LLCP at FCC-hh ($\sqrt{s}$ = 100 TeV)

Sho IWAMOTO（岩本　祥）

18 Jan. 2018
1st FCC Physics Workshop @ CERN

Based on

Jonathan. L. Feng, S.I., Yael Shadmi, Shlomit Tarem [1505.02996]

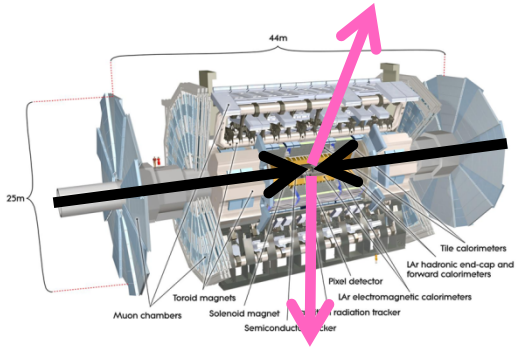
UC Irvine — Technion — ATLAS

(collected in FCC report [1606.00947])

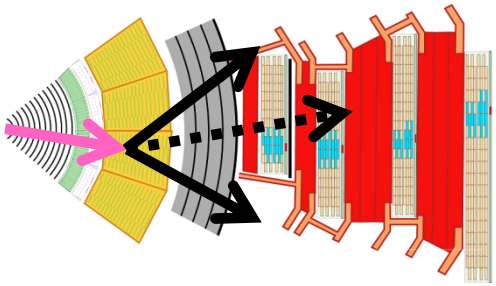
LLCP at FCC-hh ($\sqrt{s}$ = 100 TeV)

Long-lived charged particle

- **"stable"**



- in-flight decay



→ talk by José Francisco Zurita (Friday)

Why should we search for LLCP?

experimental

phenomenology

theoretical

Why should we search for LLCP?

experimental **...Why not?**

phenomenology

theoretical

Why should we search for LLCP?

<u>experimental</u> **…Why not?**

<u>phenomenology</u>

long lifetime
→ an actor in early Universe

FCC-hh will cover most of the standard thermal-WIMP scenario

non-standard DM scenarios with LLCP

- super-WIMP:

  → next slides

- co-annihilation:

  $(\widetilde{B}\text{ - }\widetilde{\tau}) \lesssim 700\,\text{GeV}$

  $(\widetilde{W}\text{ - }\widetilde{g}) \lesssim 6\text{–}7\,\text{TeV}$

  $(\widetilde{B}\text{ - }\widetilde{g})$ or $(\widetilde{B}\text{ - }\widetilde{t}) \lesssim 8\,\text{TeV}$

Cf. Harigaya, Kaneta, Matsumoto [1403.0715], Ellis, Olive, Zheng [1404.5571], etc.

<u>theoretical</u>

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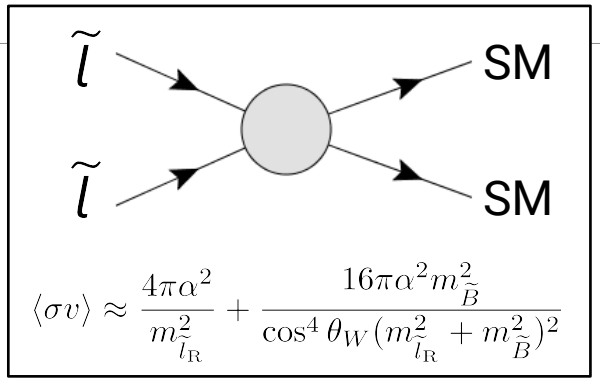
<u>theoretical</u> **… SUSY?**

- GMSB scenario: light gravitino → long-lived sleptons ($\tilde{l}$)
- split-SUSY: extremely heavy squarks → long-lived gluino ($\tilde{g}$)

- Super-WIMP:
  - NLSP slepton $\tilde{l}$ + LSP gravitino $\tilde{G}$



frozen-out

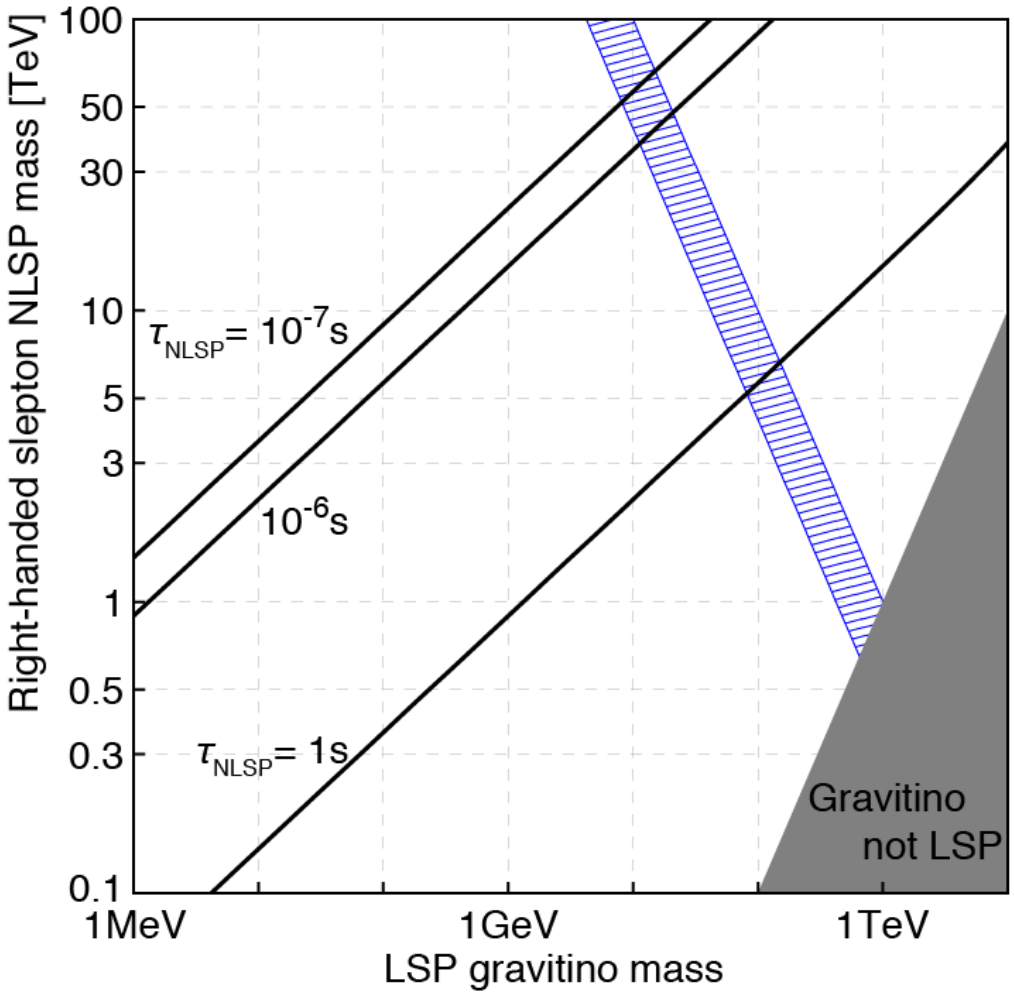
→ thermal relic with $(\Omega h^2)_{\tilde{l}} \gg 0.12$

late-time decay $\tilde{l} \to \tilde{G} + l$

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

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

Super-WIMP:



(short-lived)

LLCP search target

(BBN/CMB constraints are relevant.)

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

Why should we search for LLCP?

<u>experimental</u> **…Why not?**

<u>phenomenology</u>

long lifetime
→ an actor in early Universe

FCC-hh will cover most of the standard thermal-WIMP scenario

non-standard DM scenarios with LLCP

- super-WIMP:

  $\tilde{l} > O(1)\,\text{TeV}$

- co-annihilation:

  $(\tilde{B}\text{-}\tilde{\tau}) \lesssim 700\,\text{GeV}$

  $(\widetilde{W}\text{-}\tilde{g}) \lesssim 6\text{–}7\,\text{TeV}$

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Cf. Harigaya, Kaneta, Matsumoto [1403.0715], Ellis, Olive, Zheng [1404.5571], etc.

<u>theoretical</u> **… SUSY?**

- GMSB scenario: light gravitino → long-lived sleptons
- split-SUSY: extremely heavy squarks → long-lived gluino

Why should we search for LLCP?

experimental

phenomenolo

long lifetime
→ an actor ir

non-colored LLCP … covered in this talk

(slepton $\tilde{l}$ / stau $\tilde{\tau}$ as a benchmark case)

non-standard DM scenarios with LLCP

- super-WIMP:
  - $\tilde{l} > O(1)$ TeV
- co-annihilation:
  - $(\tilde{B}\text{-}\tilde{\tau}) \lesssim 700$ GeV
  - $(\widetilde{W}\text{-}\tilde{g}) \lesssim 6$–$7$ TeV
  - $(\tilde{B}\text{-}\tilde{g})$ or $(\tilde{B}\text{-}\tilde{t}) \lesssim 8$ TeV

Cf. Harigaya, Kaneta, Matsumoto [1403.0715], Ellis, Olive, Zheng [1404.5571], etc.

colored LLCP

(→ hadronize: "R-hadron")

- GMSB scenario: light gravitino → long-lived sleptons ($\tilde{l}$)
- split-SUSY: extremely heavy squarks → long-lived gluino ($\tilde{g}$)

Why should we search for LLCP?

exper

phen

lo

→

“Extrapolations” (√s=100 TeV, 3/ab)

$\tilde{g}$(-like) R-hadron: 11–20 TeV?

