde{l}$ as thermal relic with $(\Omega h^2)_{\tilde{l}} \gg 0.12$

l

late-time decay

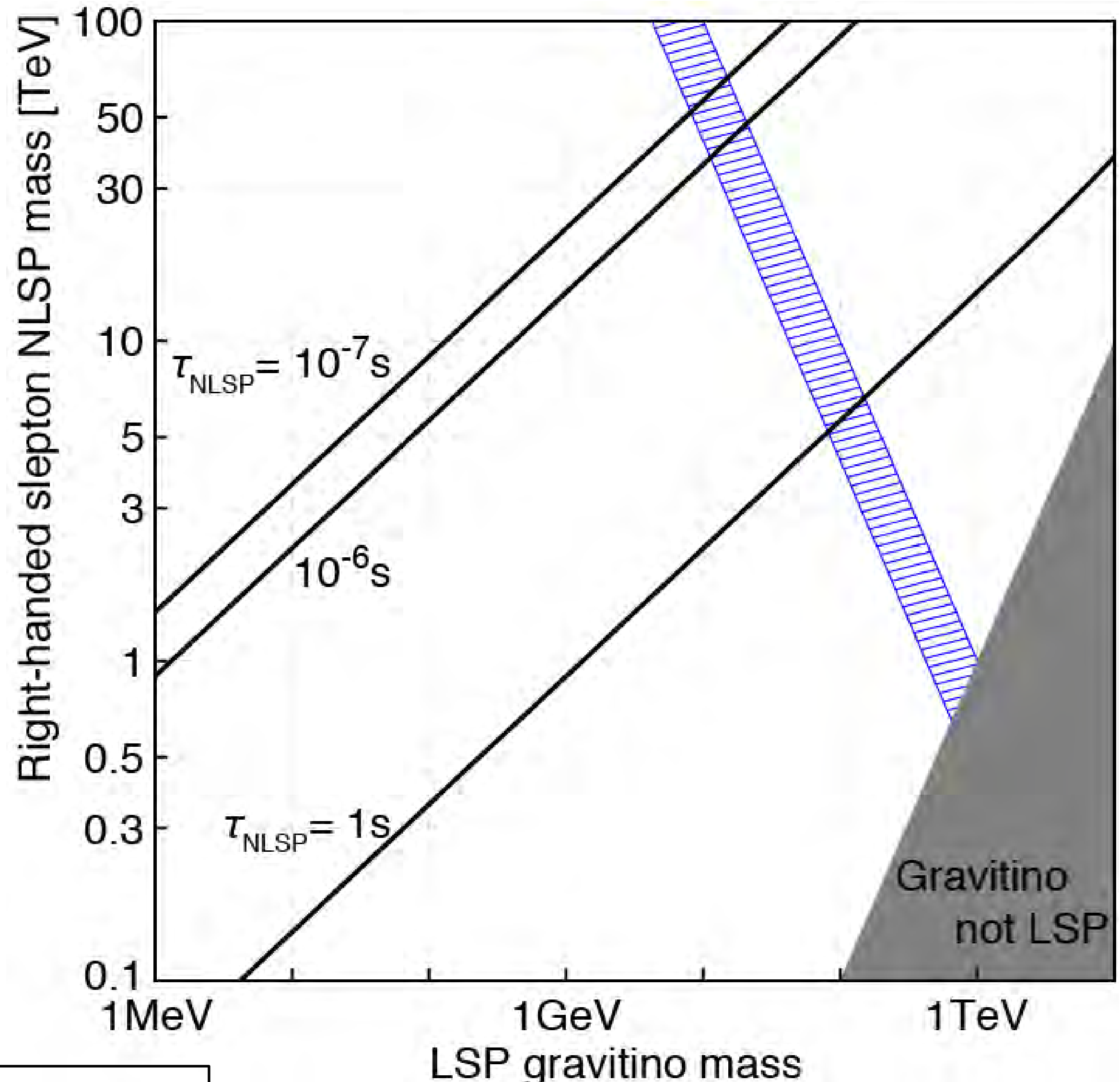
gravitino $\tilde{G}$ $\Longrightarrow$ $(\Omega h^2)_{\mathrm{DM}} = \frac{m_{\tilde{G}}}{m_{\tilde{l}}} (\Omega h^2)_{\tilde{l}}$

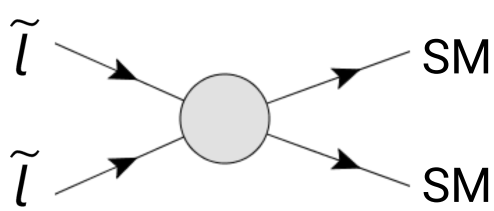
LSP (DM)

$$\tau(\tilde{l} \to l\tilde{G}) = \underline{5.7 \times 10^{-7}\,\mathrm{sec}} \cdot \left(\frac{m_{\tilde{l}}}{1\,\mathrm{TeV}}\right)^{-5} \left(\frac{m_{\tilde{G}}}{1\,\mathrm{MeV}}\right)^{2}$$

$\equiv 170\,\mathrm{m}$

Super-WIMP scenario

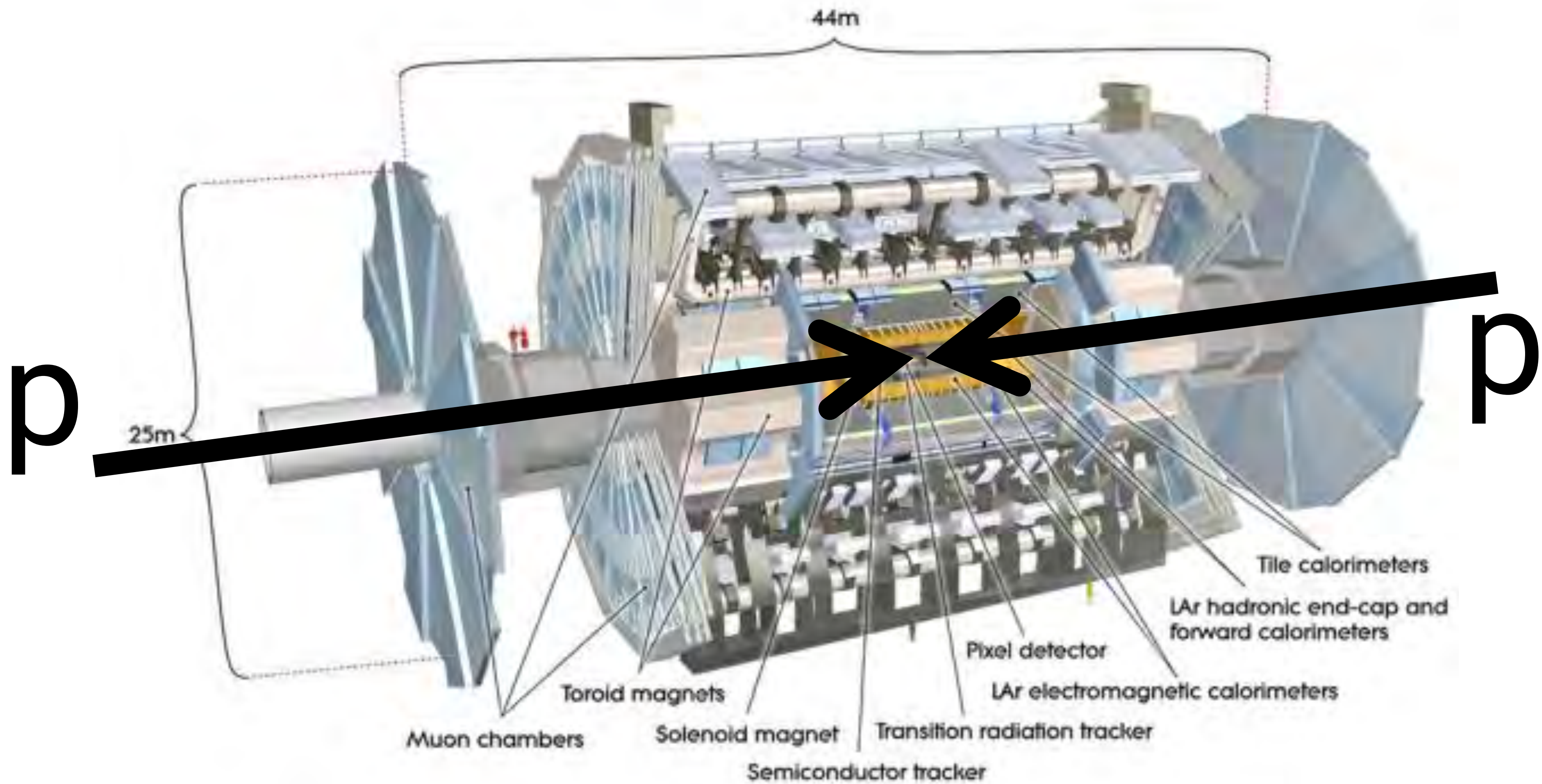


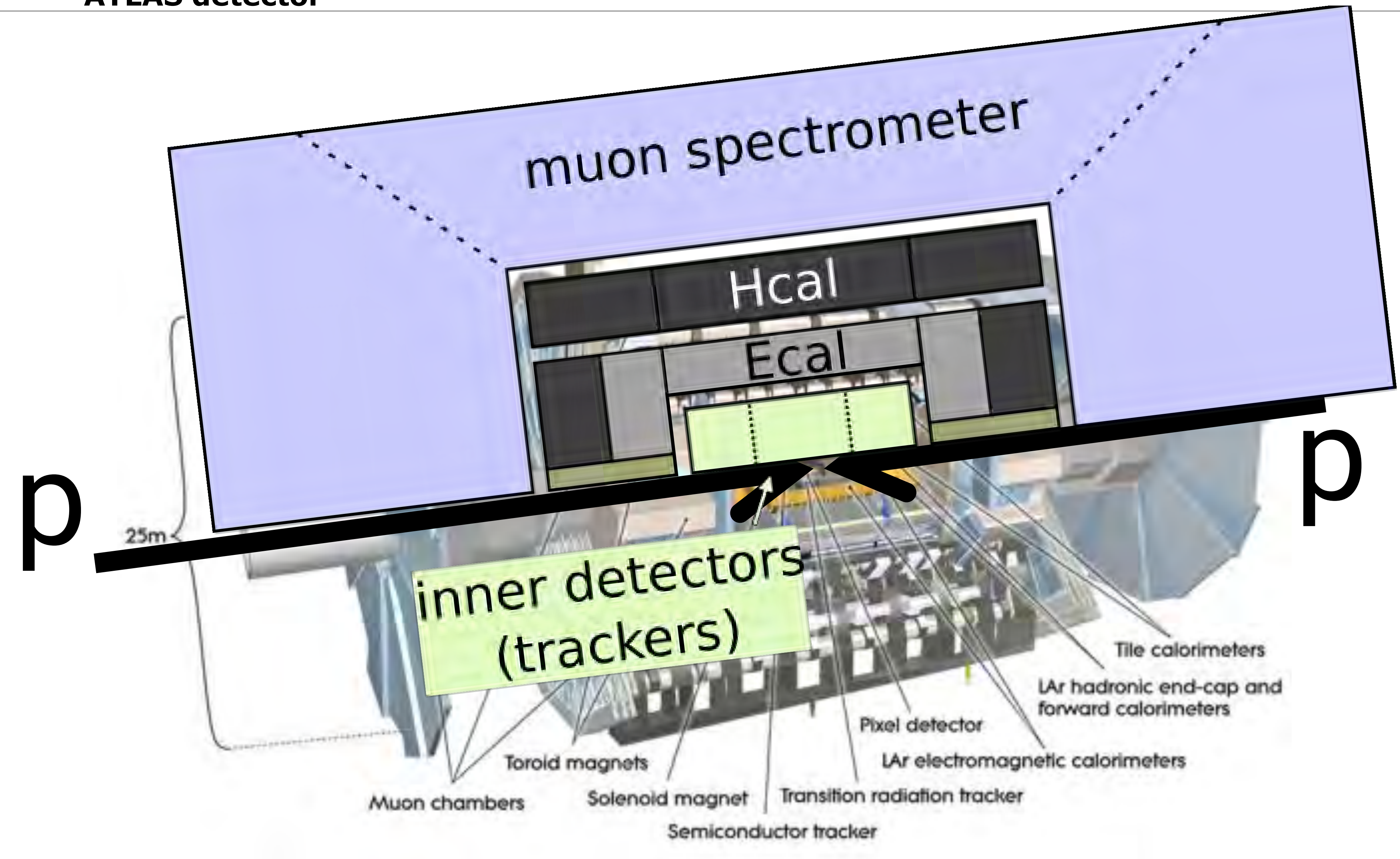


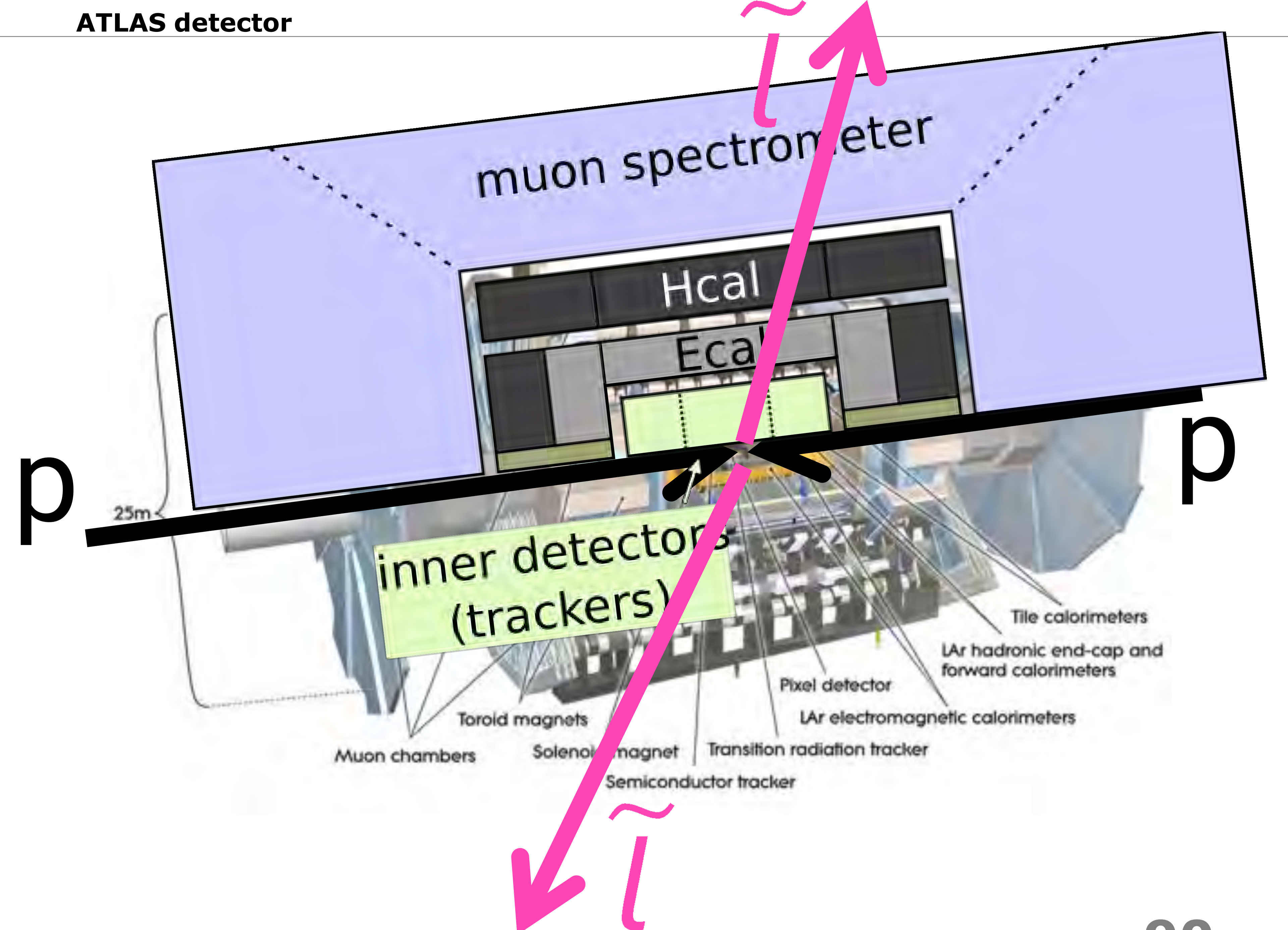
$$\langle \sigma v \rangle \approx \frac{4\pi\alpha^2}{m_{\tilde{l}_R}^2} + \frac{16\pi\alpha^2 m_{\tilde{B}}^2}{\cos^4\theta_W (m_{\tilde{l}_R}^2 + m_{\tilde{B}}^2)^2}$$

LLCP ($\tilde{\tau}$ as a working example)