$\tilde{t}$ (-like) R-hadron: 7 TeV

[cf. Barnard, Cox, Gherghetta, Spray, 1510.06405]

→ Dedicated studies after detector specs(?)

... covered in this talk

$\tilde{\tau}$ as a benchmark case)

LLCP

annihilation:

t > O(1) TeV

$(\tilde{B}$ - $\tilde{\tau})$ $\lesssim$ 700 GeV

$(\widetilde{W}$ - $\tilde{g})$ $\lesssim$ 6–7 TeV

$(\tilde{B}$ - $\tilde{g})$ or $(\tilde{B}$ - $\tilde{t})$ $\lesssim$ 8 TeV

Cf. Harigaya, Kaneta, Matsumoto [1403.0715], Ellis, Olive, Zheng [1404.5571], etc.

colored LLCP

(→ hadronize: “R-hadron”)

- GMSB scenario: light gravitino → long-lived sleptons ($\tilde{l}$)
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1. **Motivations: Why LLCP?**
2. **Searches at (HL-)LHC**
3. **Searches at FCC-hh**
   - Muon radiative energy loss
   - Muon momentum resolution
4. **Summary**

1. Motivations: Why LLCP?

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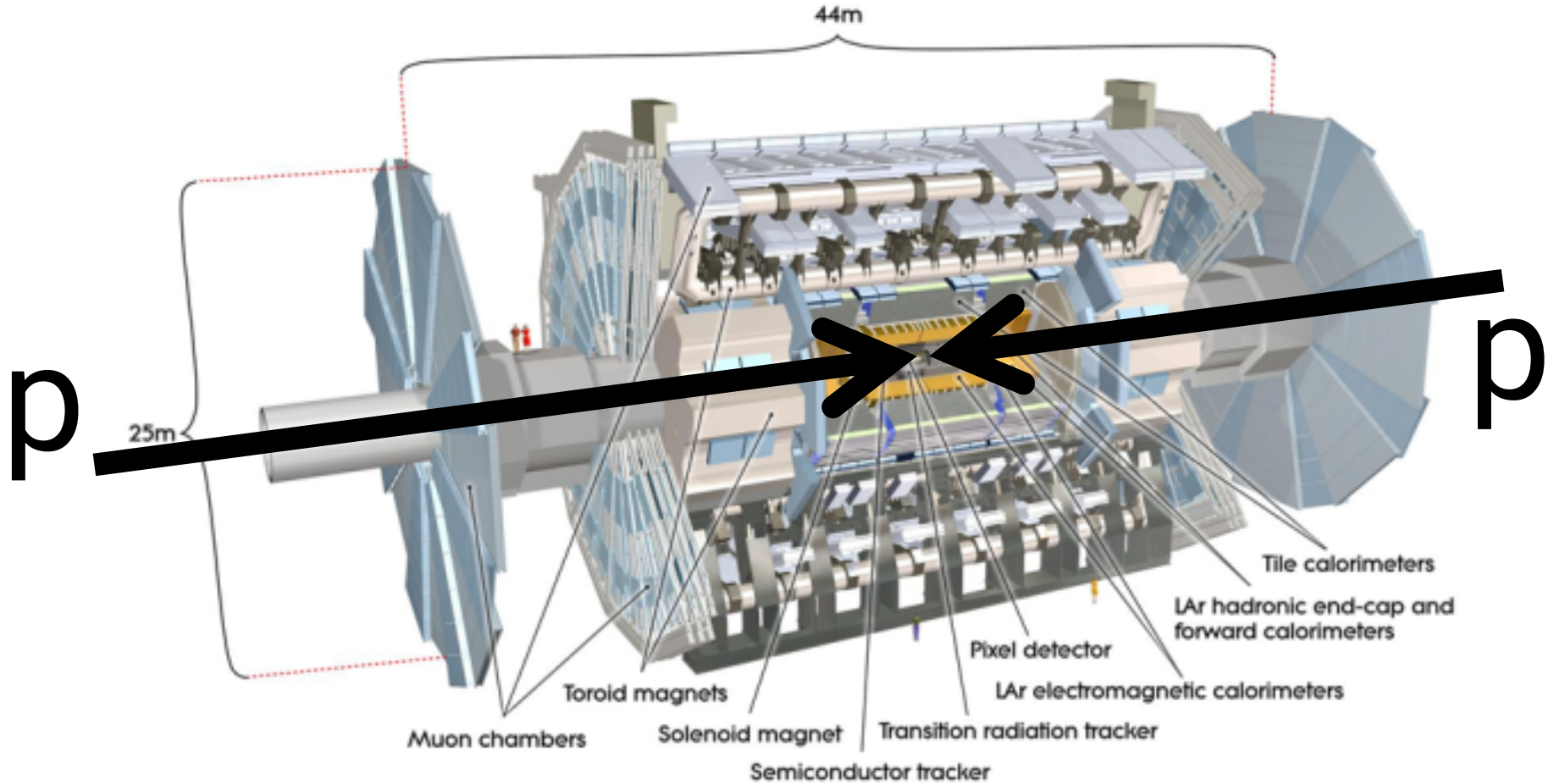
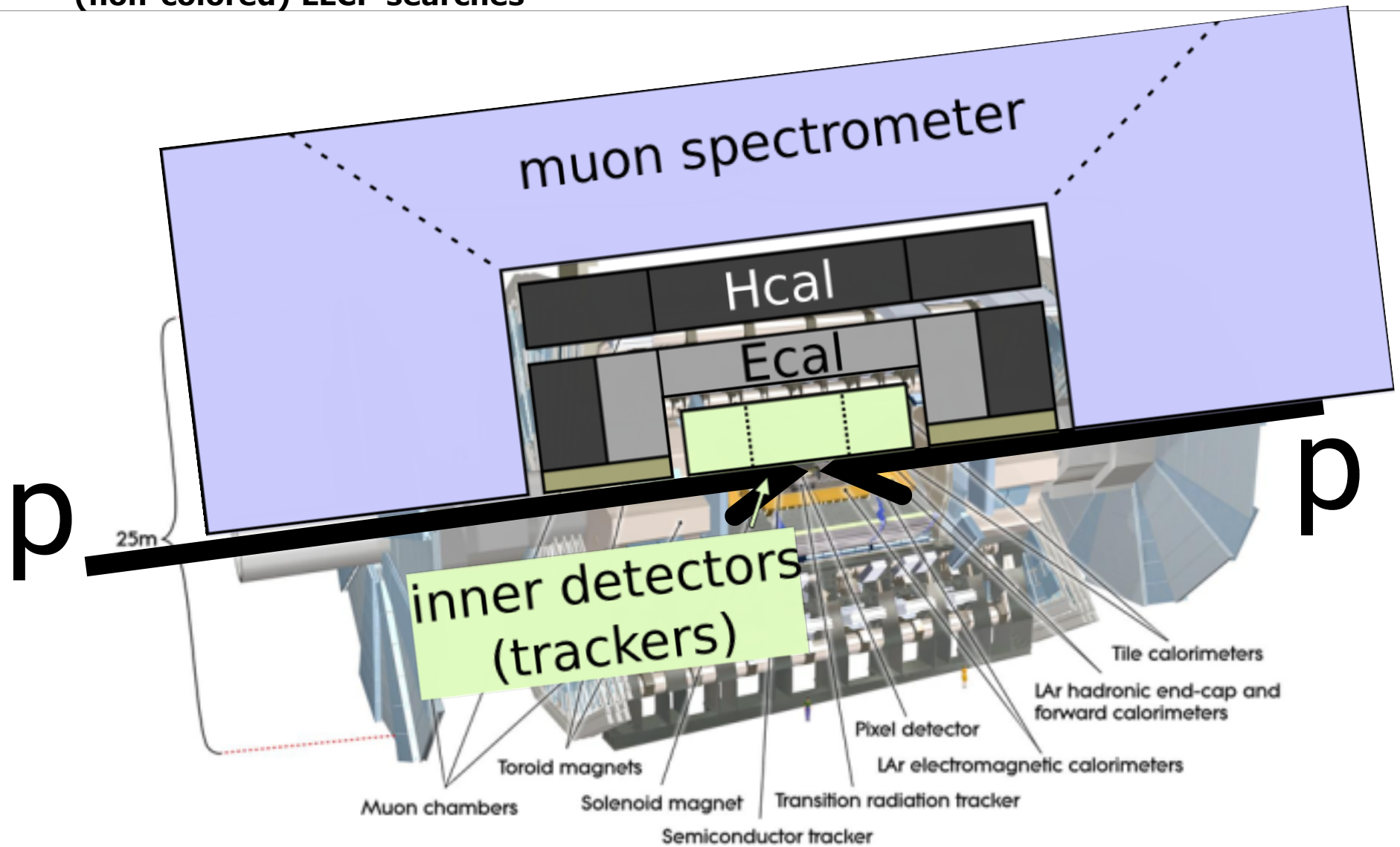
4. **Summary**


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


muon spectrometer
Hcal
Ecal
p
p
25m
inner detectors
(trackers)
Tile calorimeters
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forward calorimeters
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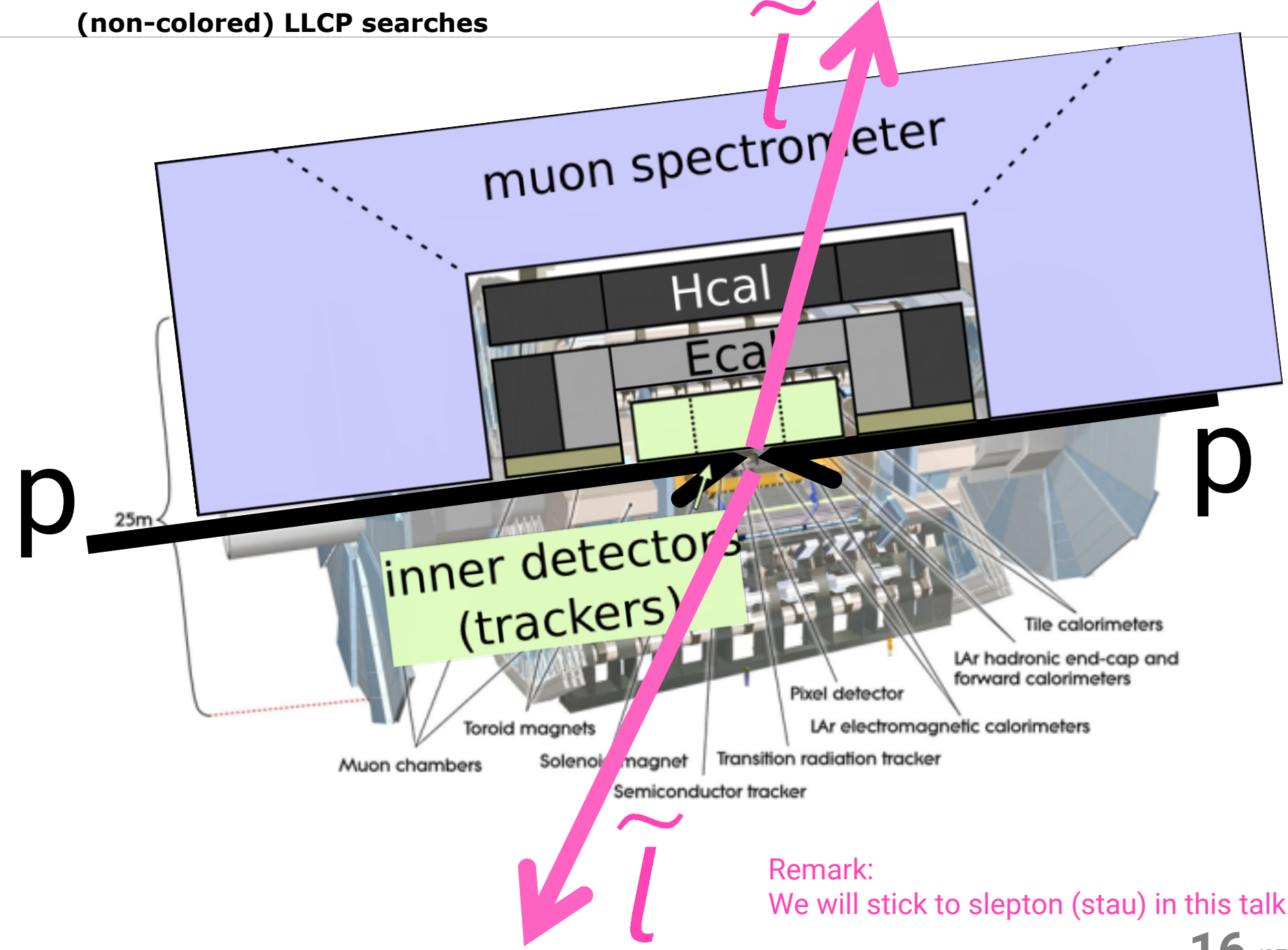
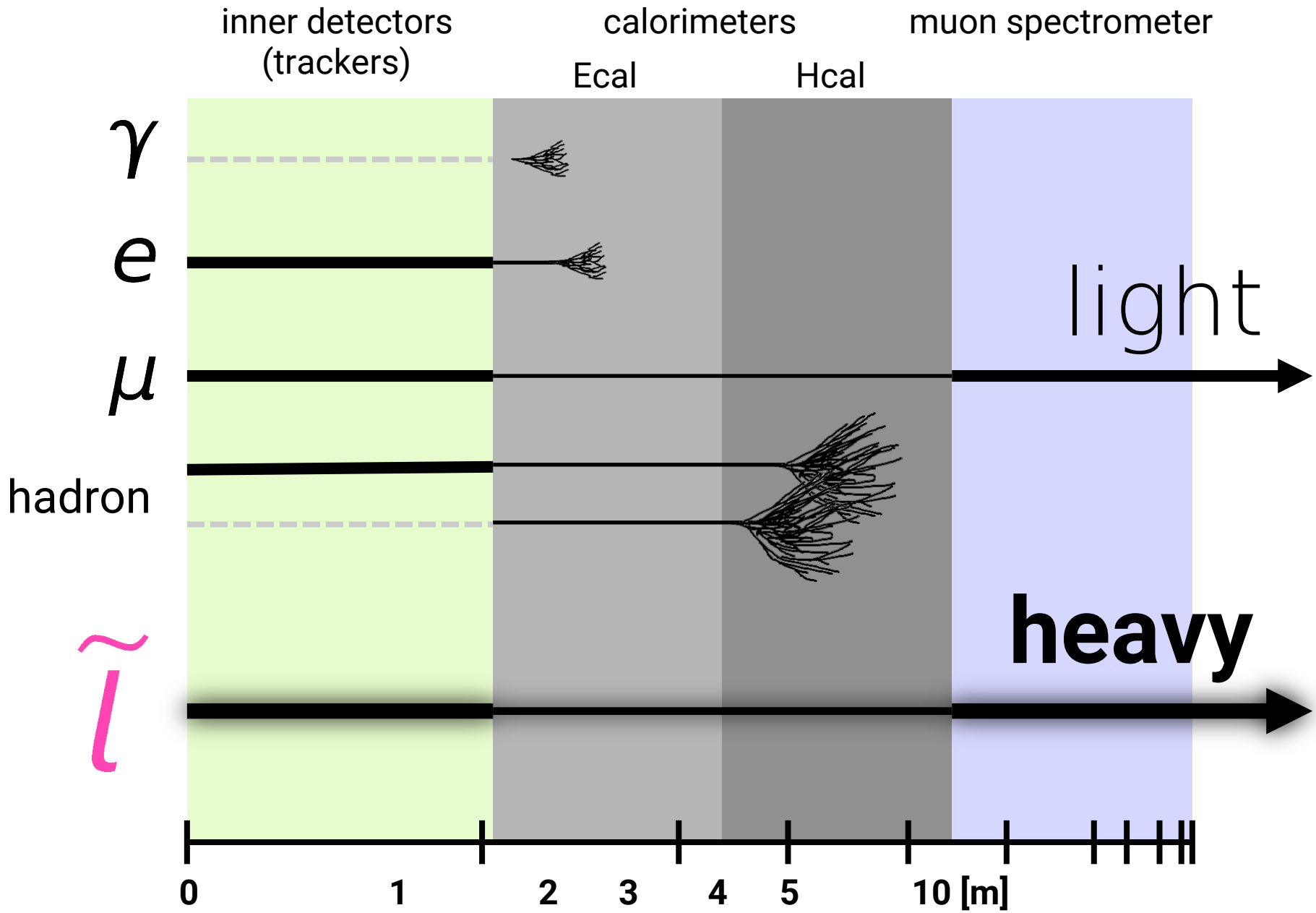
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker



Remark:
We will stick to slepton (stau) in this talk.