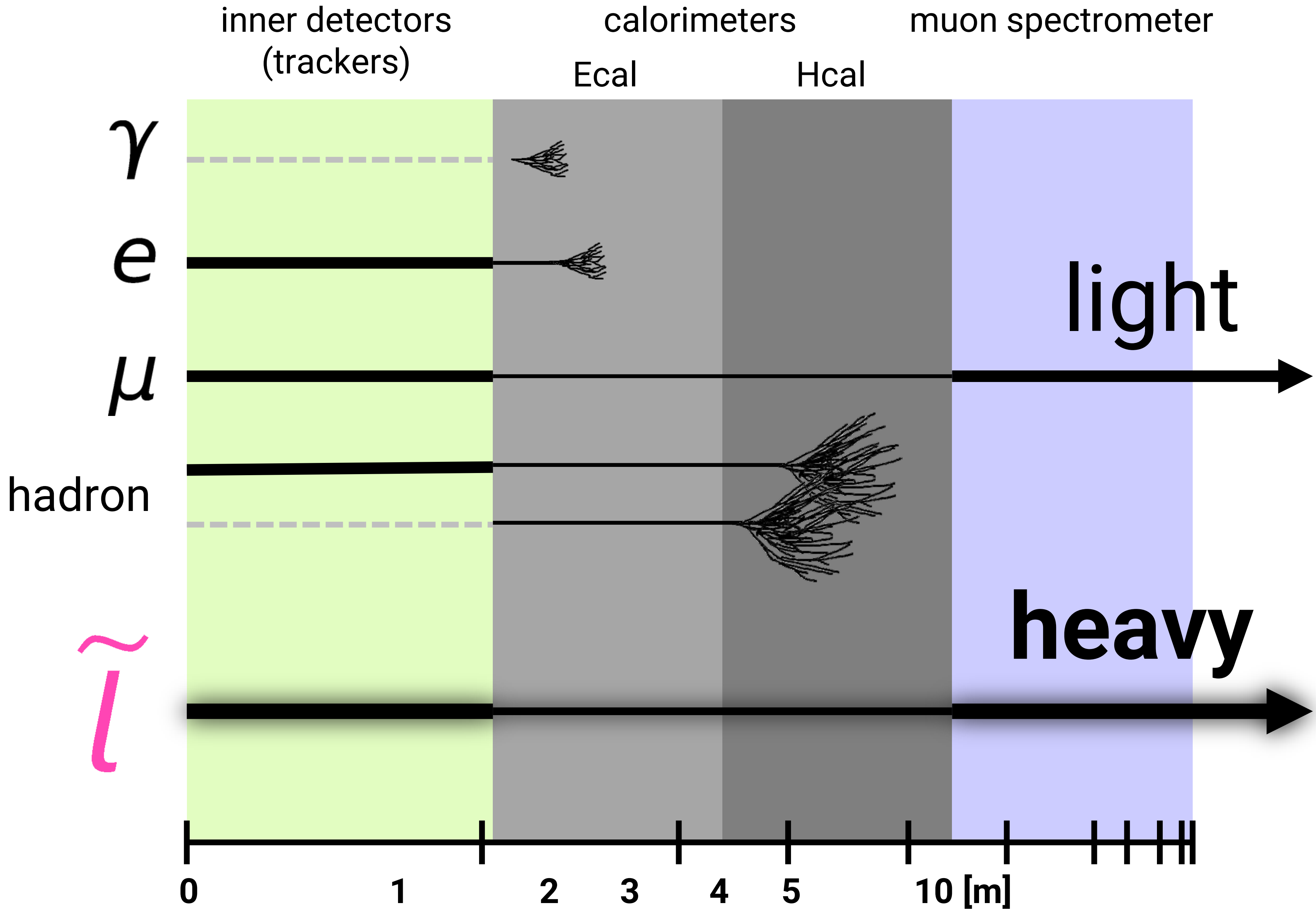
1. Motivations
2. How to detect?
3. Current and future


44m
25m
p
p
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Transition radiation tracker
Muon chambers
Solenoid magnet
Semiconductor tracker


muon spectrometer
Hcal
Ecal
inner detectors
(trackers)
p
p
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Transition radiation tracker
Muon chambers
Solenoid magnet
Semiconductor tracker



muon spectrometer
Hcal
Ecal
p
p
inner detectors
(trackers)
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Transition radiation tracker
Muon chambers
Solenoid magnet
Semiconductor tracker



inner detectors
(trackers)
calorimeters
Ecal
Hcal
muon spectrometer
γ
e
μ
hadron
$\tilde{l}$
light
heavy
0
1
2
3
4
5
10 [m]

$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

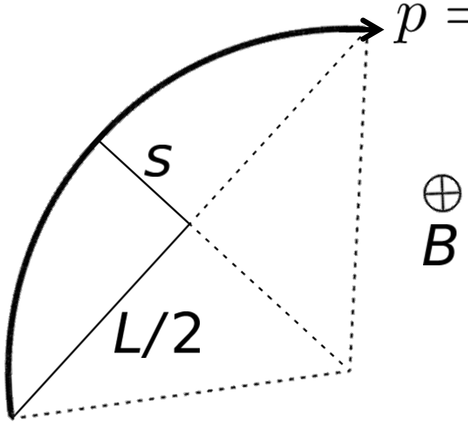
momentum & velocity

- **mass** measurement = ***p*** & ***β*** measurements

($\beta = v/c$)

- momentum

$$p = \frac{L^2}{8s}|q|B$$



- velocity
  - TOF [time-of-flight]

    $$\beta = \Delta L/\Delta t$$

  - d*E*/d*x* [ionization energy loss]

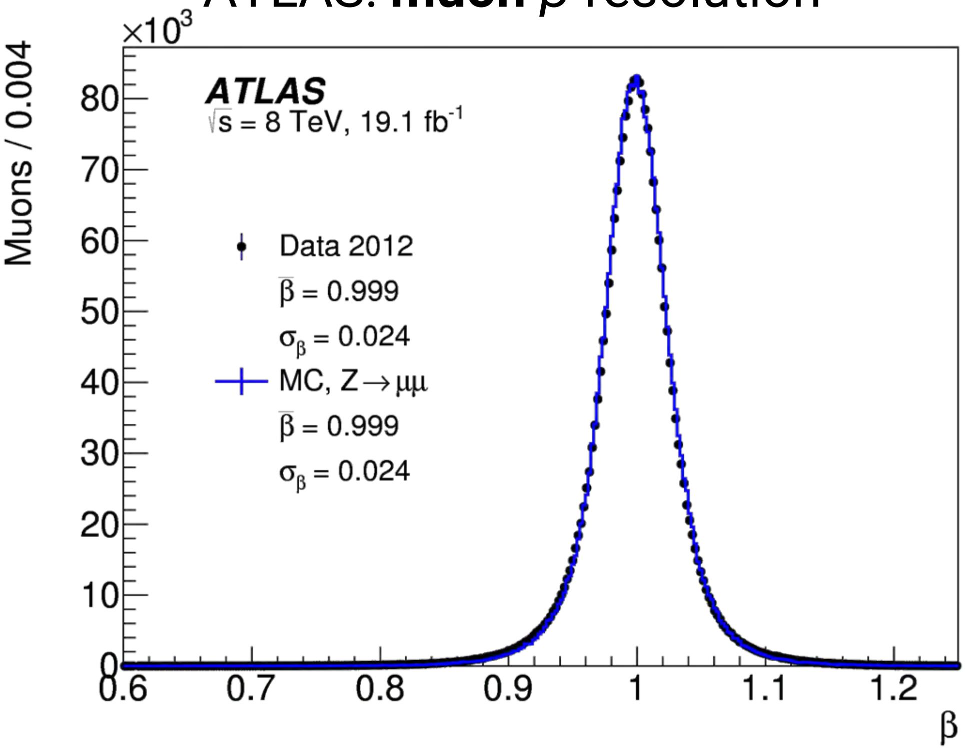
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

momentum & velocity

- **mass** measurement = ***p*** & ***β*** measurements

$(\beta = v/c)$

ATLAS: **muon** *β* resolution



➢ velocity

- TOF [time-of-flight]

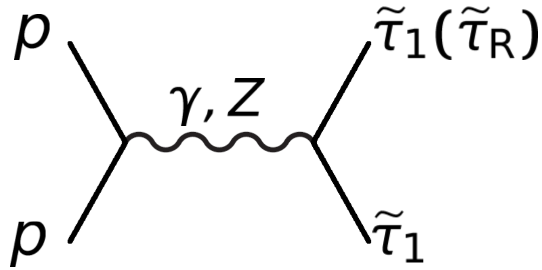
$$\beta = \Delta L/\Delta t$$

- d*E*/d*x* [ionization energy loss]

LLCP ($\tilde{\tau}$ as a working example)

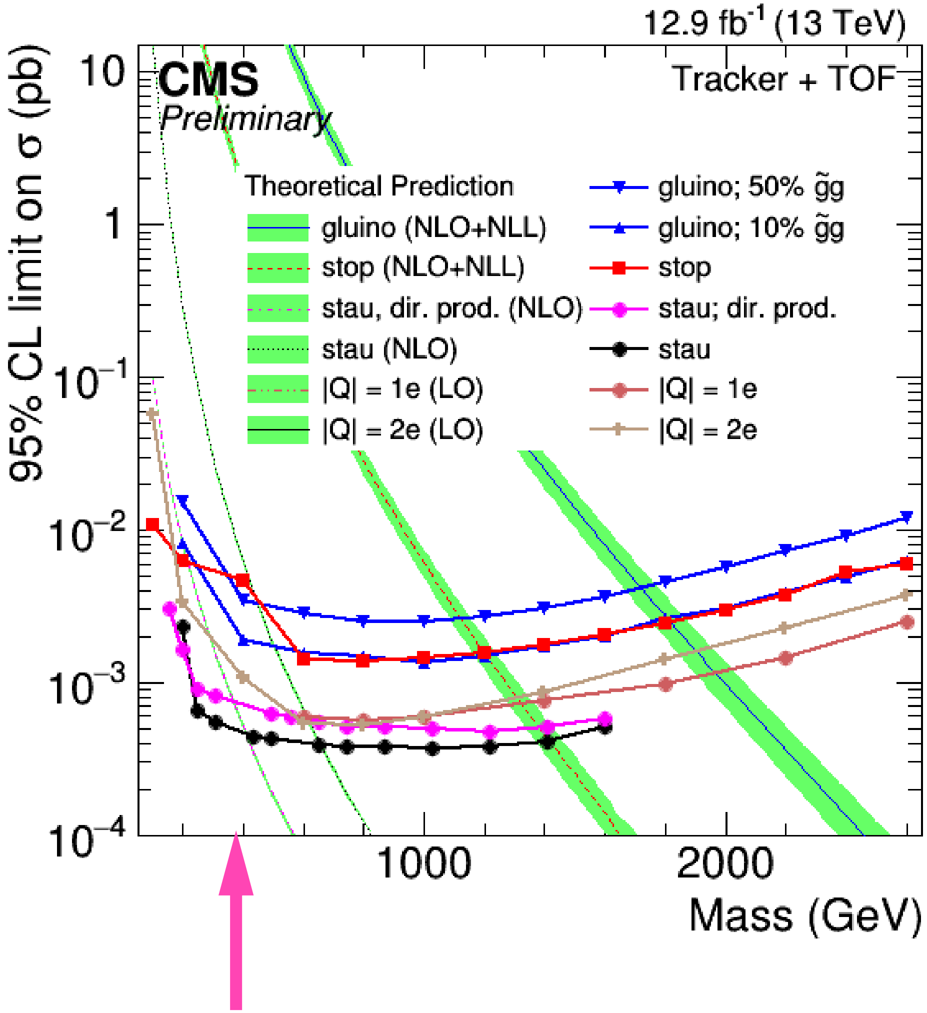
1. Motivations
2. How to detect?
3. Current and future

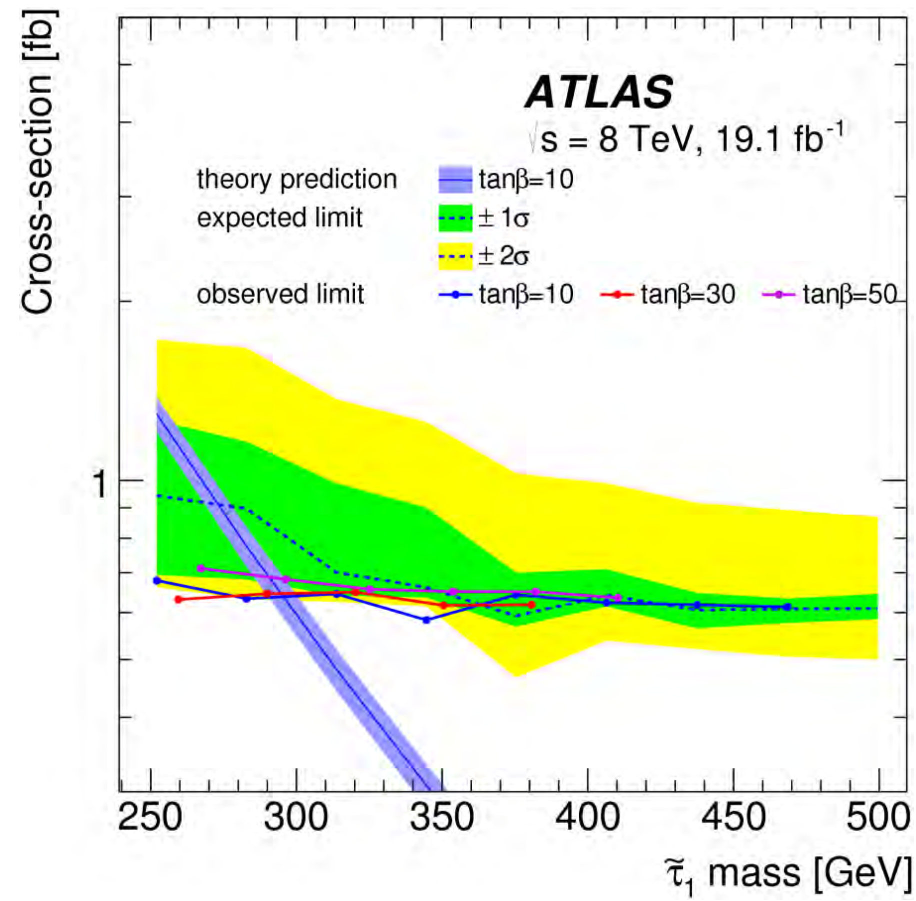
For



(**direct** production)

$$m(\tilde{\tau}_1) > \begin{cases} \text{360 GeV [CMS]} & \text{[CMS-PAS-EXO-16-036]} \\ \text{286 GeV [ATLAS]} & \text{[1411.6795]} \end{cases}$$



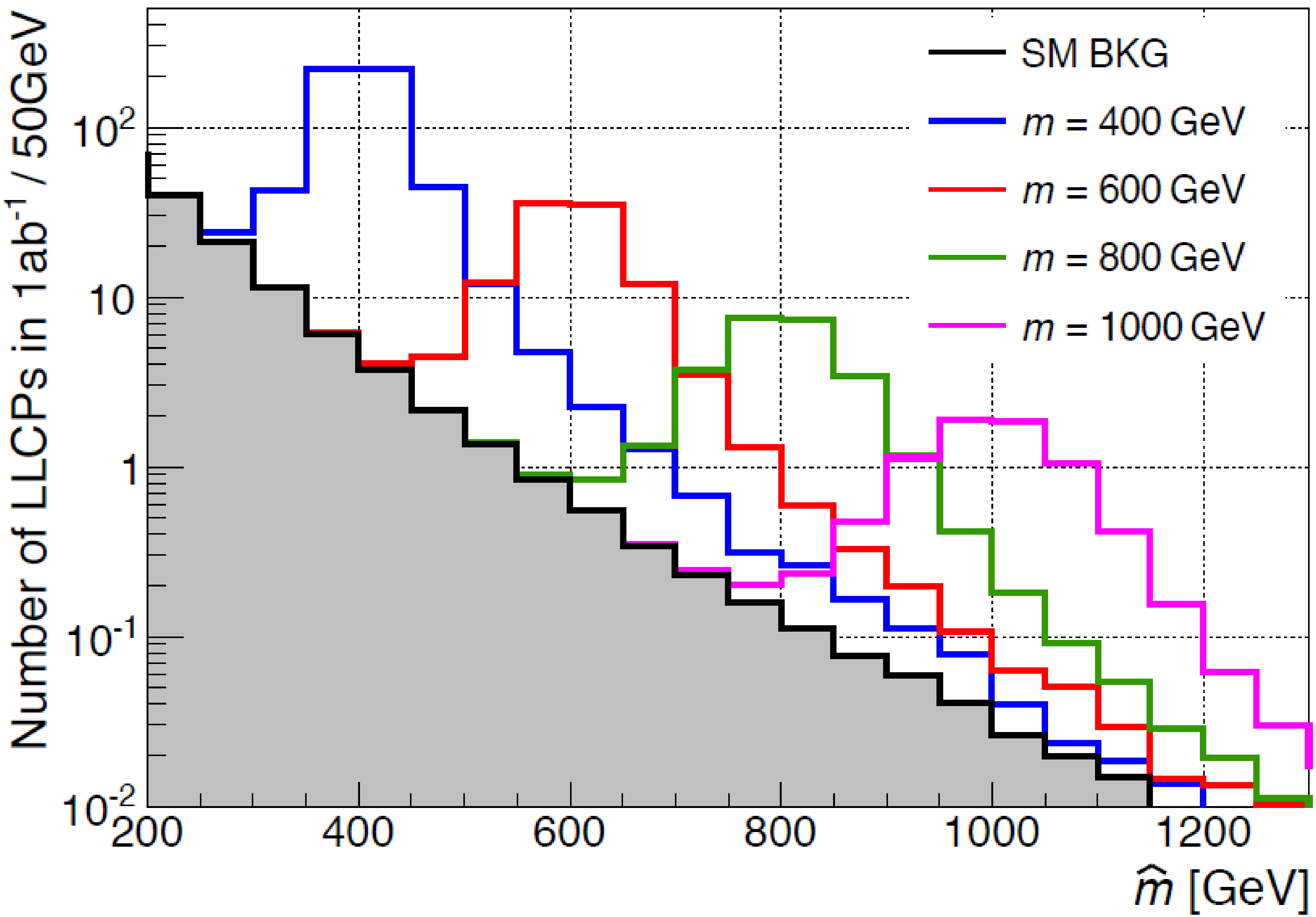


Feng, SI, Shadmi, Tarem [1505.02996]