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

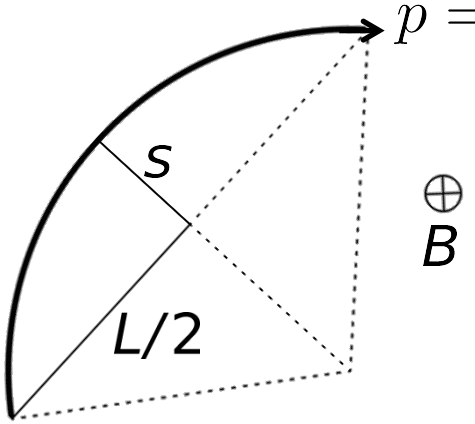
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

momentum & velocity

- **mass** measurement = ***p*** & ***β*** measurements ($\beta = v/c$)

➢ momentum

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



➢ velocity

- TOF [time-of-flight]

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

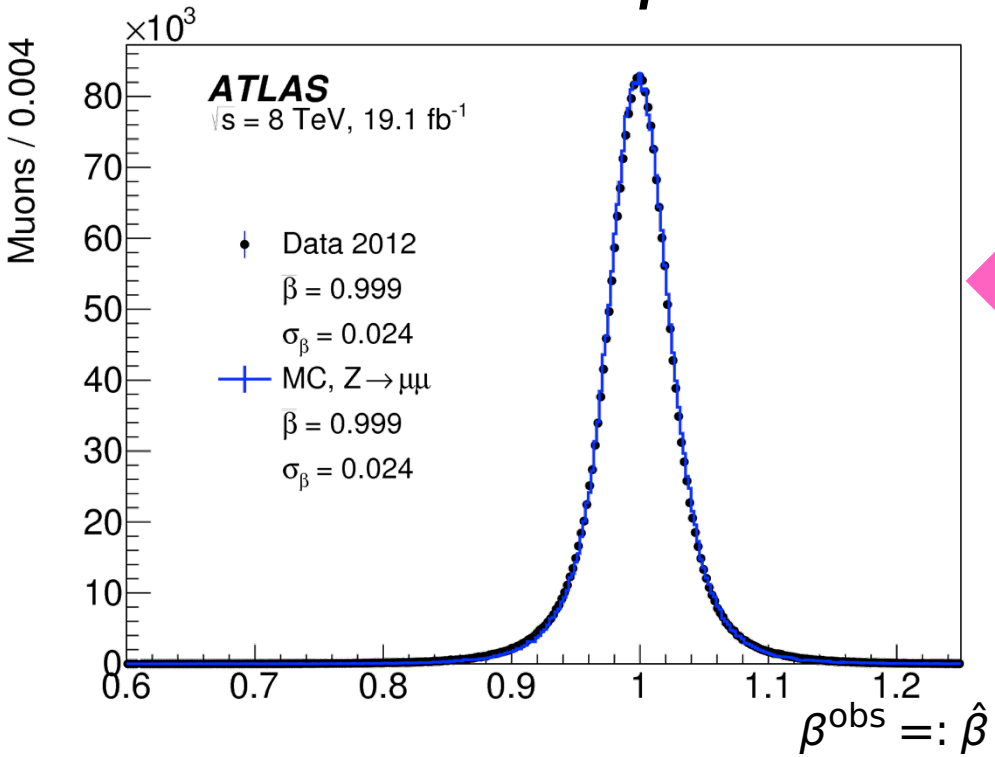
- d*E*/d*x* [ionization energy loss]

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

momentum & velocity

- **mass** measurement = ***p*** & ***β*** measurements $(\beta = v/c)$

ATLAS muon data: **Δβ = 2.4%**



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- TOF [time-of-flight]

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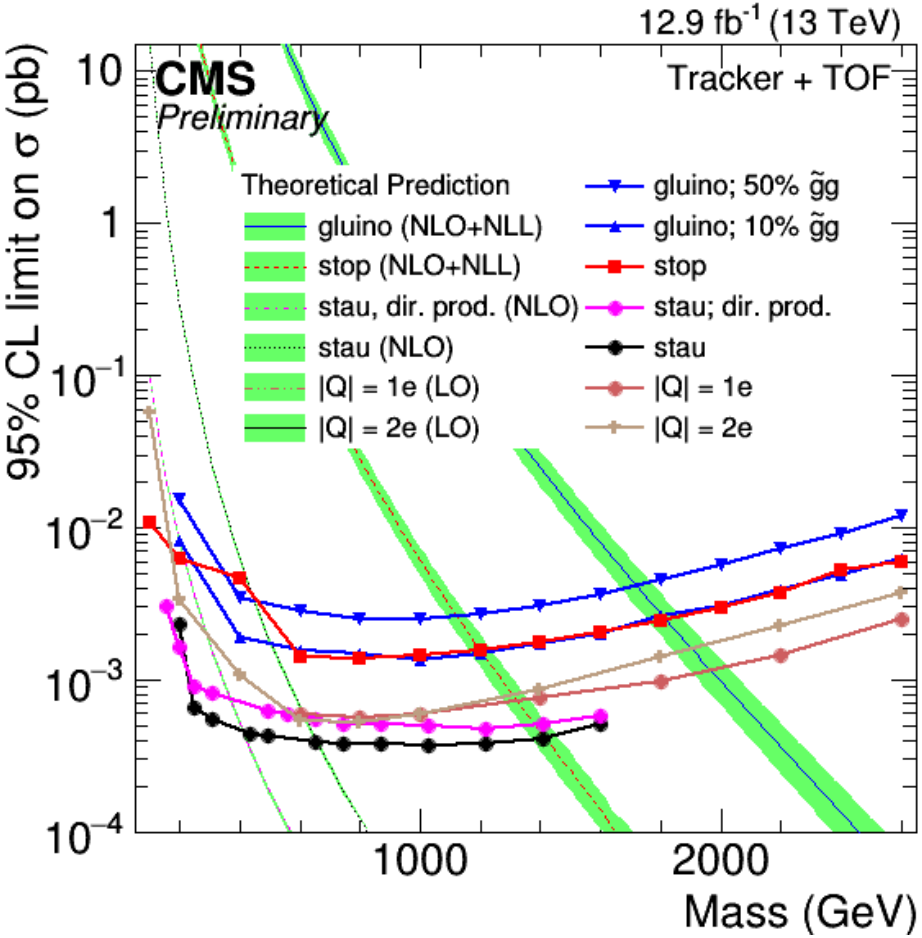
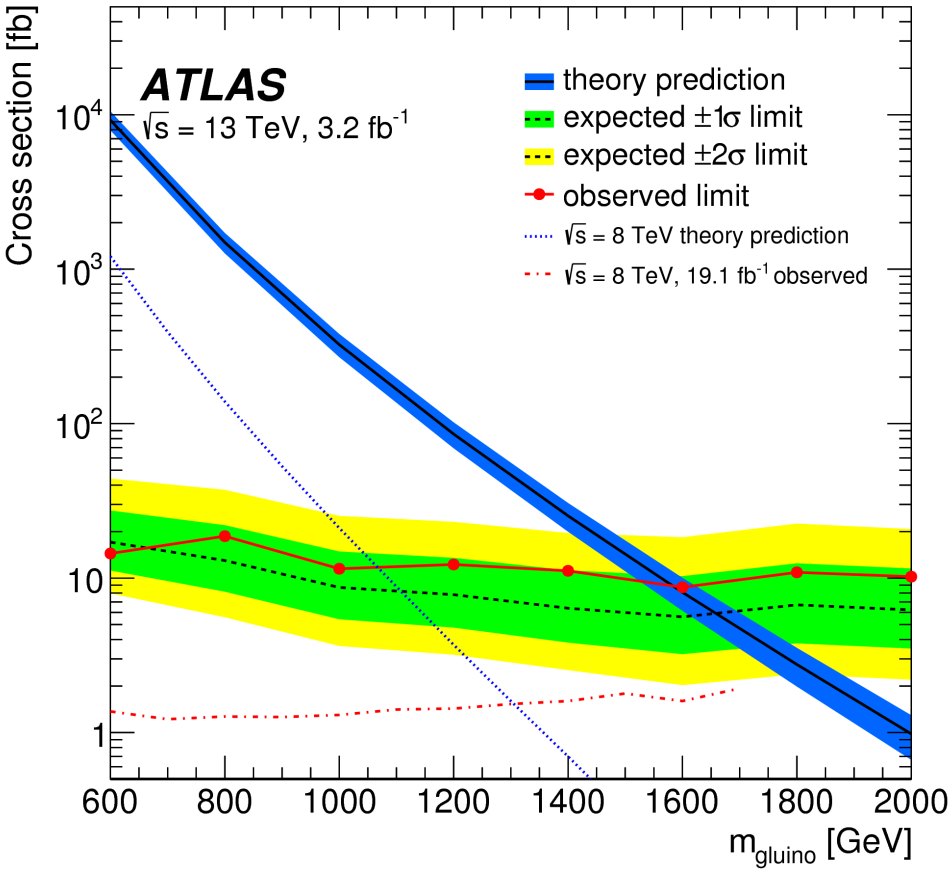
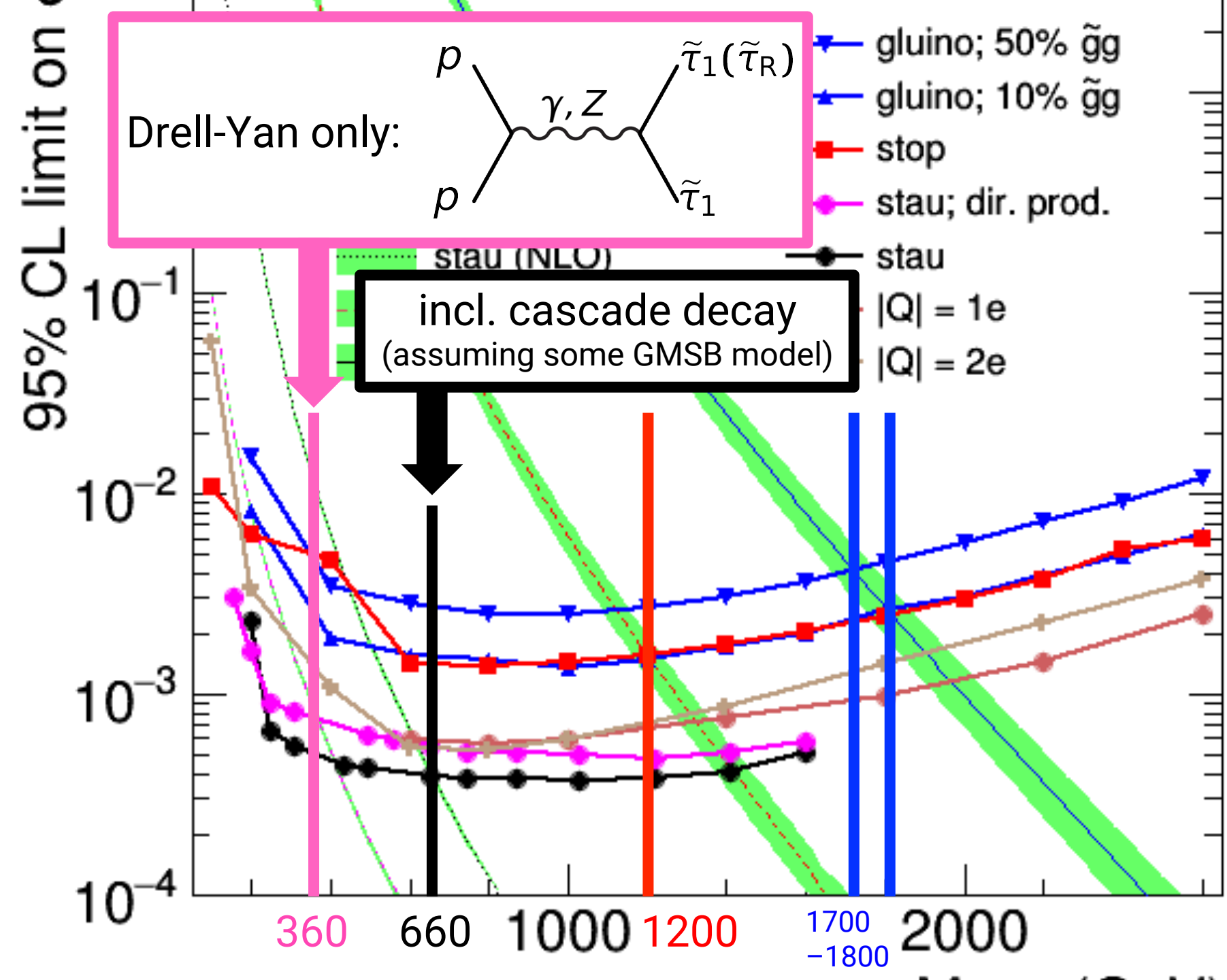
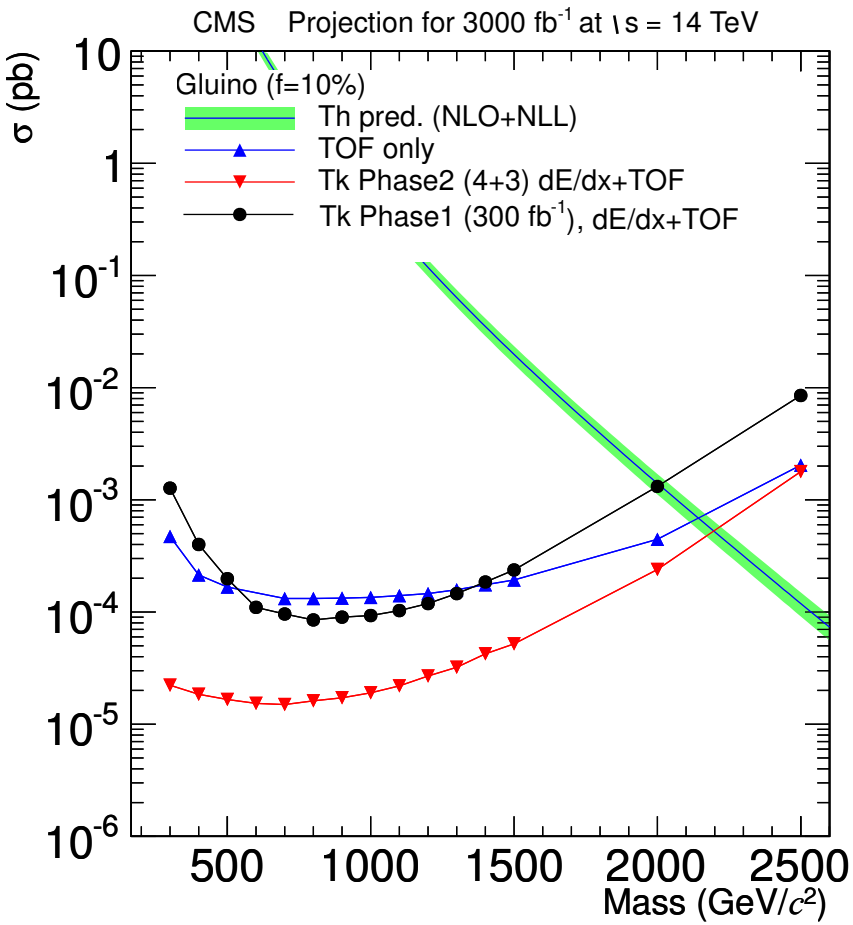
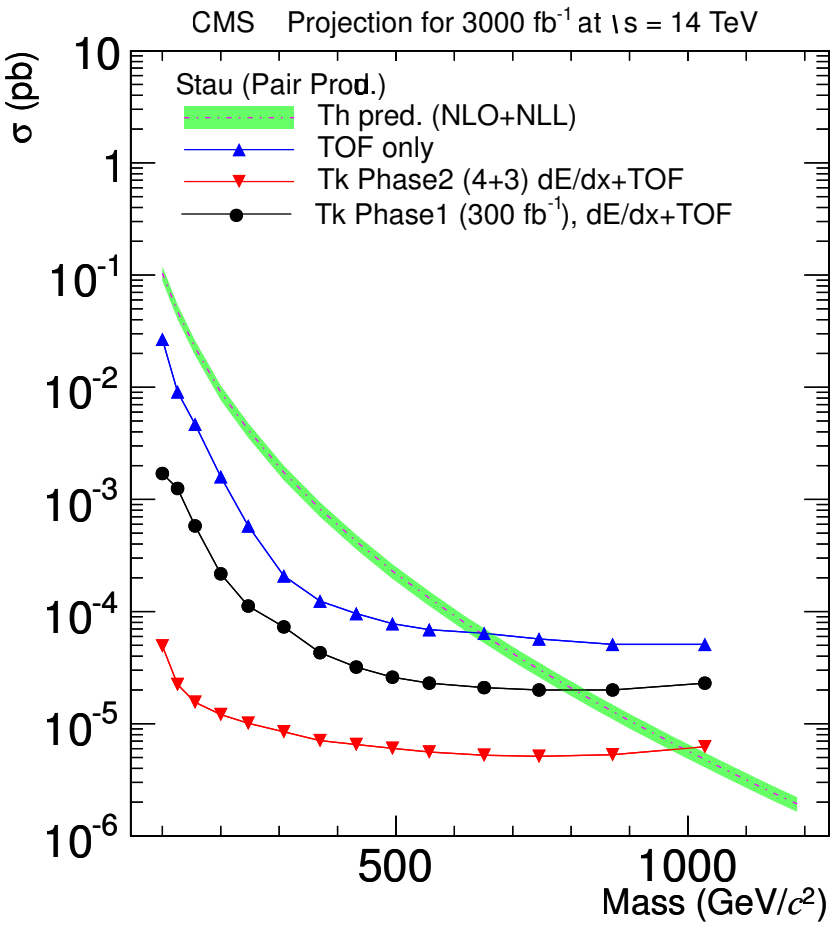

12.9 fb^{-1} (13 TeV)
CMS
Preliminary
Tracker + TOF
Theoretical Prediction
gluino (NLO+NLL)
stop (NLO+NLL)
stau, dir. prod. (NLO)
stau (NLO)
|Q| = 1e (LO)
|Q| = 2e (LO)
gluino; 50% g̃g
gluino; 10% g̃g
stop
stau; dir. prod.
stau
|Q| = 1e
|Q| = 2e
95% CL limit on σ (pb)
Mass (GeV)


ATLAS
√s = 13 TeV, 3.2 fb^{-1}
theory prediction
expected ±1σ limit
expected ±2σ limit
observed limit
√s = 8 TeV theory prediction
√s = 8 TeV, 19.1 fb^{-1} observed
Cross section [fb]
m$_{gluino}$ [GeV]


Drell-Yan only:
p
p
γ, Z
τ̃1(τ̃R)
τ̃1
incl. cascade decay
(assuming some GMSB model)
gluino; 50% g̃g
gluino; 10% g̃g
stop
stau; dir. prod.
stau
|Q| = 1e
|Q| = 2e
stau (NLO)
95% CL limit on
10−1
10−2
10−3
10−4
360
660
1000
1200
1700
−1800
2000

CMS-PAS-EXO-14-007 (sept. 2016)





	current	HL-LHC
gluino:	1.7 TeV	→ 2.2 TeV?
stop:	1.2 TeV	→ 1.7 TeV?
stau (GMSB):	660 GeV	→ 1.2 TeV?
stau (DY):	360 GeV	→ 1.0 TeV?