- Detector
  - similar to ATLAS/CMS
  - β-resolution same as ATLAS (resolution: 2.4%)
- Signal: Madgraph5 + Pythia6 + Delphes3 (calculated at the LO)
- BKG: "Snowmass 2013" BKG set for **14** TeV (publicly available)
- Pile-up not considered

- $\tilde{l}$-selection flow

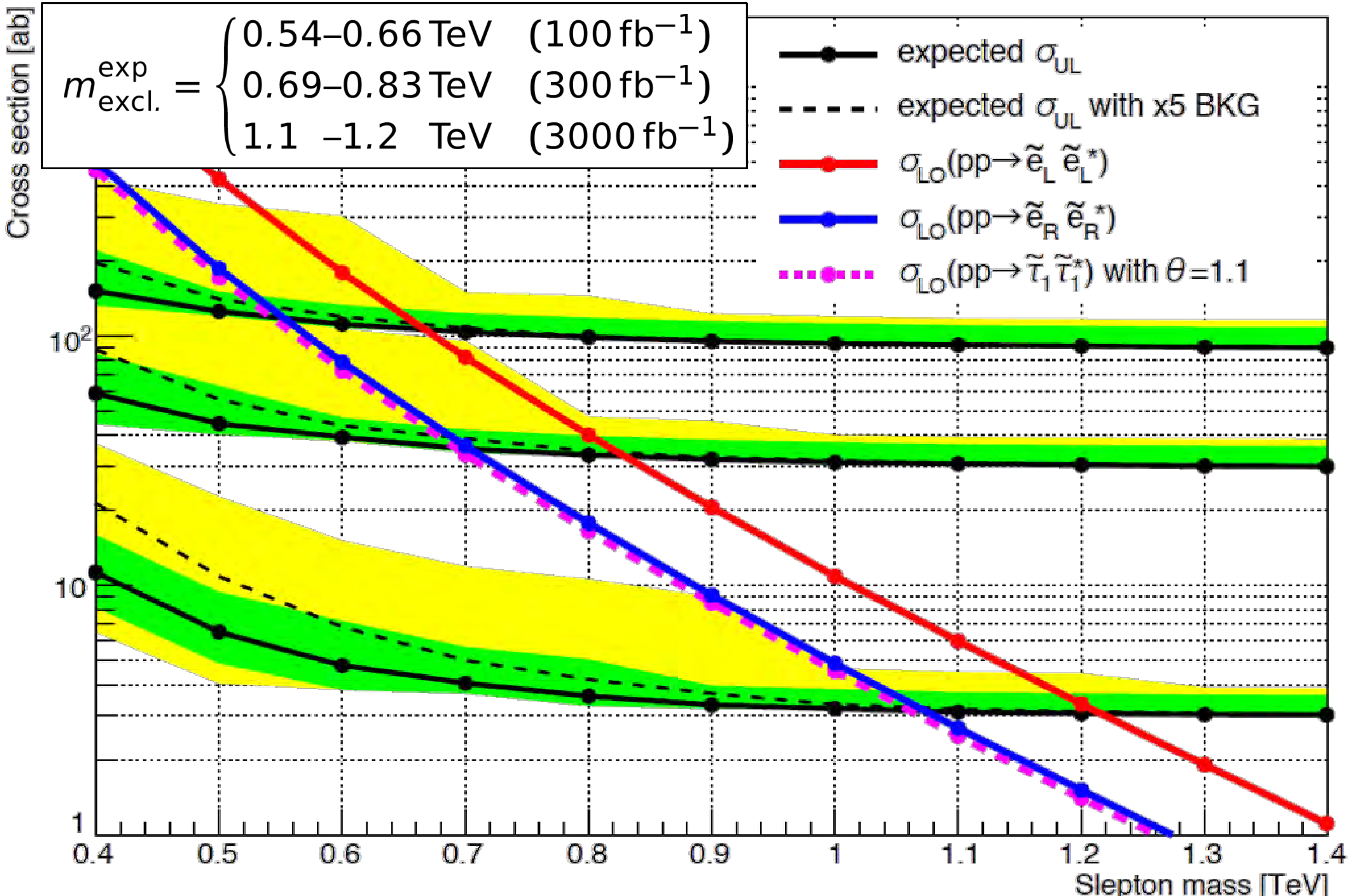
  reconstructed "muon" w.
  - $p_T >$ **100** GeV
  - $|\eta| < 2.4$
  - $0.3 < \hat{\beta} < 0.95$
- Event selection
  - two $\tilde{l}$-candidates



SM BKG
m = 400 GeV
m = 600 GeV
m = 800 GeV
m = 1000 GeV
Number of LLCPs in 1ab⁻¹ / 50GeV
10²
10
1
10⁻¹
10⁻²
200
400
600
800
1000
1200
m̂ [GeV]

14 TeV LHC expectation

14 TeV LHC prospects are also studied in [1106.0764] & [1203.1581] by J. Heisig and J. Kersten.

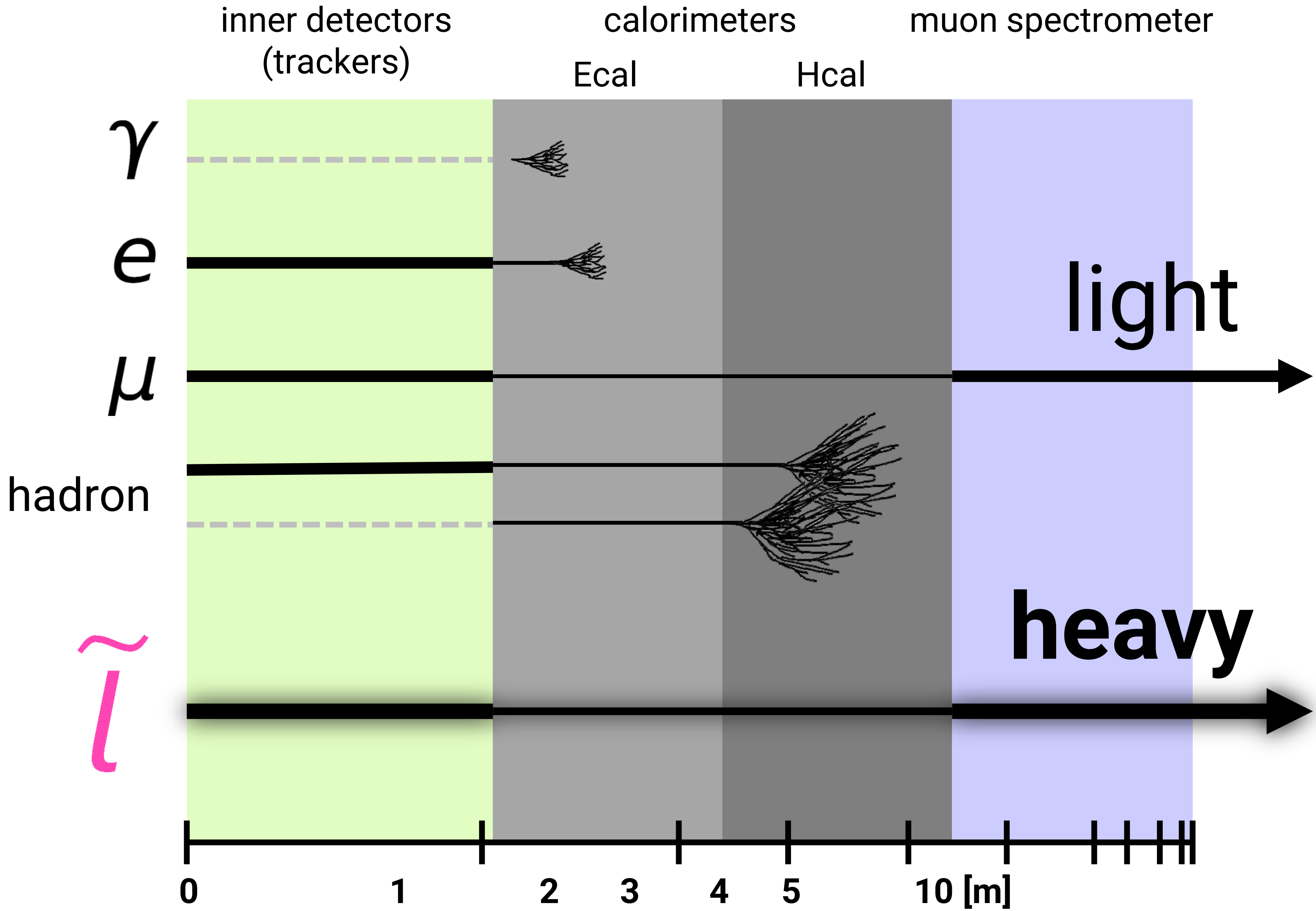


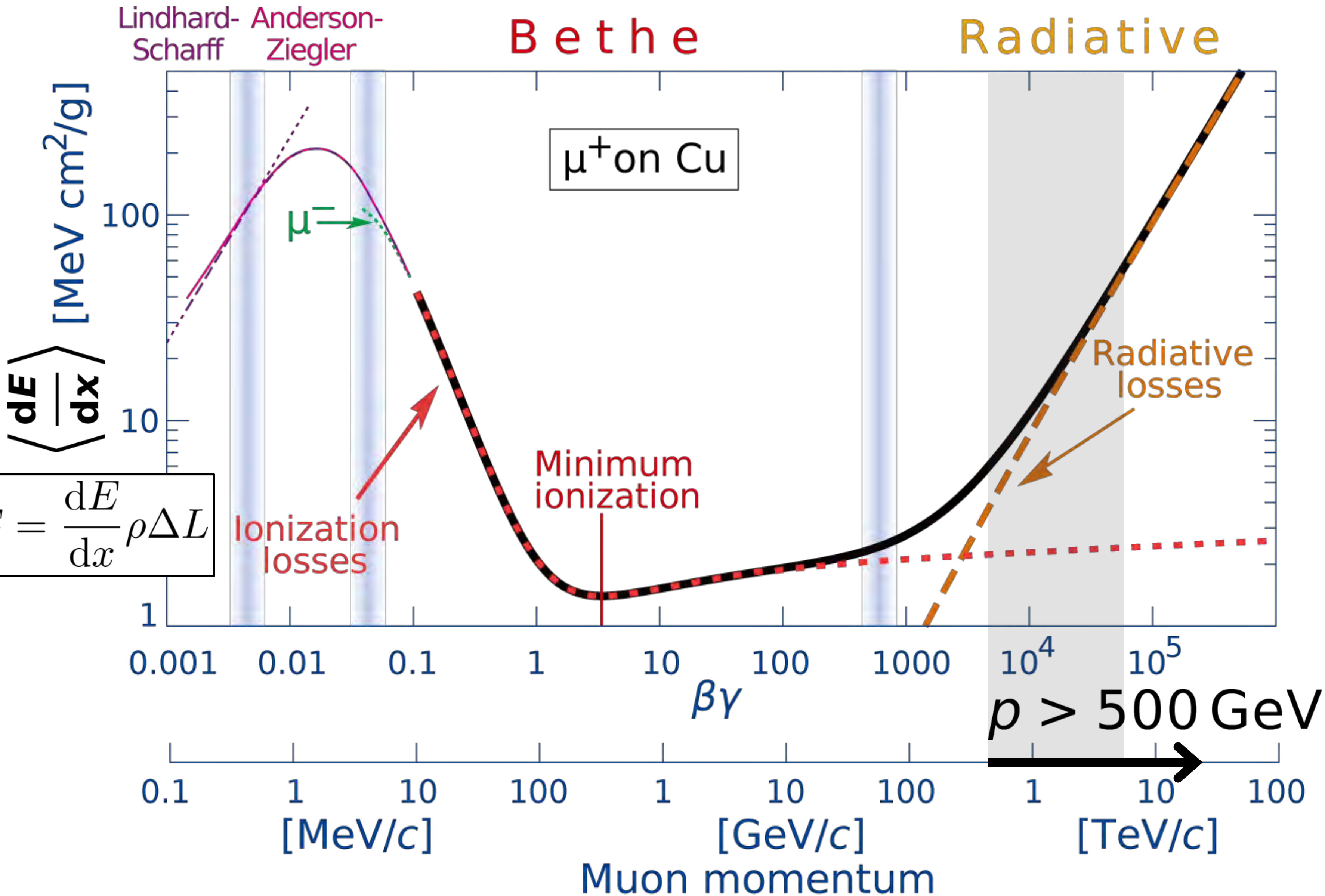
LLCP ($\tilde{\tau}$ as a working example)

1. Motivations

2. How to detect?

3. Current and future **and more**


inner detectors
(trackers)
calorimeters
Ecal
Hcal
muon spectrometer
γ
e
μ
hadron
$\tilde{l}$
light
heavy
0
1
2
3
4
5
10 [m]



$$\Delta E = \frac{\mathrm{d}E}{\mathrm{d}x}\rho\Delta L$$

Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

Muon radiative energy loss

- Bremsstrahlung
- Photonuclear interaction
- e^+-e^- pair-production

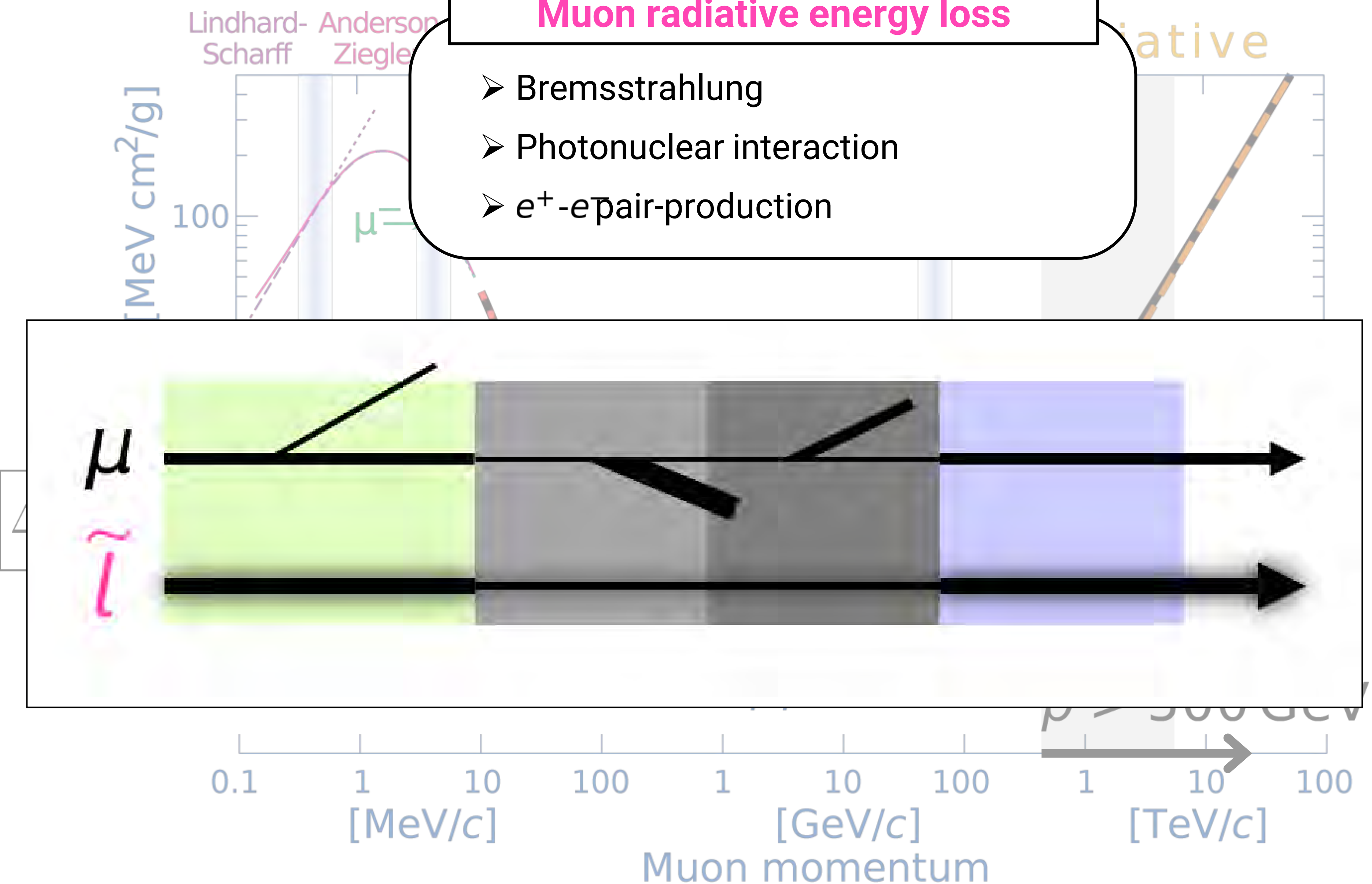
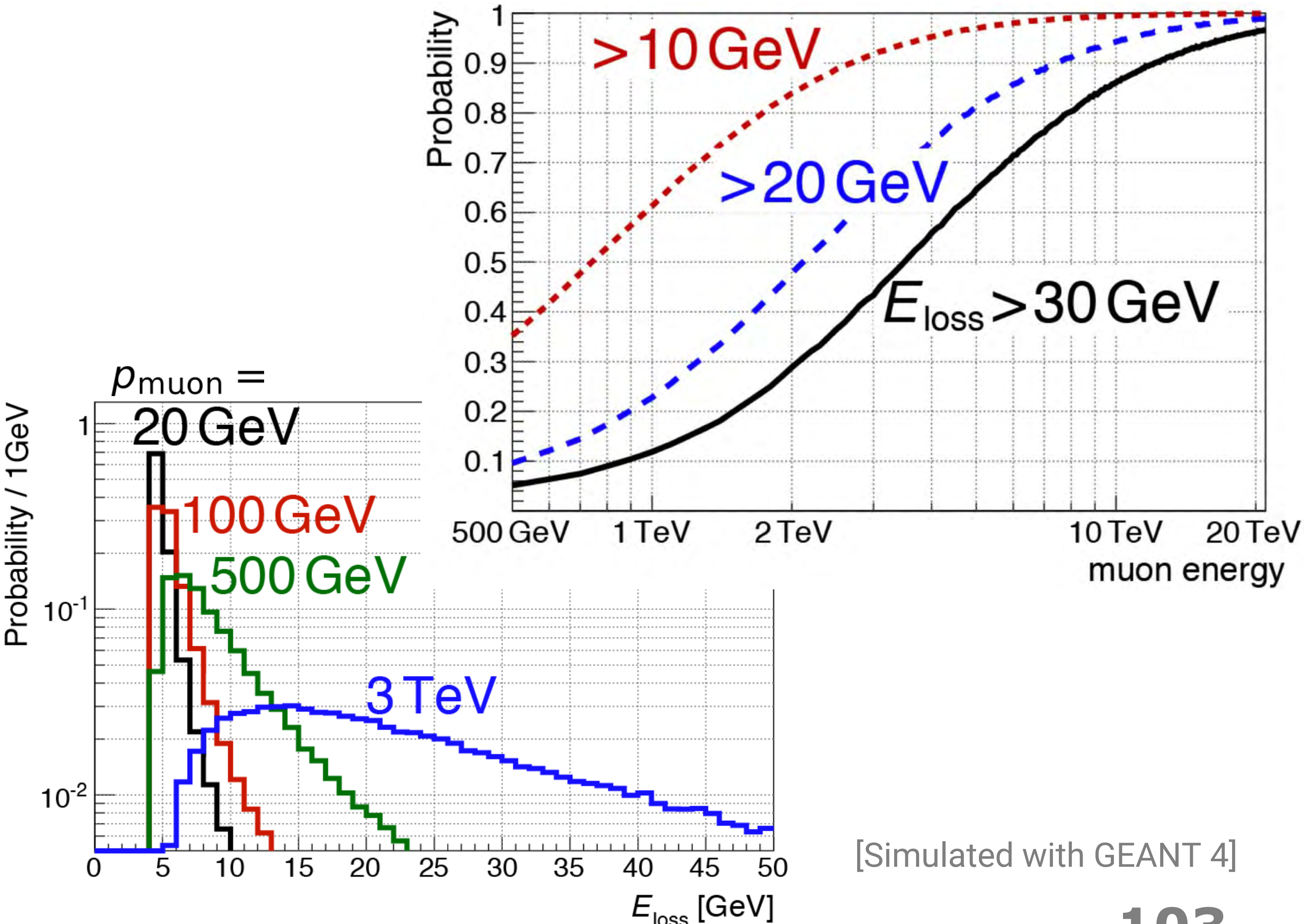


Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

Muon energy loss in 3m iron (Fe) "calorimeter"

Feng, SI, Shadmi, Tarem [1505.02996]



[Simulated with GEANT 4]

- Detector
  - similar to ATLAS/CMS
  - β-resolution same as ATLAS (resolution: 2.4%)
- Signal: Madgraph5 + Pythia6 + Delphes3 (calculated at the LO)
- BKG: "Snowmass 2013" BKG set for 100TeV (publicly available)
- Pile-up not considered

- $\tilde{l}$-selection flow

  reconstructed "muon" w.
  - $p_T > 500\,\mathrm{GeV}$
  - $|\eta| < 2.4$
  - $0.4 < \hat{\beta} < 0.95$
  - $E_{\mathrm{loss}} < 30\,\mathrm{GeV}$
- Event selection
  - two $\tilde{l}$-candidates

LLCP selection flow $(\int L = 1\,\mathrm{ab}^{-1})$

	signal $\tilde{l} = 1$ TeV	signal 3 TeV	SM BKG
total	2570	31.8	—
p_T & η	1840	28.5	9.19×10^6
β	1230	24.6	3.41×10^5
E_{loss}	1230	24.6	2.78×10^5
$\epsilon_{\mathrm{acc}}\epsilon_{\mathrm{eff}}$	48%	77%	—

Event categorization $(\int L = 1\,\mathrm{ab}^{-1})$

	1 TeV	3 TeV	BKG
$N_{\mathrm{LLCP}} = 0$	483	1.34	(a lot)
$N_{\mathrm{LLCP}} = 1$	378	4.46	2.78×10^5
$N_{\mathrm{LLCP}} = 2$	424	10.1	34.6

SR

- $\tilde{l}$-selection flow

  reconstructed "muon" w.

  - $p_T > 500\,\mathrm{GeV}$
  - $|\eta| < 2.4$
  - $0.4 < \hat{\beta} < 0.95$
  - $E_{\mathrm{loss}} < 30\,\mathrm{GeV}$

- Event selection
  - two $\tilde{l}$-candidates

Feng, SI, Shadmi, Tarem [1505.02996]

LLCP selection flow ($\int L = 1\,\mathrm{ab}^{-1}$)

	signal $\tilde{l} = 1$ TeV	signal 3 TeV	SM BKG
total	2570	31.8	—
p_T & η	1840	28.5	9.19×10^6
β	1230	24.6	3.41×10^5
E_{loss}	1230	24.6	2.78×10^5
$\epsilon_{\mathrm{acc}}\epsilon_{\mathrm{eff}}$	48%	77%	—

$\times 0.82$

E_{loss} reduces **34%** of BKG ($\because\ 0.82^2 = 0.66$)

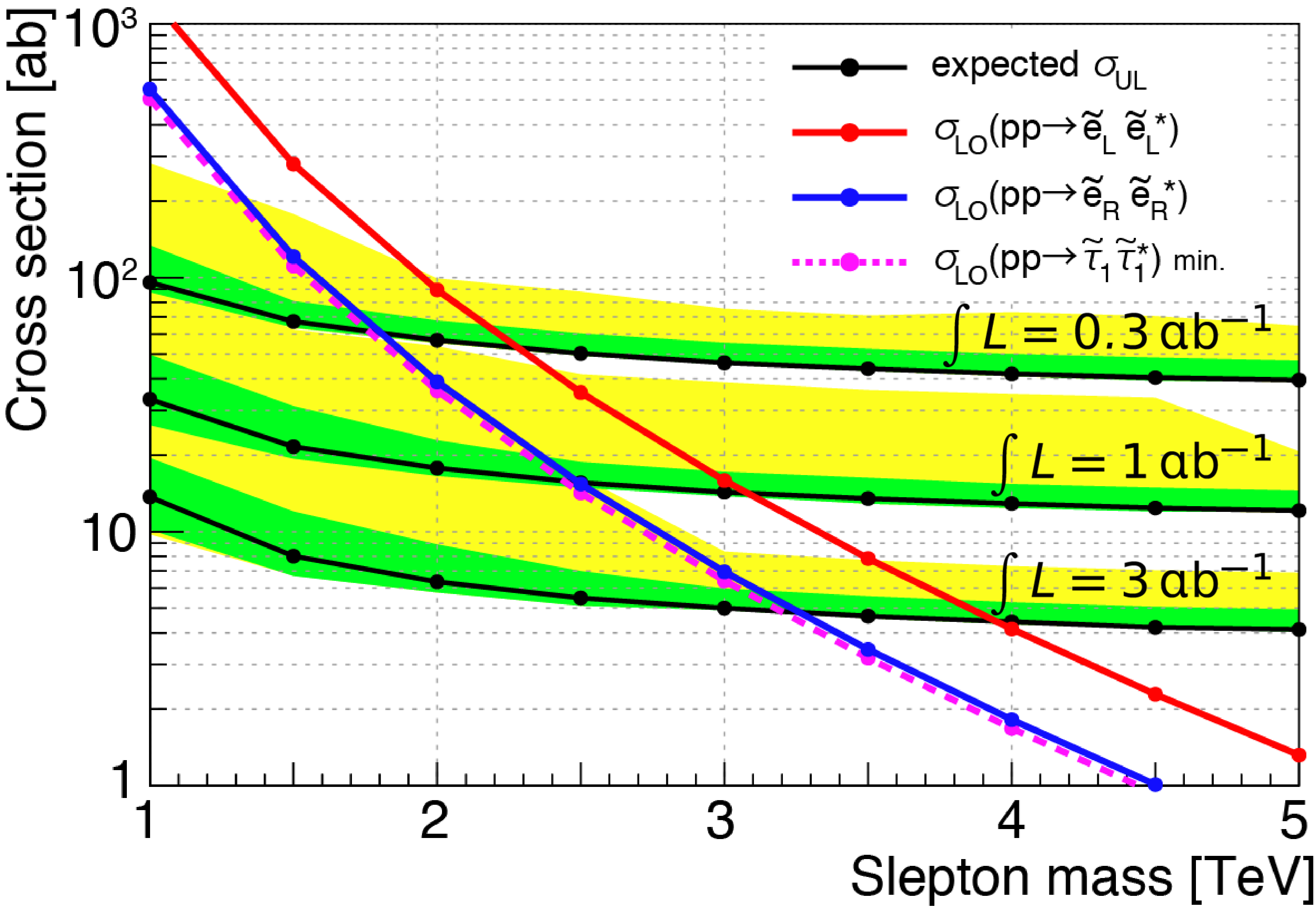
- $|\eta| < 2.4$
- $0.4 < \hat{\beta} < 0.95$
- $E_{\mathrm{loss}} < 30\,\mathrm{GeV}$

Event categorization ($\int L = 1\,\mathrm{ab}^{-1}$)

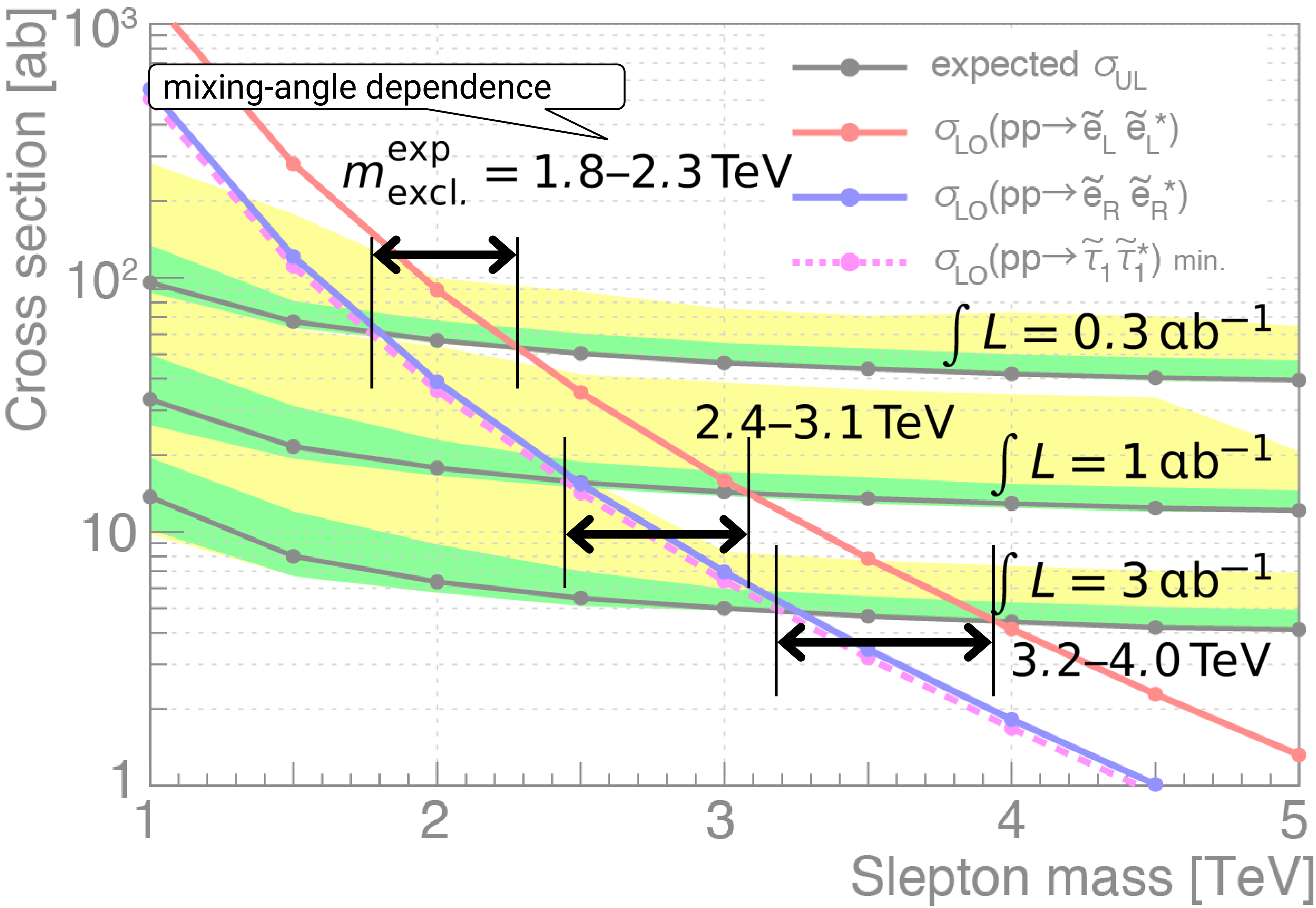
	1 TeV	3 TeV	BKG
$N_{\mathrm{LLCP}} = 0$	483	1.34	(a lot)
$N_{\mathrm{LLCP}} = 1$	378	4.46	2.78×10^5
$N_{\mathrm{LLCP}} = 2$	424	10.1	34.6

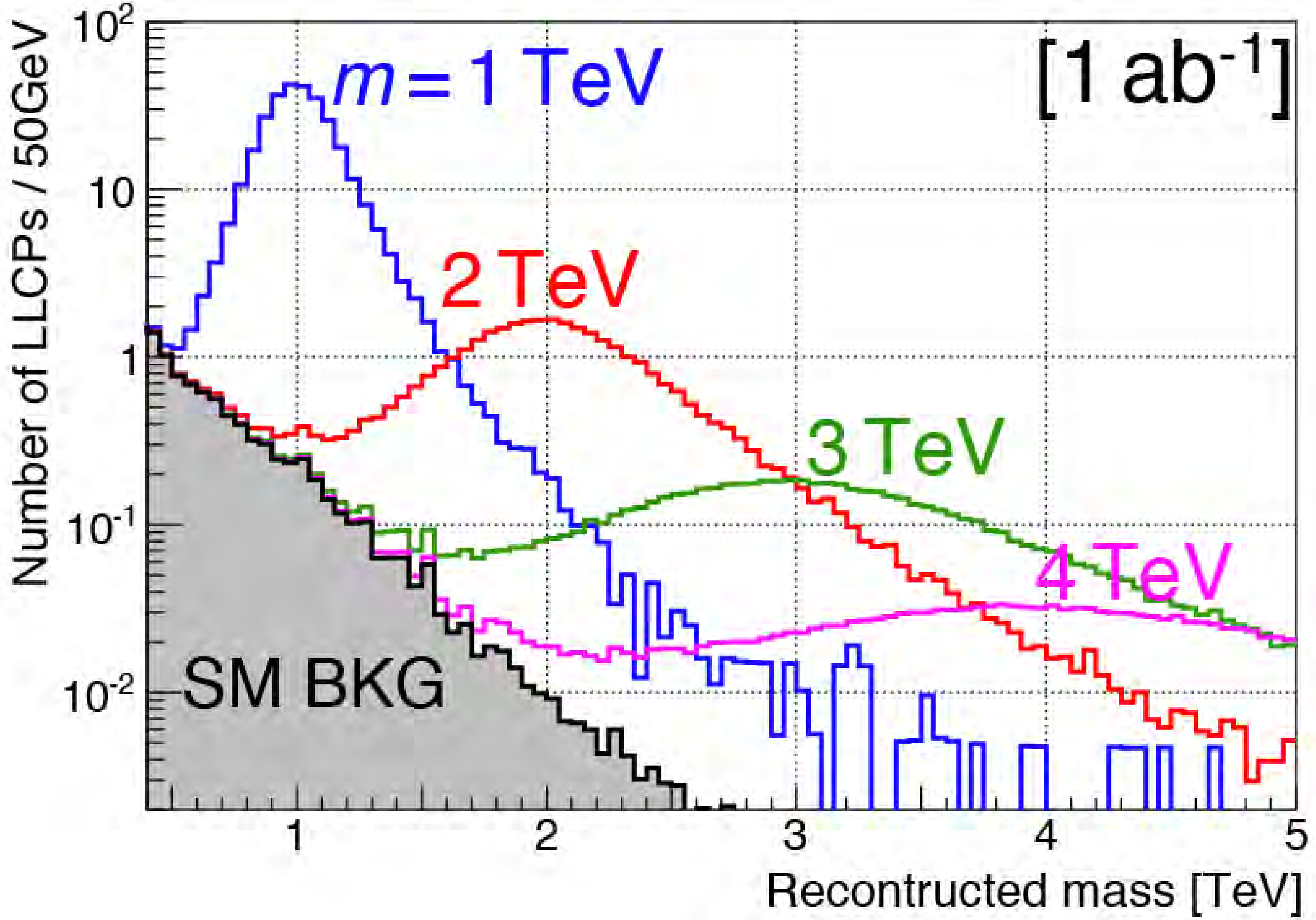
SR

- Event selection
  - two $\tilde{l}$-candidates


Cross section [ab]
10^3
10^2
10
1
expected σ_{UL}
$\sigma_{LO}(pp \to \tilde{e}_L \tilde{e}_L^*)$
$\sigma_{LO}(pp \to \tilde{e}_R \tilde{e}_R^*)$
$\sigma_{LO}(pp \to \tilde{\tau}_1 \tilde{\tau}_1^*)$ min.
$\int L = 0.3\,\mathrm{ab}^{-1}$
$\int L = 1\,\mathrm{ab}^{-1}$
$\int L = 3\,\mathrm{ab}^{-1}$
1
2
3
4
5
Slepton mass [TeV]