(or discovery?)

1. Motivations: Why LLCP?

2. Searches at (HL-)LHC

3. **Searches at FCC-hh**

- Muon radiative energy loss
- Muon momentum resolution

4. **Summary**

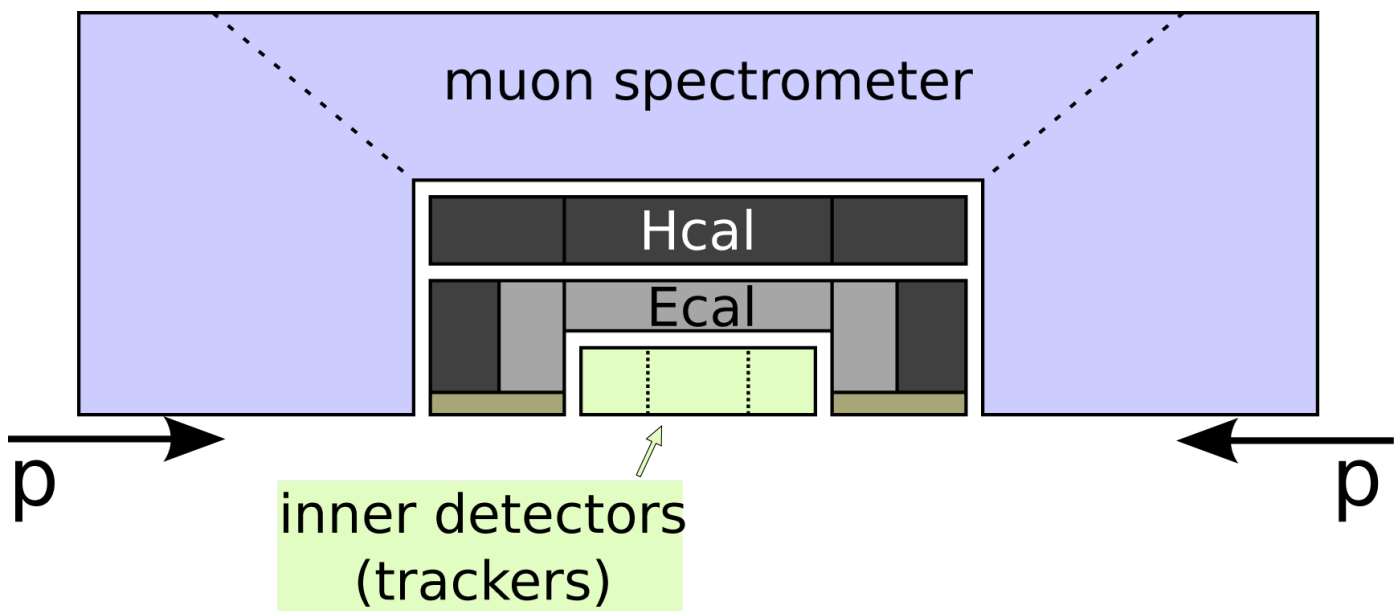
our selection flow

$\tilde{l}$ = reconstructed "muon" with

- $P_T > 500\,\text{GeV}$
- $|\eta| < 2.4$
- $0.4 < \hat{\beta} < 0.95$ (from ToF)
- $E_{\text{loss}} < 30\,\text{GeV}$

Cf.) ATLAS 8 TeV [**1411.6795**]

- $P_T > 70\,\text{GeV}$
- $|\eta| < 2.4$
- $0.2 < \hat{\beta} < 0.95$



1. Motivations: Why LLCP?

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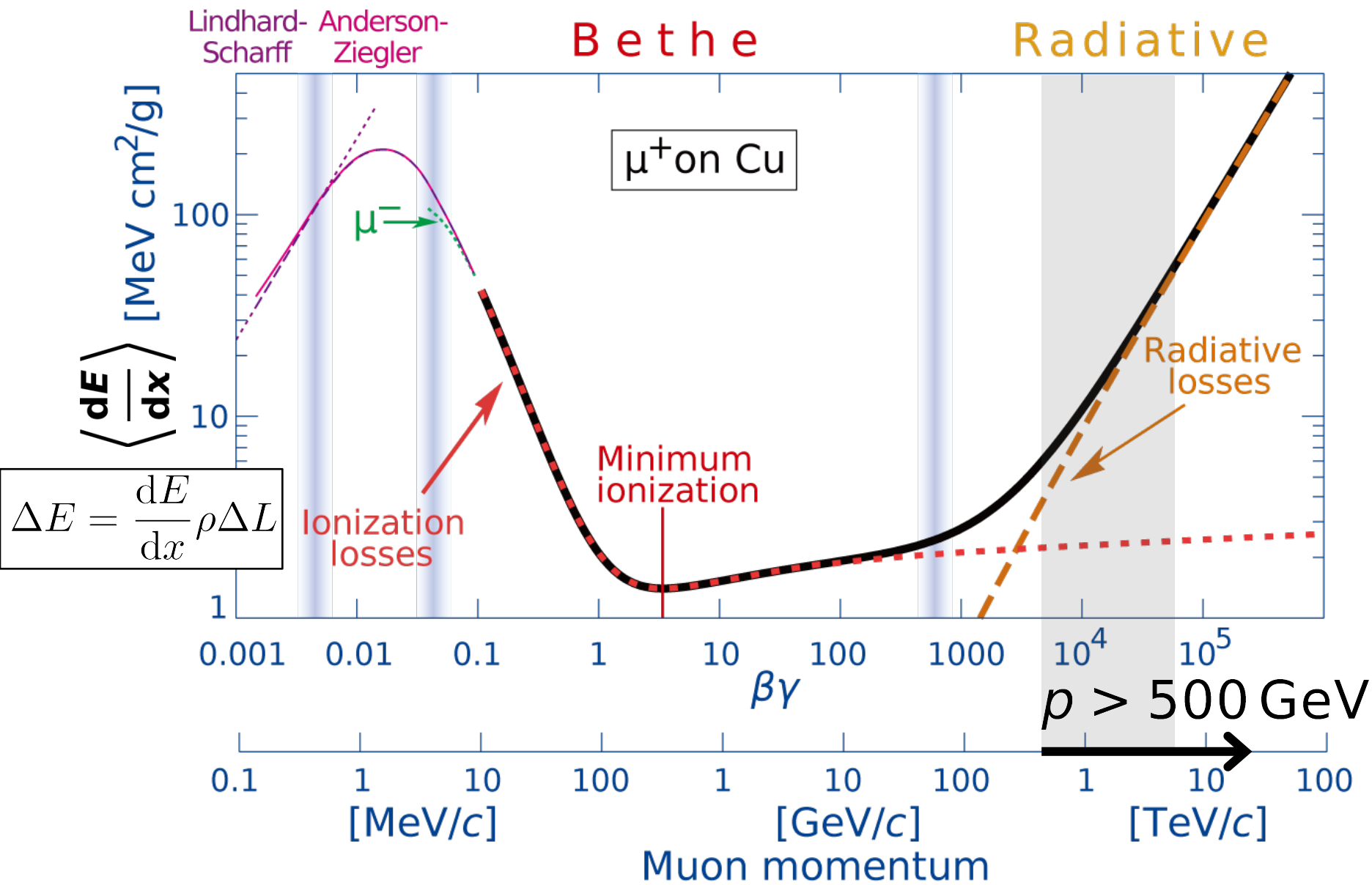
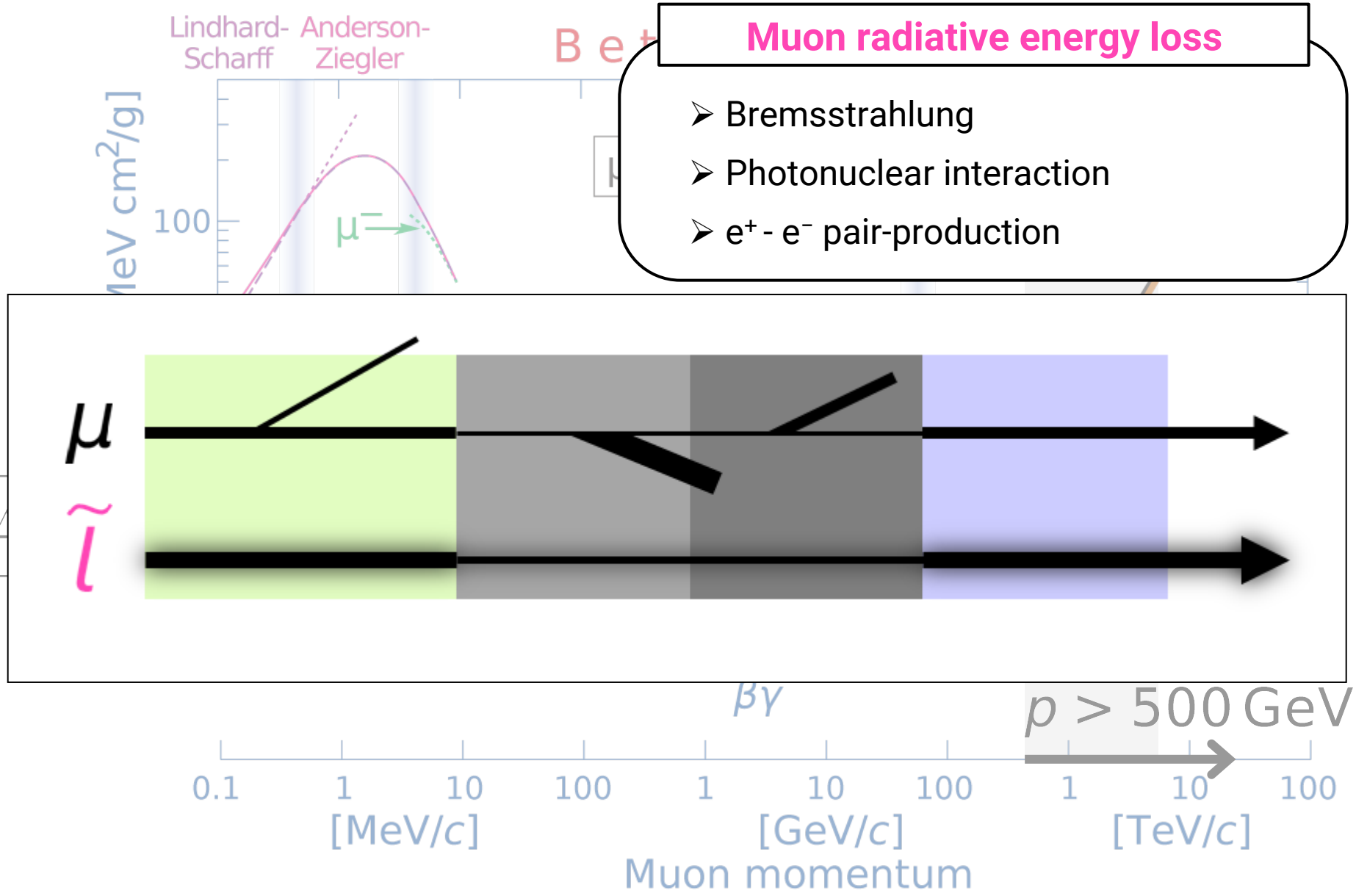
- **Muon radiative energy loss** for BKG rejection
- Muon momentum resolution