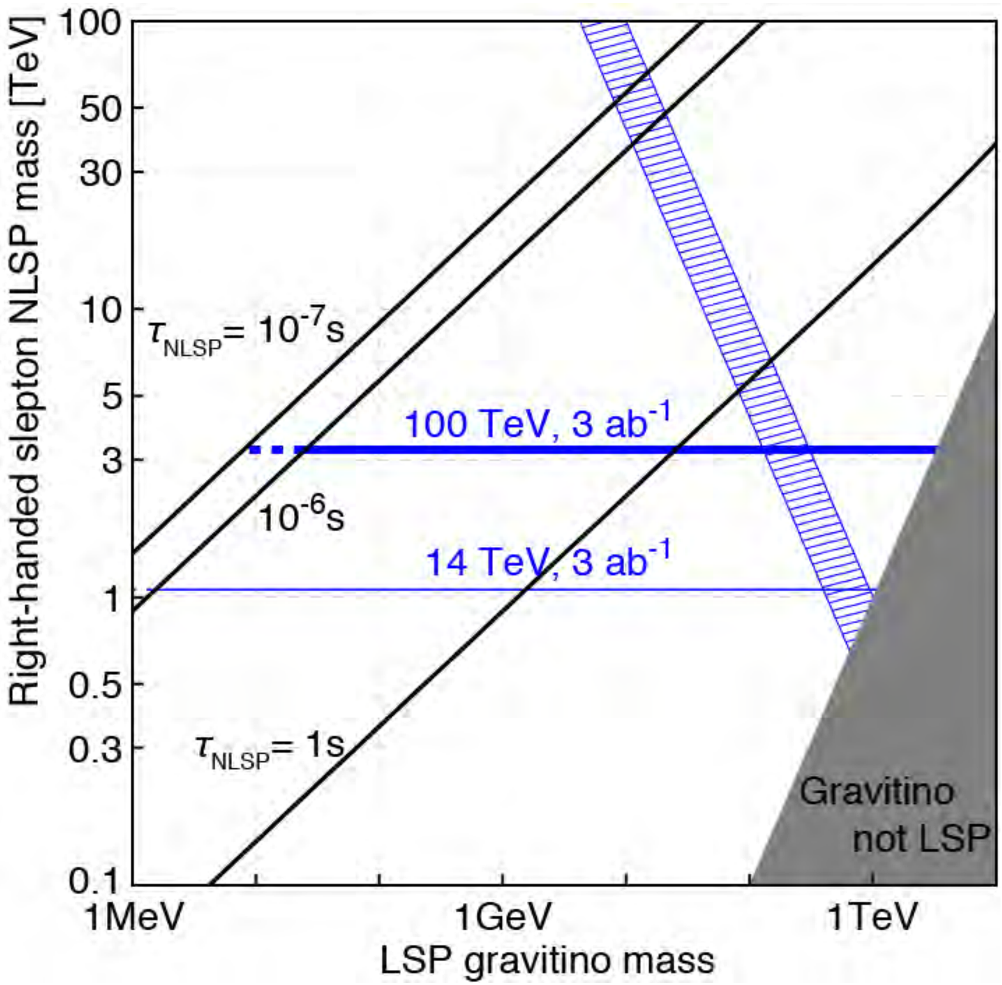
Feng, SI, Shadmi, Tarem [1505.02996]





$$\left(= \frac{p}{\beta\gamma} = \frac{p_{\rm T}\cosh\eta}{\beta\gamma} \right)$$

- SuperWIMP scenario



- $\tilde{B}$–$\tilde{l}$ co-annihilation

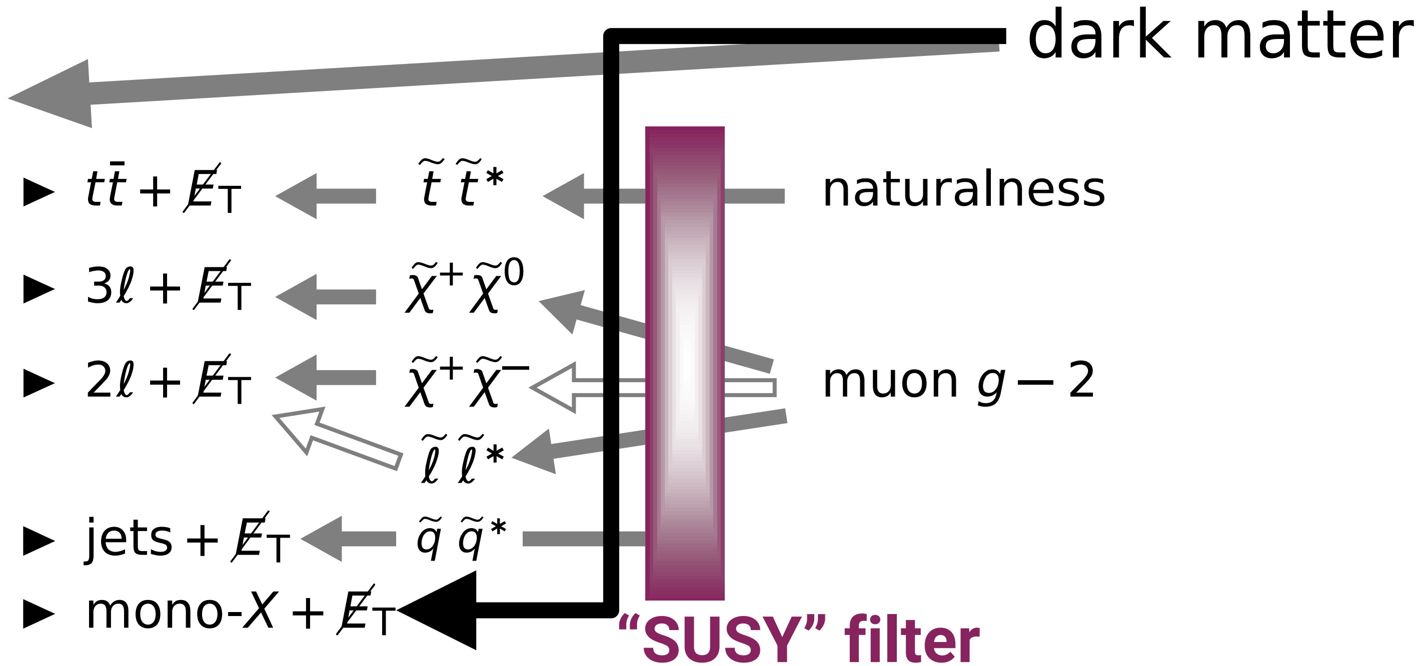
... $m_{\tilde{l}} \lesssim 700\,\text{GeV}$

will covered @ LHC

$$14\,\text{TeV}: \begin{cases} 0.54\text{–}0.66\,\text{TeV} & (0.1\,\text{ab}^{-1}) \\ 0.69\text{–}0.83\,\text{TeV} & (0.3\,\text{ab}^{-1}) \\ 1.1\ \text{–}1.2\ \ \text{TeV} & (3\,\text{ab}^{-1}) \end{cases}$$

$$100\,\text{TeV}: \begin{cases} 1.8\text{–}2.3\,\text{TeV} & (0.3\,\text{ab}^{-1}) \\ 2.4\text{–}3.1\,\text{TeV} & (1\,\text{ab}^{-1}) \\ 3.2\text{–}4.0\,\text{TeV} & (3\,\text{ab}^{-1}) \end{cases}$$

1) $\not{E}_T$



2) LLCP ← cosmology (Ωh^2, Li)

- co-annihilation in coming years!

  (R-hadron, displaced vertex, disappearing track, ...)

(ph/0511034, 1403.0715, 1409.4533,1504.00504, 1506.08206, ...)

3) more exotic

"Exotic" searches by ATLAS + CMS

Log In
CMSPublic

CMSPublic Web
CMSPrivate Web
Create New Topic
Index
Search
Changes
Notifications
Statistics
Preferences

Create a LeftBar

Public webs

Jump | Search | CMS | All webs

TWiki > CMSPublic Web > PhysicsResults > PhysicsResultsEXO (2016-10-12, SlavaValuev)

Edit | Attach | Pr

CMS Exotica Public Physics Results

This page is still maintained on a best-effort basis, but please see the official CMS Publications page for the fully up-to-date list of results

CMS EXO Conveners

- Oliver Buchmueller, Slava Valuev

CMS EXO Summary Plots

- **EXO Summary for ICHEP 2016** NEW :
  - Resonances, extra dimensions, etc.: pdf, png
  - Searches for long-lived particles: pdf, png
  - Searches for dark matter: pdf

Journal Publications - Run 2

Analysis	ArXiv Entry	Luminosity	Publication Status	Approved Plots
Search for high-mass Zγ resonances in $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ final states at 8 and 13 TeV NEW	arXiv:1610.02960	2.7 fb^{-1} (2015) + 19.7 fb^{-1} (Run I)	Submitted to JHEP	EXO-16-02
Search for long-lived charged particles NEW	arXiv:1609.08382	2.5 fb^{-1} (2015)	Submitted to Phys. Rev. D	EXO-15-01
Search for narrow resonances in dilepton mass spectra at 13 TeV and combination with 8 TeV data NEW	arXiv:1609.05391	2.9 fb^{-1} (2015) + 19.7 fb^{-1} (Run I)	Submitted to Phys. Lett. B	EXO-15-00
Search for high-mass diphoton resonances at 13 TeV and combination with 8 TeV search NEW	arXiv:1609.02507	12.9 fb^{-1} (2016) + 3.3 fb^{-1} (2015) + 19.7 fb^{-1} (Run I)	Submitted to Phys. Lett. B	EXO-16-02
Search for resonant production of high-mass photon pairs at 8 and 13 TeV	arXiv:1606.04093	3.3 fb^{-1} (2015) + 19.7 fb^{-1} (Run I)	10.1103/PhysRevLett.117.051802	EXO-16-01
Search for narrow resonances decaying to dijets	arXiv:1512.01224	2.4 fb^{-1} (2015)	10.1103/PhysRevLett.116.071801	EXO-15-00

Preliminary Results - 2016 Run

Analysis	Approved Plots	CDS Entry	Luminosi

AtlasPublic Web | Physics Groups | Summary Plots | Other Groups | Account

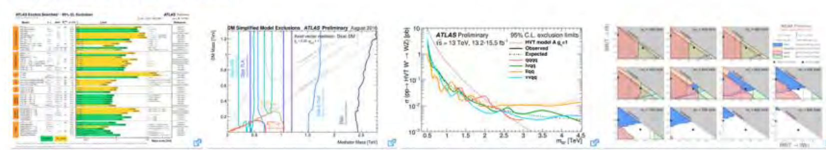
Jump | Search | Atlas | All webs | Edit | Attach

ATLAS EXPERIMENT - Public Results

Exotics Public Results

This page contains results approved for public presentations from the ATLAS Exotics group. Only this material is approved for showing in public by speakers from ATLAS or other collaborations. In case of doubt, please contact the group conveners: Klaus Moenig and Gabriel Facini and or email atlas-phys-exotics-conveners.

Exotics summary plots



Results based on the 13 TeV 2015/2016 Data Taking Period

Conference Notes with 2015/2016 data

Title	Conference Note and Plots	Int. luminosity	Date
Search for new phenomena in $t\bar{t}$ final states with additional heavy-flavour jets in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector NEW	ATLAS-CONF-2016-104	13.3/fb	Sep 2016
Search for pair production of heavy vector-like quarks decaying to high-p_T W bosons and b quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector NEW	ATLAS-CONF-2016-102	13.3/fb	Sep 2016

■ List of 13 TeV EXO results (ATLAS-EXO, CMS-EXO, CMS-B2G)

DM searches

- Search for dark matter and extra dimensions in photon+MET final state
- Search for dark matter and large extra dimensions in photon+MET final state
- Search for dark matter in final states with an energetic jet or a hadronically decaying W or Z boson
- Search for dark matter in H(bb)+MET final state
- Search for dark matter in H(γγ)+MET final state
- Search for dark matter in top(had)+MET final state
- Search for dark matter in ttbar+MET final state
- Search for dark matter in Z(ll)+MET final state
- Search for dark matter produced in association with a hadronically decaying vector boson in pp collisions at √s =13 TeV with t
- Search for dark matter produced in association with bottom quarks
- Search for dark matter production in association with jets, or hadronically decaying W or Z boson

Resonances

- Search for diboson resonance production in the lnuqq final state using pp collisions at √s=13 TeV with the ATLAS detector at t
- Search for diboson resonances in the llqq final state in pp collisions at √s = 13 TeV with the ATLAS detector
- Search for diboson resonances in the vvqq final state in pp collisions at √s = 13 TeV with the ATLAS detector
- Search for heavy ZZ and ZW resonances in the llqq and vvqq final states in pp collisions at √s=13 TeV with the ATLAS detector
- Search for heavy diboson resonances in pp coll… …tector
- Search for heavy neutral resonances in vector … 13 TeV with the ATLAS detector at the Larg
- Search for heavy resonances decaying to a Z boson and a photon in pp collisions at √s =13 TeV with the ATLAS detector
- Search for high-mass diphoton resonances at 13 TeV and combination with 8 TeV search
- Search for high-mass resonances and quantum black holes in the eμ final state
- Search for high-mass resonances decaying to a pair of taus
- Search for high-mass resonances in dilepton final states
- Search for high-mass resonances in Z(ll)γ final state
- Search for high-mass resonances in Z(qq)γ final state
- Search for high-mass Zγ resonances in e+e-γ and μ+μ-γ final st
- Search for light dijet resonances with the ATLAS detector usi
- Search for low-mass resonances decaying to boosted jets
- Search for narrow resonances decaying to dijets
- Search for narrow resonances in dilepton mass spectra at 13 Te
- Search for new high-mass resonances in the dilepton final stat
- Search for new light resonances decaying to jet pairs and proc
- Search for new light resonances decaying to jet pairs and proc
- Search for resonances decaying into pairs of boosted W and Z b
- Search for Resonances Decaying to a W or Z Boson and a Higgs B
- Search for resonances in diphoton events
- Search for resonances in the mass distribution of jet pairs wi
- Search for resonances with boson-tagged jets in 15.5/fb of pp
- Search for resonant production of high-mass photon pairs at 8
- Search for WW/WZ resonance production in the lvqq final state
- Search for scalar diphoton resonances with 15.4/fb of data col
- Search for new resonances decaying to a charged lepton and a r
- Search for new resonances decaying to a W or Z boson and a Hig
- Search for new resonances in events with one lepton and missir
- Search for heavy particles decaying to pairs of highly-boostec

LLCP and new signature

- Search for long-lived charged particles
- Search for long-lived neutral particles decaying in the hadronic calorimeter of ATLAS at √s = 13 TeV in 3.2 fb-1 of data new.jpg
- Search for long-lived neutral particles decaying … 3 TeV with the ATLAS detector
- Search for displaced leptons in eμ final state
- Search for heavy stable charged particles

"new phenomena" (signature based)