4. **Summary**



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

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
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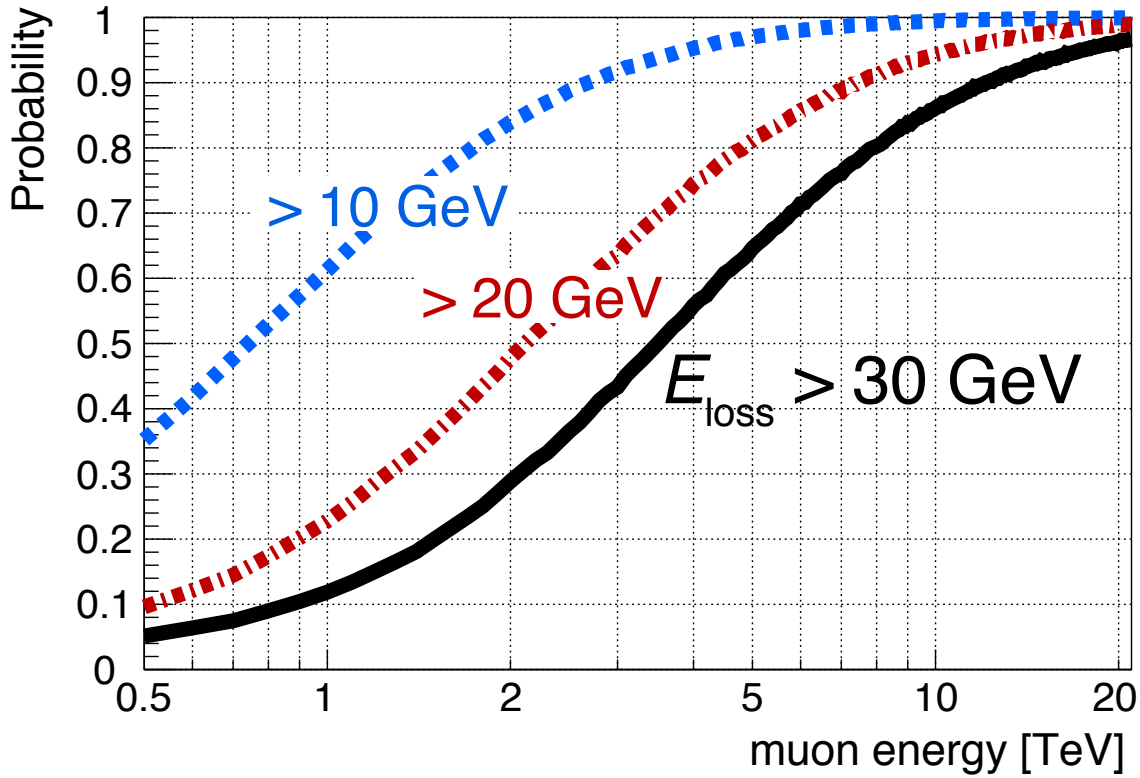
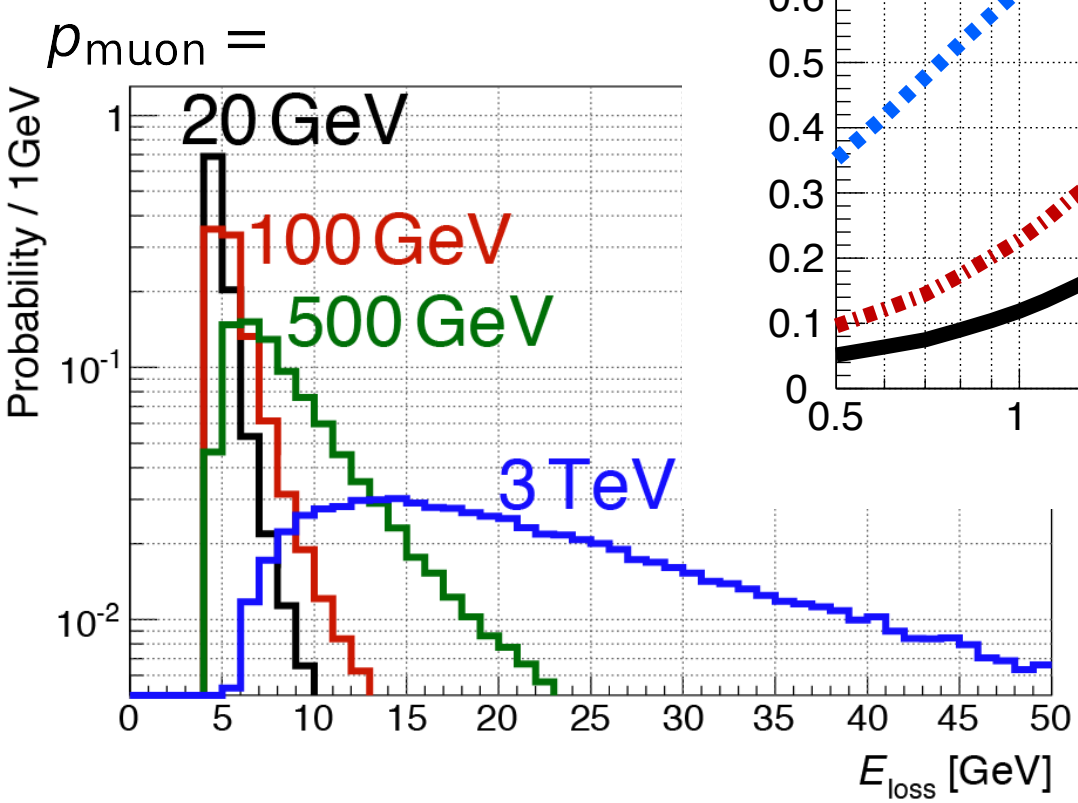
"calorimeter": approximated by iron (Fe) with 3m thickness.