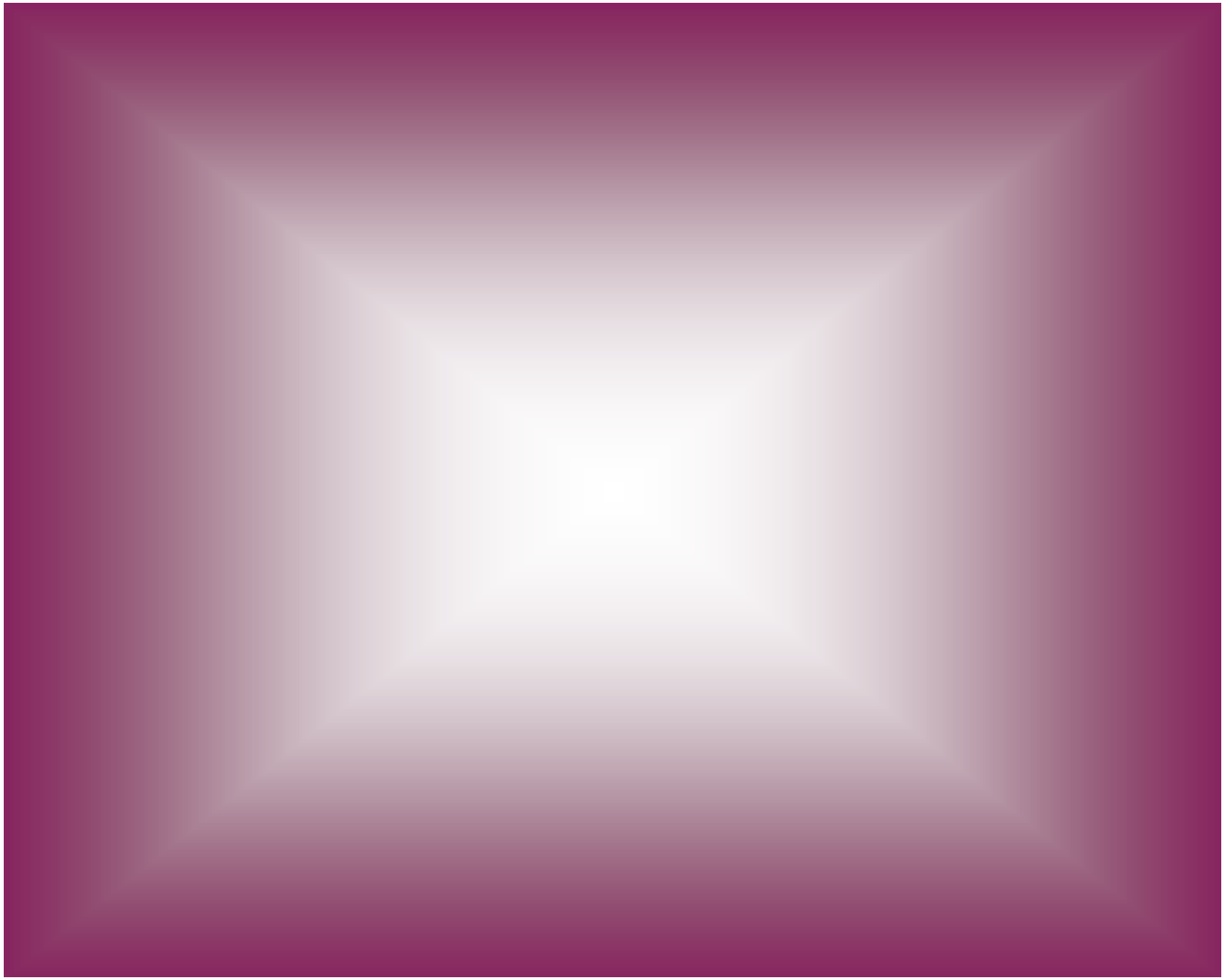
- Search for beyond the Standard Model phenomena in eμ final states in pp collisions at √s = 13 TeV with the ATLAS detector
- Search for new phenomena in different-flavour high mass dilepton final states in pp collisions at a centre-of-mass energy of 13 TeV with the ATLAS det
- Search for new phenomena in dijet events collected in 2015 and 2016 pp collisions with the ATLAS detector at √s=13 TeV
- Search for new phenomena in dijet mass and angular distributions from pp collisions at √s = 13 TeV with the ATLAS detector
- Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at √s = 13 TeV with the ATLAS detector
- Search for new phenomena in final … the ATLAS detect
- Search for new phenomena … coll…
- Search for new phenomena in tt final states with additional heavy-flavour jets in pp collisions at √s=13 TeV with the ATLAS detector new.jpg
- Search for new phenomena using events with b-jets and a pair of same-charge leptons in 3.2 fb-1 of pp collisions at √s=13 TeV with the ATLAS detector
- Search for new phenomena with photon+jet events in proton-proton collisions at √s = 13 TeV with the ATLAS detector
- Search for high-mass new phenomena in the dilepton final state using proton--proton collisions at √s =13 TeV with the ATLAS detector

OTHERS

- Search for black holes
- Search for doubly-charged Higgs bosons in same-charge electron pair final states using proton-proton collisions at √s=13 TeV with the ATLAS detector
- Search for evidence for strong gravity in jet final states produced in pp collisions at √s = 13 TeV using the ATLAS detector at the LHC
- Search for excited leptons in ℓℓγ final state
- Search for excited quarks in γ+jet final state
- Search for four-top-quark production in final states with one charged lepton and multiple jets using 3.2/fb of proton-proton collisions at √s=13 TeV w
- Search for heavy composite Majorana neutrinos in 2l+2jets final state
- Search for pair production of first-generation scalar leptoquarks
- Search for pair production of heavy vector-like quarks decaying to high-pt W bosons and b quarks in the lepton-plus-jets final state in pp collisions
- Search for pair production of Higgs bosons in the bbbb final state using proton-proton collisions at √s =13 TeV with the ATLAS detector
- Search for pair production of second-generation sc… lep…
- Search for pair production of vector-like top par…rs … eve…s wi… exa…ly …ne lep…on … …ge missing transverse momentum in √s=13 TeV pp collisi
- Search for pair-produced resonances in four jets …nal …tes …t √s … wi… … …etec…
- Search for production of vector-like top quark pa… …r… of f… …r top quar… … the l… …on…lu… …jet… final state in pp collisions at √s =13 TeV with th
- Search for quark contact interactions and extra spatial dimensions with dijet angular distributions
- Search for right-handed W and third-generation leptoquarks in 2tau_had+2jets final state
- Search for scalar leptoquarks in pp collisions at a centre-of-mass energy of 13 TeV with the ATLAS experiment
- Search for single production of vector-like quarks decaying into Wb in pp collisions at √s=13 TeV with the ATLAS detector
- Search for strong gravity in multijet final states produced in pp collisions at √s = 13 TeV using the ATLAS detector at the LHC
- Search for TeV-scale gravity signatures in high-mass final states with leptons and jets with the ATLAS detector at √s = 13 TeV
- Search for third-generation scalar leptoquarks and heavy right-handed neutrinos in τℓτhjj final states
- Search for type-III seesaw mechanism in multilepton events
- Search for W' in lepton+MET events
- Search for W' in tau+MET events

- "others" ?
  - black holes
  - doubly-charged Higgs
  - strong gravity
  - TeV-scale gravity signatures
  - excited leptons / quarks
  - four-top-quark production
  - composite Majorana neutrinos
  - quark contact interactions & extra dim
  - type-III seesaw fermion
  - pair-produced Higgs
  - pair-produced resonances in four jets
  - pair-produced first- / second-generation scalar LQ
  - right-handed W and third-generation scalar LQ
  - right-handed nu and third-generation scalar LQ
  - vector-like quarks (pair-production) (single-production)

- "others" ?



  - vector-like quarks (pair-production) (single-production)

- SM + vector-like fermions:

one Dirac fermion
"vector-like fermion"

$$\mathrm{SM} \quad + \quad F + \overline{F}$$

$$\mathcal{L} \sim \mathcal{L}_{\mathrm{SM}} + M_F F\bar{F} + (\mathrm{Yukawas})$$

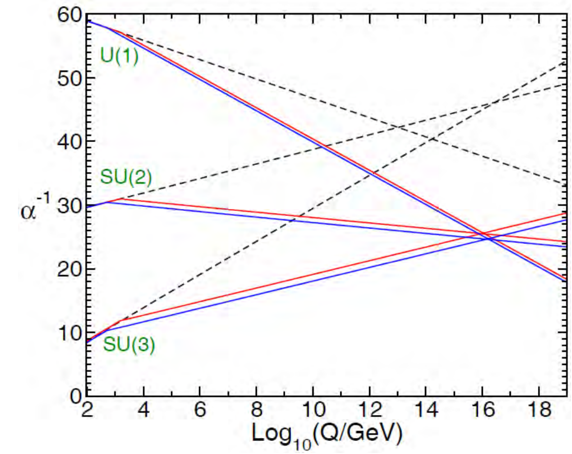
- MSSM + vector-like fermions

$$\mathrm{MSSM} \quad + \quad F + \overline{F} \quad + \quad \widetilde{F} + \overline{\widetilde{F}}$$

$$W = W_{\mathrm{MSSM}} + M_F F\bar{F} + (\mathrm{Yukawas})$$

✓ no gauge anomaly

✓ consistent w. EWPT & Higgs data (unlike chiral 4th gen)



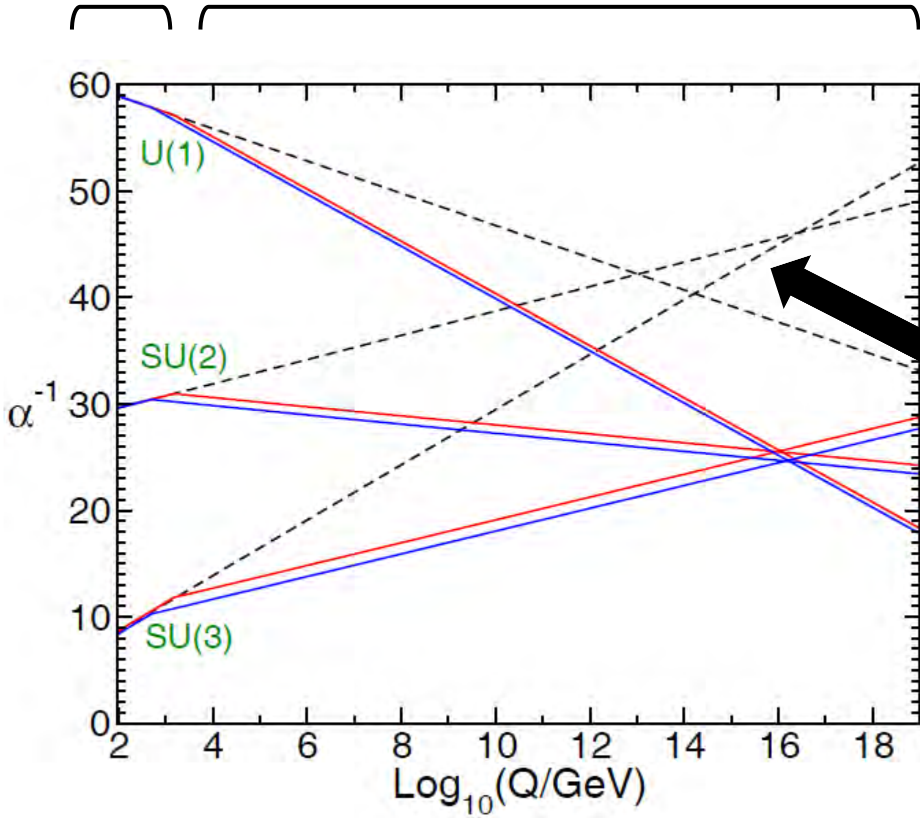
MSSM + VLF

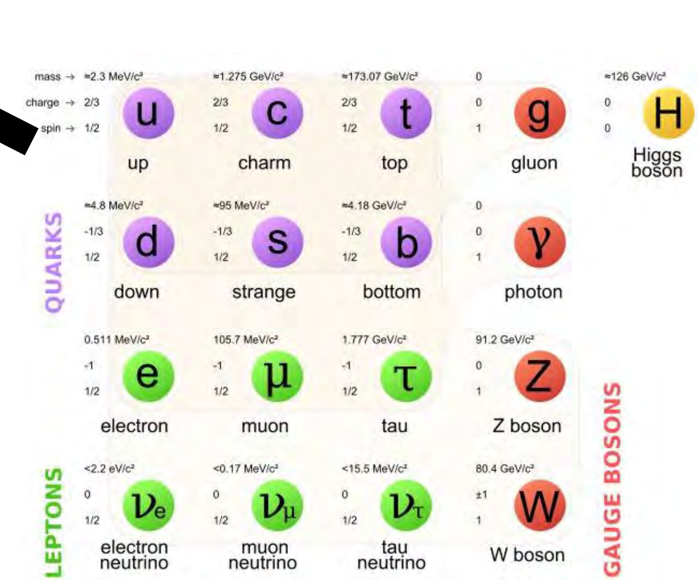
- 2 models for coupling unification
  - **QUE model** : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$
    - ✓ gauge coupling unification
    - ✓ SU(5) GUT
    - extra $H_u Q_4 \bar{U}_4$ interaction → m_h UP
  - **QDEE model** : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$
    - ✓ gauge coupling unification
    - ✗ SU(5) GUT
    - extra $H_d Q_4 \bar{D}_4$ coupling → m_h slightly UP

(you can also append $\mathbf{5} + \overline{\mathbf{5}} = (\boldsymbol{L}, \bar{\boldsymbol{D}}) + (\bar{\boldsymbol{L}}, \boldsymbol{D})$ pairs)

- Gauge coupling unification

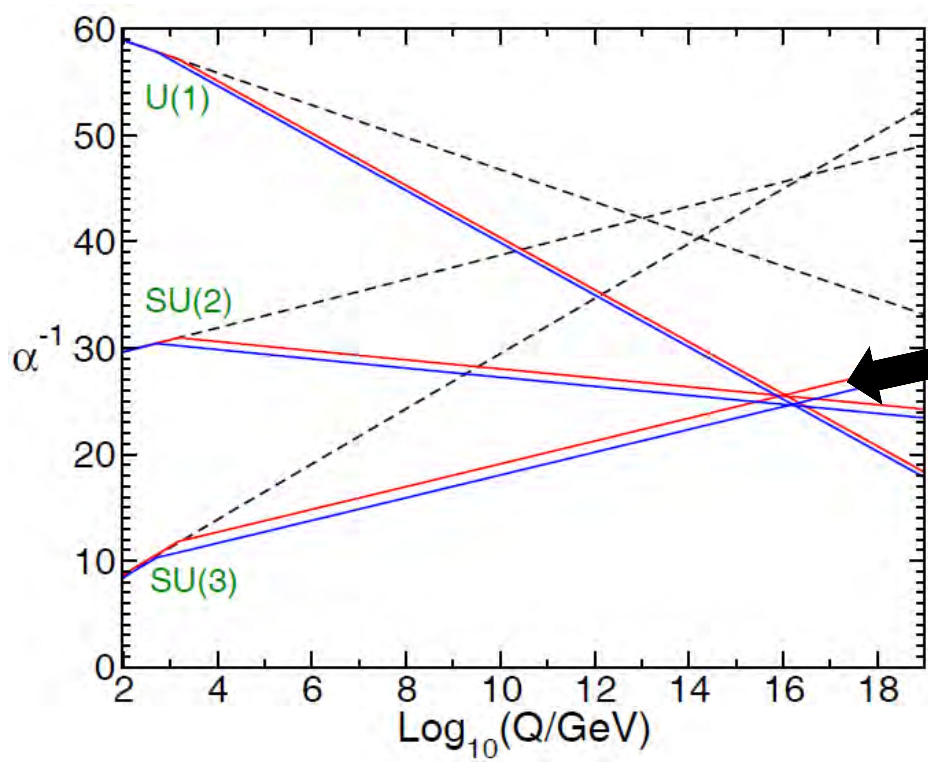
measured theoretical prediction

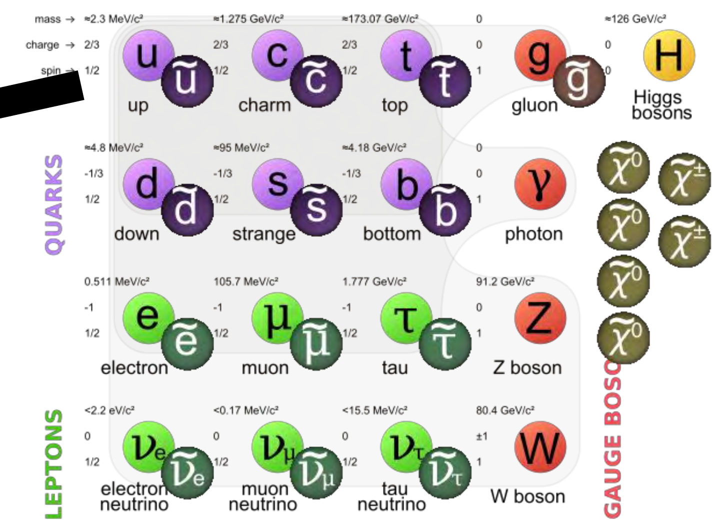


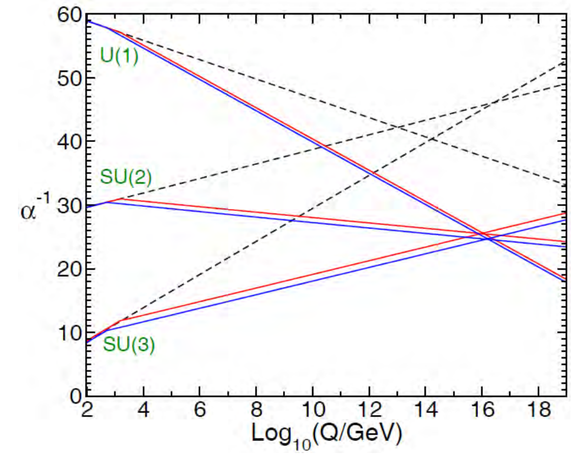


- Gauge coupling unification

measured theoretical prediction







■ MSSM + VLF

- 2 models for coupling unification
  - **QUE model** : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$
    - ✓ gauge coupling unification
    - ✓ SU(5) GUT
    - extra $H_u Q_4 \bar{U}_4$ interaction → m_h UP

$$W = W_{\mathrm{MSSM}} + Y' H_u Q_4 \bar{U}_4 + Y'' H_d \bar{Q}_4 U_4$$

$$m_h^2(\mathrm{MSSM}) \approx m_Z^2 + \frac{3 g_W^2 m_t^4}{8\pi^2 m_W^2}\left(\ln \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{12\alpha^2 - \alpha^4}{12}\right) + \frac{3v^2 Y'^4 \sin\beta^4}{4\pi^2}\left(\log \frac{m_{\tilde{t}'}^2}{m_{t'}^2} - \frac{5}{6} + \frac{m_{t'}^2}{m_{\tilde{t}'}^2} + \alpha'^2 + \cdots\right)$$

→ SUSY scale can be lowered.

(but still unnatural because μ is enhanced.)

$$W = W_{\mathrm{MSSM}} + Y' H_u Q_4 \bar{U}_4 + Y'' H_d \bar{Q}_4 U_4 + M_{Q'} Q_4 \bar{Q}_4 + M_{U'} U_4 \bar{U}_4$$
$$+ \epsilon_i H_u Q_4 \bar{U}_i + \epsilon'_i H_u Q_i \bar{U}_4 + \cdots$$

(otherwise stable VLQ)

(QUE model)

$$t'_1 \to qW,\quad qZ,\quad qh\ (\to qb\bar{b})$$

depending on mixing
btw. vec-like/SM quarks.

(usually 3rd gen is chosen to avoid flavor constraints)

$$pp \to t'_1 \bar{t}'_1 \to \begin{pmatrix} bW \\ tZ \\ th \end{pmatrix} \otimes \begin{pmatrix} \bar{b}W \\ \bar{t}Z \\ \bar{t}h \end{pmatrix}$$

→ multi *b*-quark signature
with BR dependence

$$W = W_{\mathrm{MSSM}} + Y' H_u Q_4 \bar{U}_4 + Y'' H_d \bar{Q}_4 U_4 + M_{Q'} Q_4 \bar{Q}_4 + M_{U'} U_4 \bar{U}_4$$
$$+ \epsilon_i H_u Q_4 \bar{U}_i + \epsilon'_i H_u Q_i \bar{U}_4 + \cdots$$

(QUE model)

(otherwise stable VLQ)

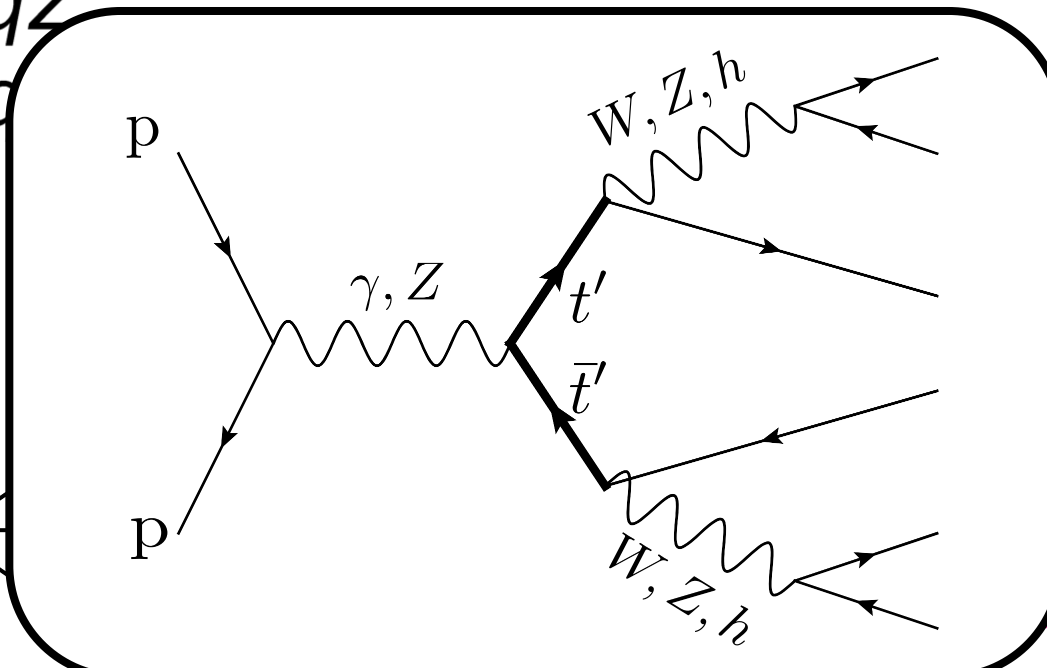
$t'_1 \to qW,\ qZ,\ q$...

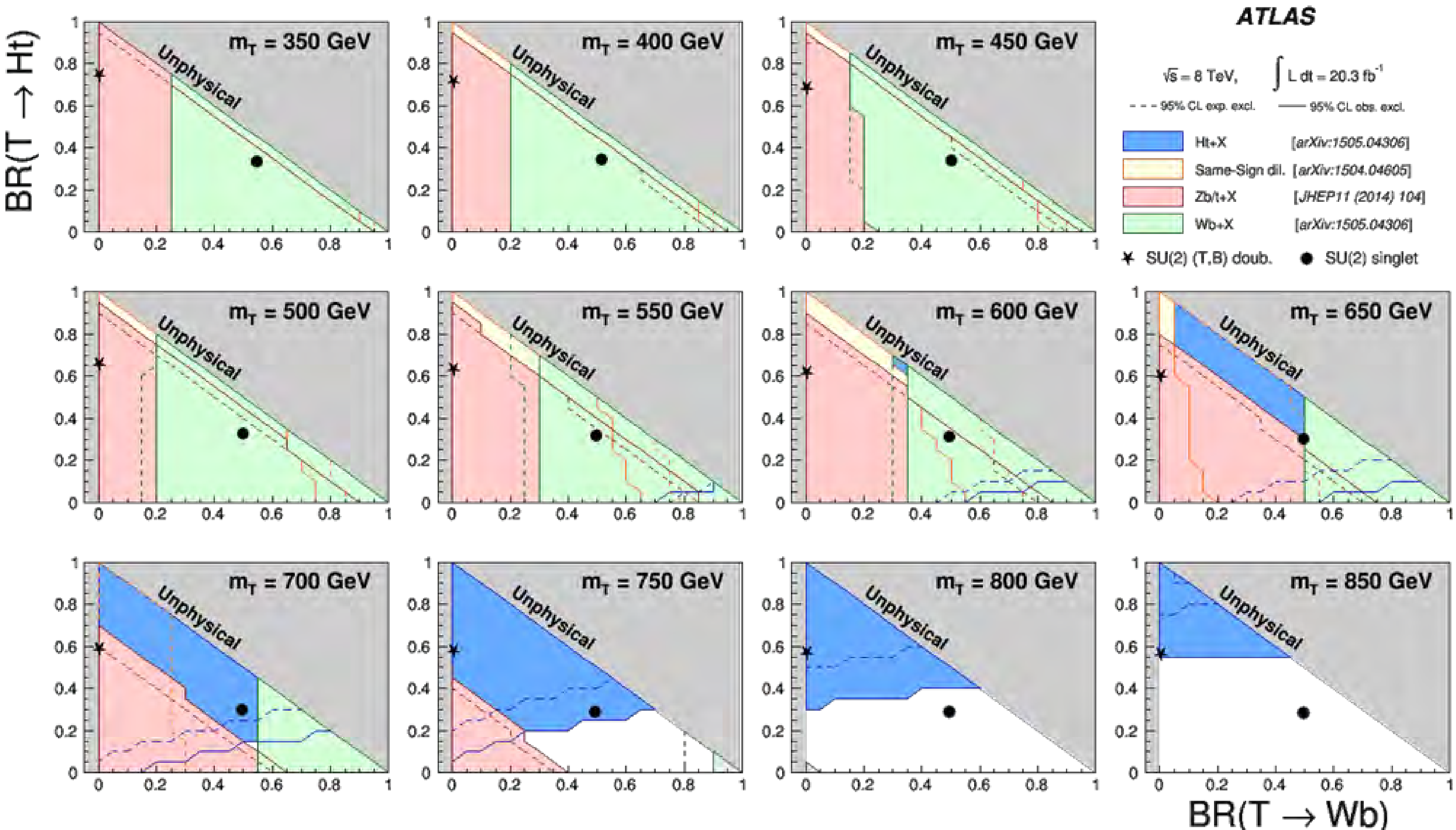
depending on mixing
btw. vec-like/SM quarks.

...raints)

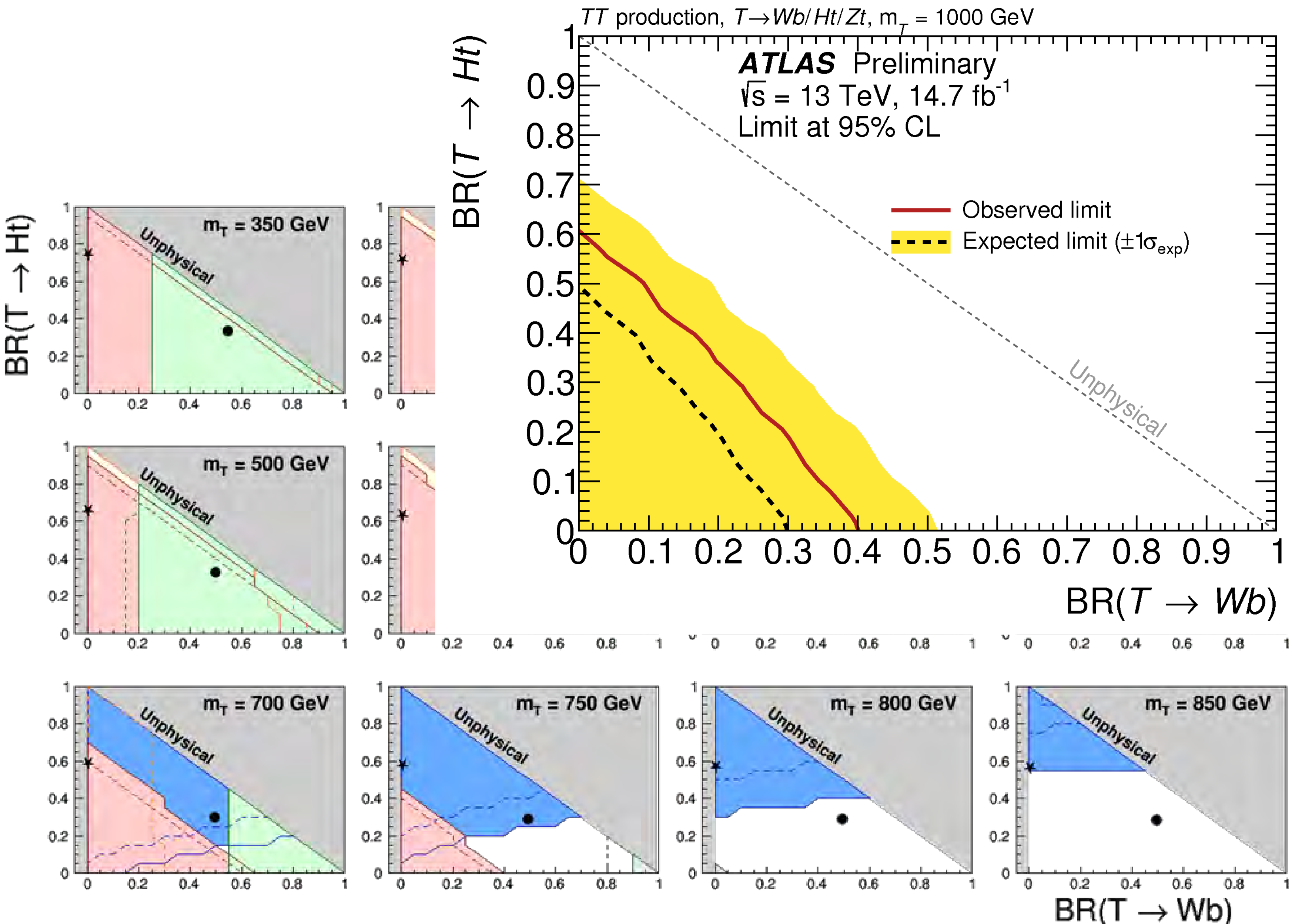
$pp \to t'_1 \bar{t}'_1$

...nature
...ence




ATLAS
√s = 8 TeV, ∫ L dt = 20.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Ht+X [arXiv:1505.04306]
Same-Sign dil. [arXiv:1504.04605]
Zb/t+X [JHEP11 (2014) 104]
Wb+X [arXiv:1505.04306]
SU(2) (T,B) doub.
SU(2) singlet
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700 GeV
m_T = 750 GeV
m_T = 800 GeV
m_T = 850 GeV
Unphysical
BR(T → Ht)
BR(T → Wb)

Vector-like quark search (Run 1 summary + Run 2 ATL-CONF-2016-101)



1) $\not{E}_T$ ← dark matter

- $t\bar{t} + \not{E}_T$ ← $\tilde{t}\,\tilde{t}^*$ ← naturalness
- $3\ell + \not{E}_T$ ← $\tilde{\chi}^+\tilde{\chi}^0$ ← muon $g-2$
- $2\ell + \not{E}_T$ ← $\tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\ell}\,\tilde{\ell}^*$ ← muon $g-2$
- $\text{jets} + \not{E}_T$ ← $\tilde{q}\,\tilde{q}^*$
- $\text{mono-}X + \not{E}_T$ ← dark matter

"SUSY" filter

2) LLCP ← cosmology (Ωh^2, Li)

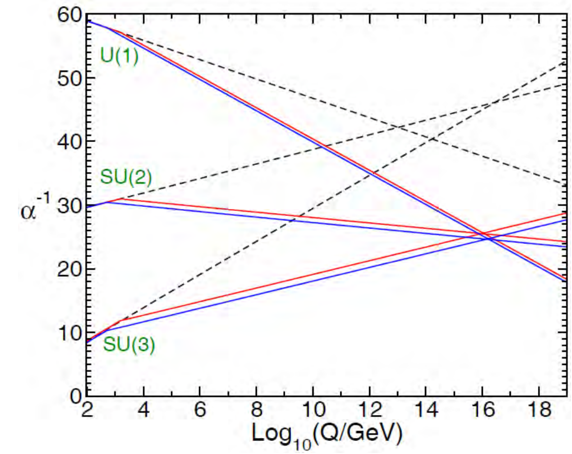
- co-annihilation in coming years!

  (R-hadron, displaced vertex, disappearing track, …)

(ph/0511034, 1403.0715, 1409.4533,1504.00504, 1506.08206, …)

3) more exotic

- many more searches…
- VLQ ← $m_h = 125\,\text{GeV}$
- VLL ← Ωh^2



■ MSSM + VLF

➢ 2 models for coupling unification

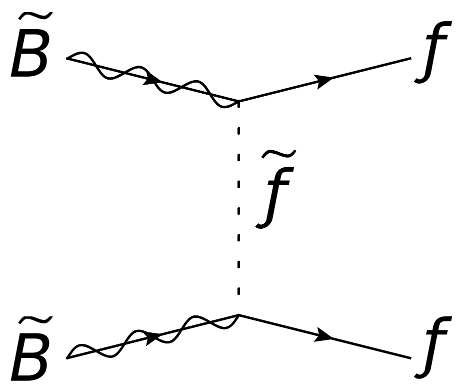
- **QUE model** : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$
  - ✅ gauge coupling unification
  - ✅ SU(5) GUT
  - ➢ extra $H_u Q_4 \bar{U}_4$ interaction → m_h UP

- **QDEE model** : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$
  - ✅ gauge coupling unification
  - ❌ SU(5) GUT
  - ➢ extra $H_d Q_4 \bar{D}_4$ coupling → m_h slightly UP

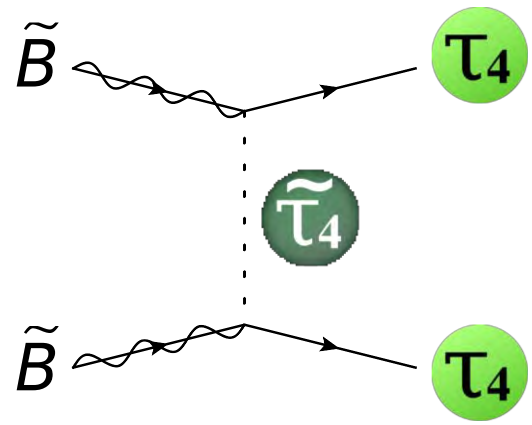
(you can also append $\mathbf{5} + \overline{\mathbf{5}} = (\boldsymbol{L}, \bar{\boldsymbol{D}}) + (\bar{\boldsymbol{L}}, \boldsymbol{D})$ pairs)

- pure-Bino DM with $m_{\tilde{B}} \gtrsim 100$ GeV → Ωh^2 overabundant

Increase $\langle \sigma v \rangle$!!



+

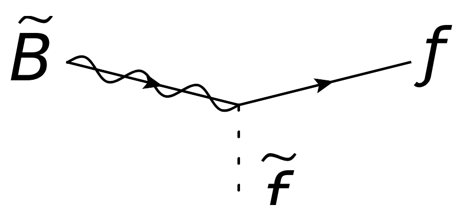


extra annihilation channel
→ larger $\langle \sigma v \rangle$
→ "proper" Ωh^2

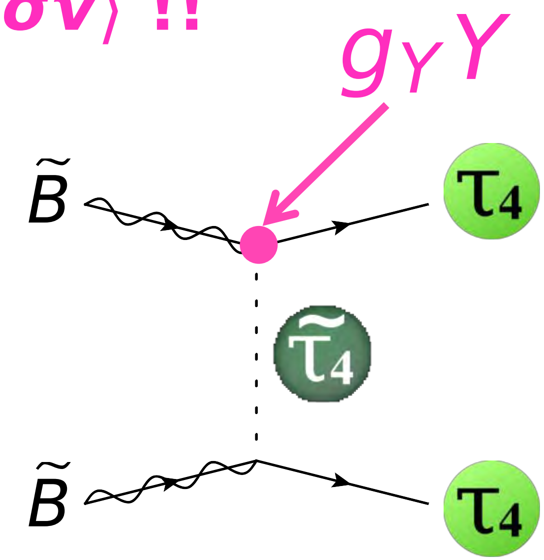
if $\tilde{\tau}_4 \gtrsim \tilde{B} > \tau_4$

- pure-Bino DM with $m_{\tilde{B}} \gtrsim 100$ GeV → Ωh^2 overabundant

Increase $\langle \sigma v \rangle$!!



+



	$SU(3)_{color}$	$SU(2)_{weak}$	$U(1)_Y$
Q_i	$\mathbf{3}$	$\mathbf{2}$	$1/6$
$\bar{U}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
$\bar{E}_i$	$\mathbf{1}$	$\mathbf{1}$	1
$\bar{D}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$\bar{E}_4$	$\mathbf{1}$	$\mathbf{1}$	1
E_4	$\mathbf{1}$	$\mathbf{1}$	-1

$\Longrightarrow \langle \sigma v \rangle \propto Y^4$

if $\tilde{\tau}_4 \gtrsim \tilde{B} > \tau_4$

$$W = W_{\mathrm{MSSM}} + M_{E'} E_4 \bar{E}_4 + \epsilon_i H_d L_i \bar{E}_4$$ (QUE model)

(otherwise stable VLL)

$$\Rightarrow \quad \tau' \to \nu_i W, \quad l_i Z, \quad l_i h$$

BR fixed but

***e* : *μ* : *τ* ratio not fixed**

depending on mixing btw. vec-like/SM leptons.

(flavor constraints are not strict)

$$\Rightarrow \quad pp \to \tau' \bar{\tau}' \to \begin{pmatrix} \nu_i W \\ l_i Z \\ l_i h \end{pmatrix} \otimes \begin{pmatrix} \bar{\nu}_i W \\ \bar{l}_i Z \\ \bar{l}_i h \end{pmatrix}$$

→ multi lepton signature dependent on ***e* : *μ* : *τ*** ratio

- IF $e:\mu:\tau = 1:0:0$ or $0:1:0$

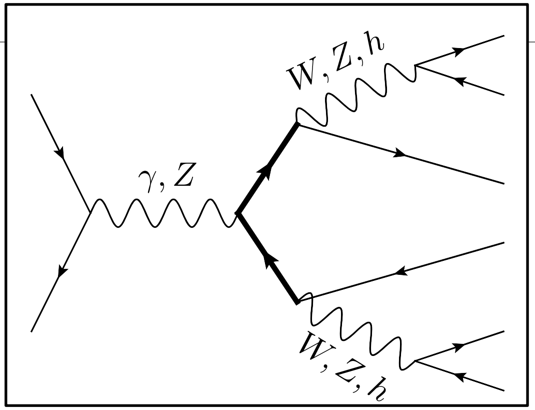
$$\left(\tau' \xrightarrow{100\%} e + V \quad \text{or} \quad \tau' \xrightarrow{100\%} \mu + V\right)$$

⇨ **LHC constraints!**

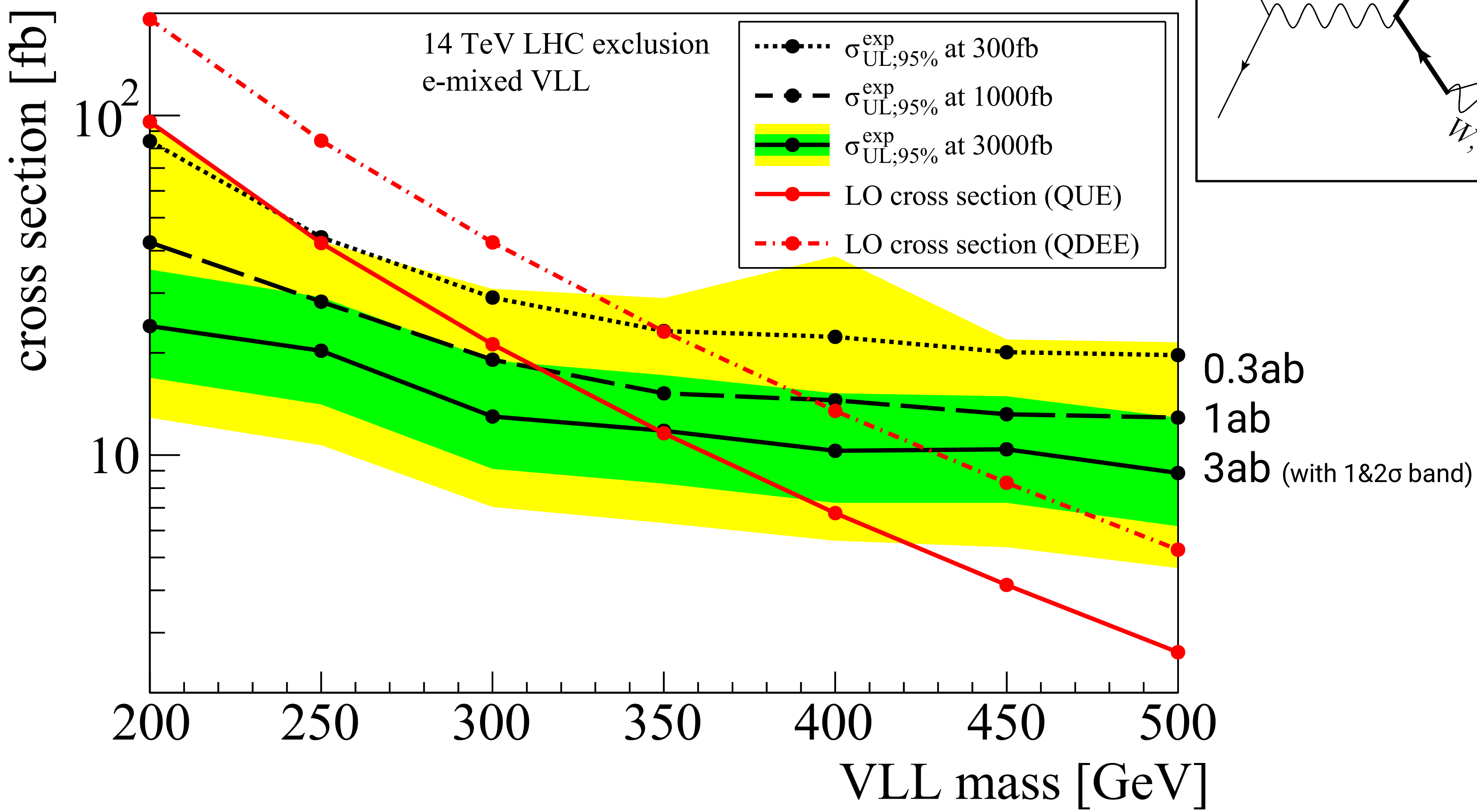
- IF $e:\mu:\tau = 0:0:1$ $\left(\tau' \xrightarrow{100\%} \tau + V\right)$

⇨
❖ No constraints from LHC or HL-LHC.

❖ This scenario will be perfectly searched by **CTA gamma-ray observation**.

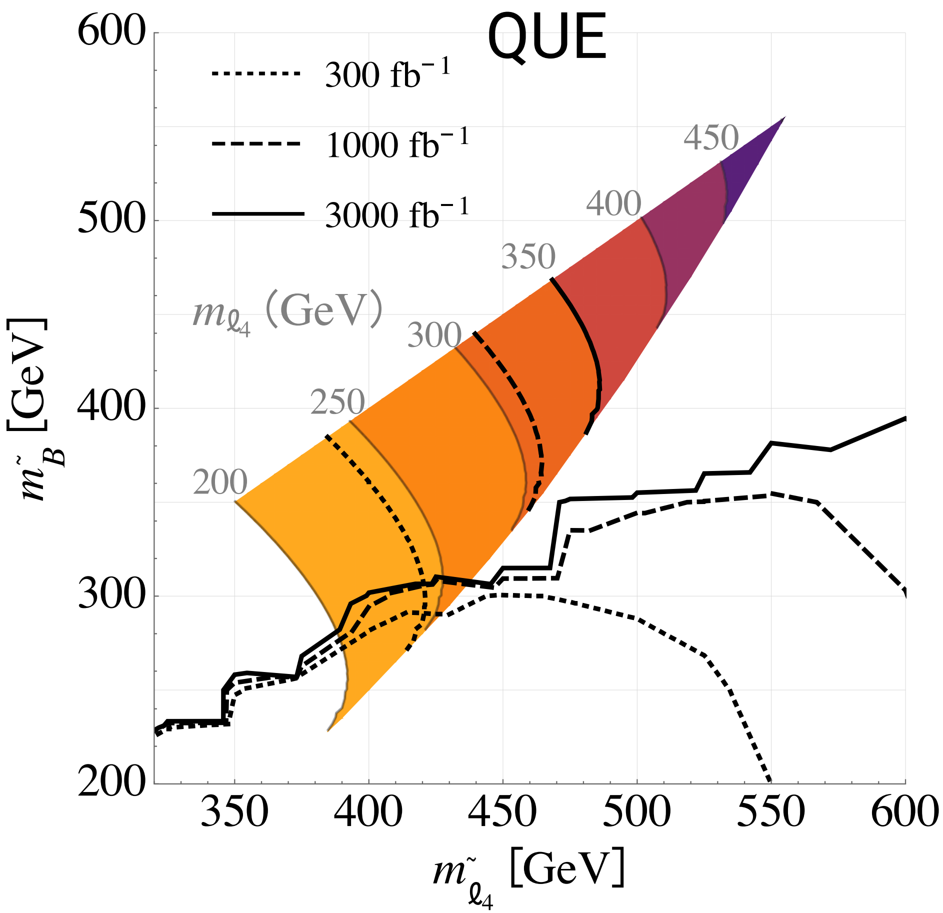


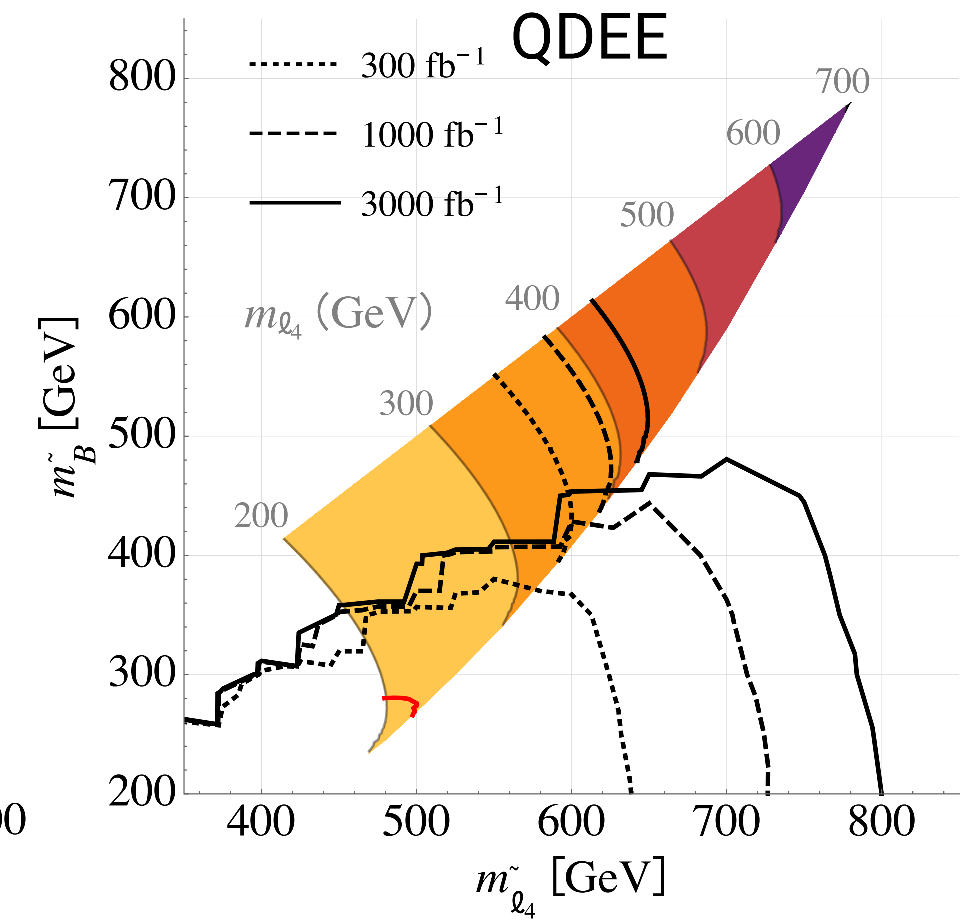
■ IF $e:\mu:\tau = 1:0:0$ or $0:1:0$



- Snowmass BKG set is used.
  - MG5−Pythia−Delphes + NLO *K*-factor
  - di-boson + *tt* dominated
- Signal by FR−MG5aMC−Pythia−Delphes (LO)
- SR dedicated for WZ / ZZ + leptons
  - 3L, 4L for WZ, and 4L, 5L for ZZ
  - tau-tag / b-tag not used (avoided)
- Uncertainties = stat. + 20% syst.

■ $e:\mu:\tau = 1:0:0$ or $0:1:0$

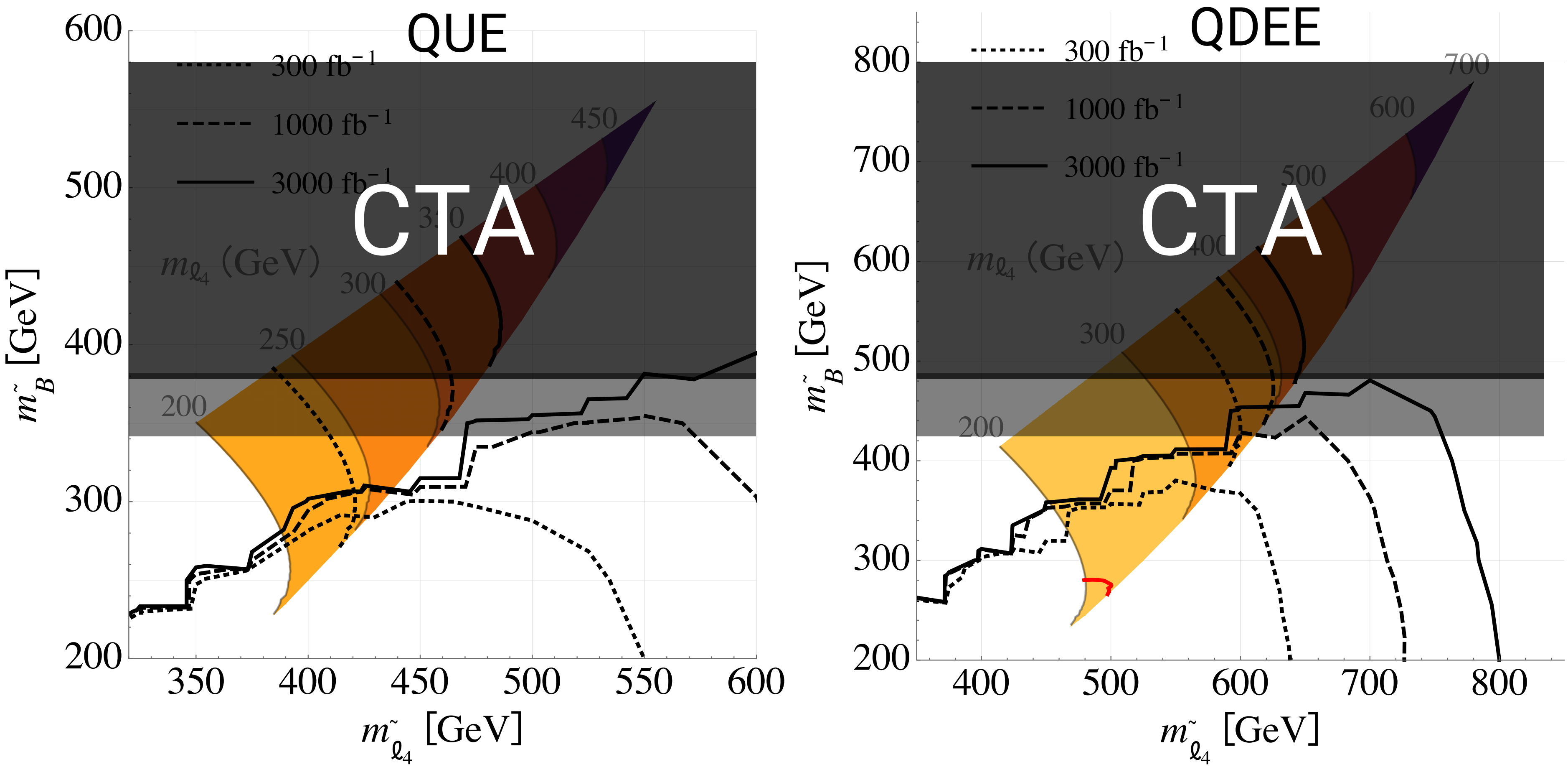




■ $e:\mu:\tau = 0:0:1$

➢ LHC insensitive, but CTA covers full region

- $e : \mu : \tau = 1 : 0 : 0$ or $0 : 1 : 0$



- $e : \mu : \tau = 0 : 0 : 1$
  - ➢ LHC insensitive, but CTA covers full region

1) $\not{E}_T$

dark matter

- $t\bar{t} + \not{E}_T$ ← $\tilde{t}\,\tilde{t}^*$ ← naturalness
- $3\ell + \not{E}_T$ ← $\tilde{\chi}^+\tilde{\chi}^0$
- $2\ell + \not{E}_T$ ← $\tilde{\chi}^+\tilde{\chi}^-$ ← muon $g-2$
- $\tilde{\ell}\,\tilde{\ell}^*$
- $\text{jets} + \not{E}_T$ ← $\tilde{q}\,\tilde{q}^*$
- $\text{mono-}X + \not{E}_T$

"SUSY" filter

2) LLCP

← cosmology (Ωh^2, Li)

- co-annihilation in coming years!

(R-hadron, displaced vertex, disappearing track, ...)

(ph/0511034, 1403.0715, 1409.4533,1504.00504, 1506.08206, ...)

3) more exotic

- many more searches...
- VLQ
- VLL

$m_h = 125\,\text{GeV}$

Ωh^2