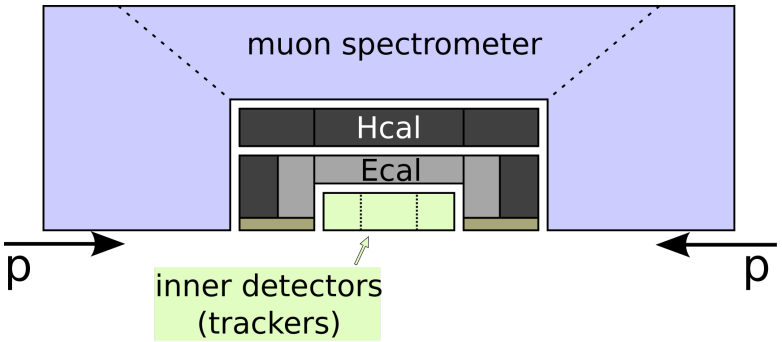
→ some of μ (P_T > 500 GeV): > 30 GeV energy deposit.





[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
- Pile-up not considered



- $\tilde{l}$-selection flow

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  - $P_T > 500$ GeV
  - $|\eta| < 2.4$
  - $0.4 < \hat{\beta} < 0.95$ (from ToF)
  - $E_{loss} < 30$ 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
$\epsilon_{acc}\epsilon_{eff}$	48%	77%	—

$\times 0.82$

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

- $|\eta| < 2.4$
- $0.4 < \hat{\beta} < 0.95$ (from ToF)
- $E_{loss} < 30$ GeV

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

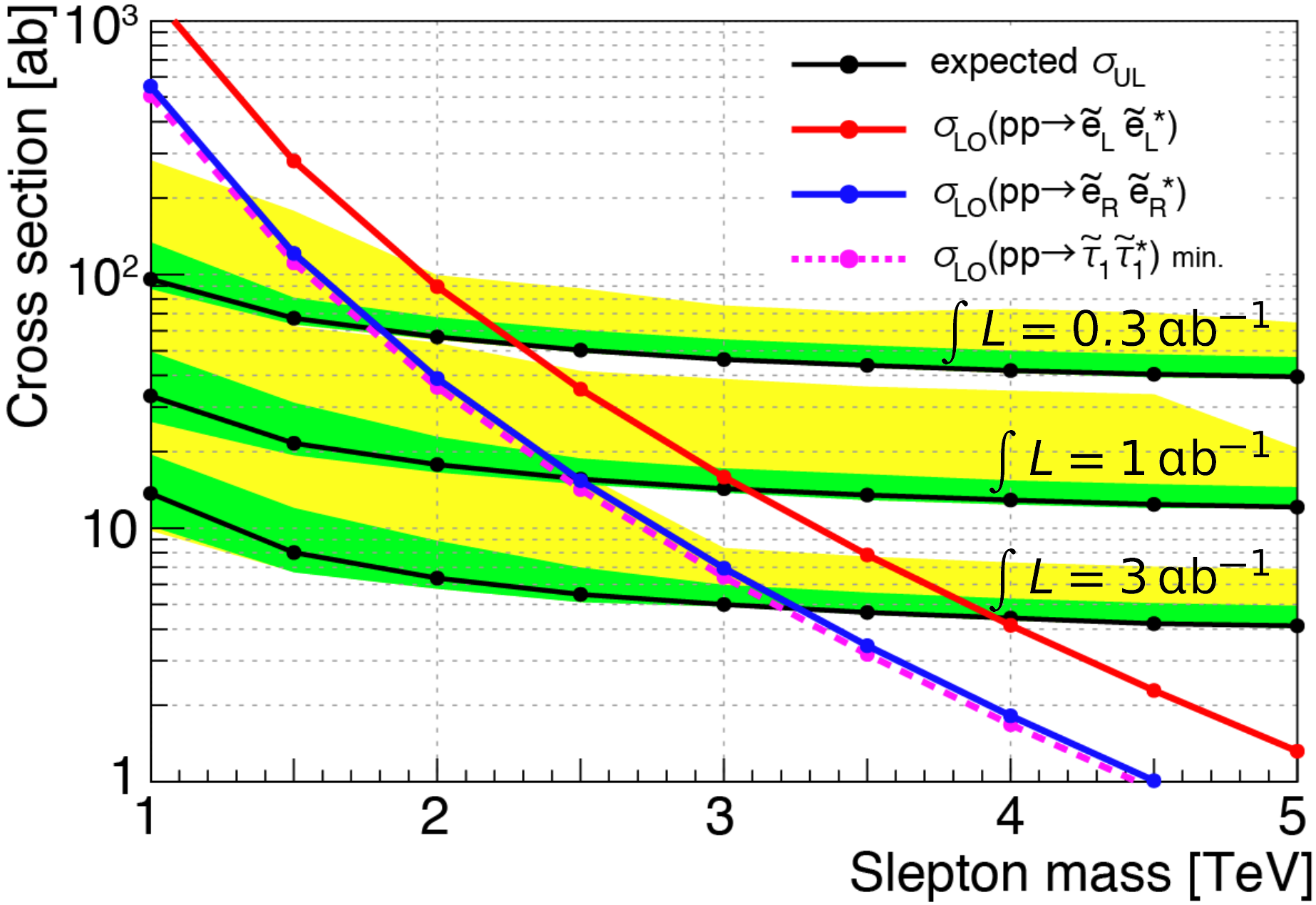
	1 TeV	3 TeV	BKG
$N_{LLCP} = 0$	483	1.34	(a lot)
$N_{LLCP} = 1$	378	4.46	2.78×10^5
$N_{LLCP} = 2$	424	10.1	34.6

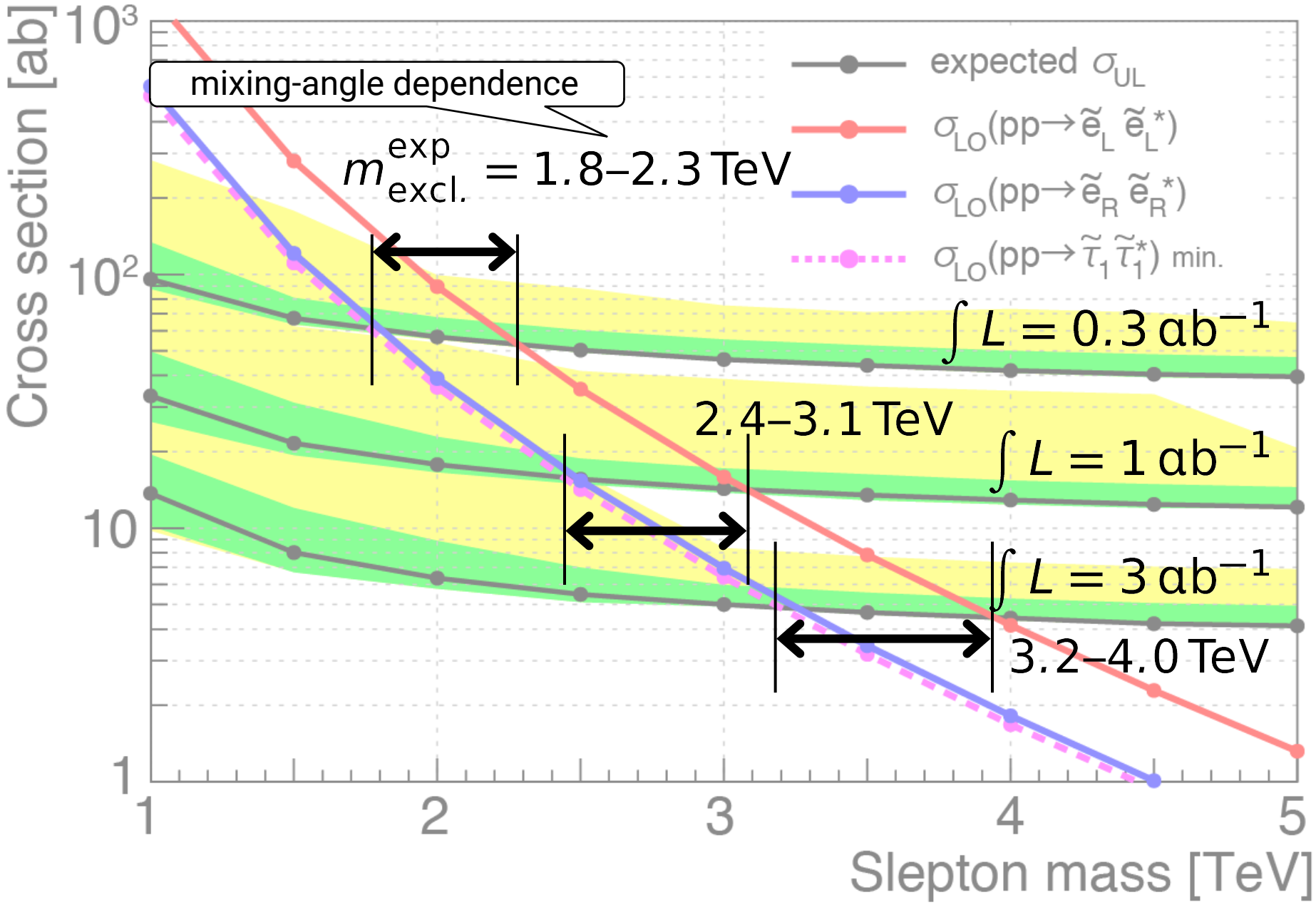
SR

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

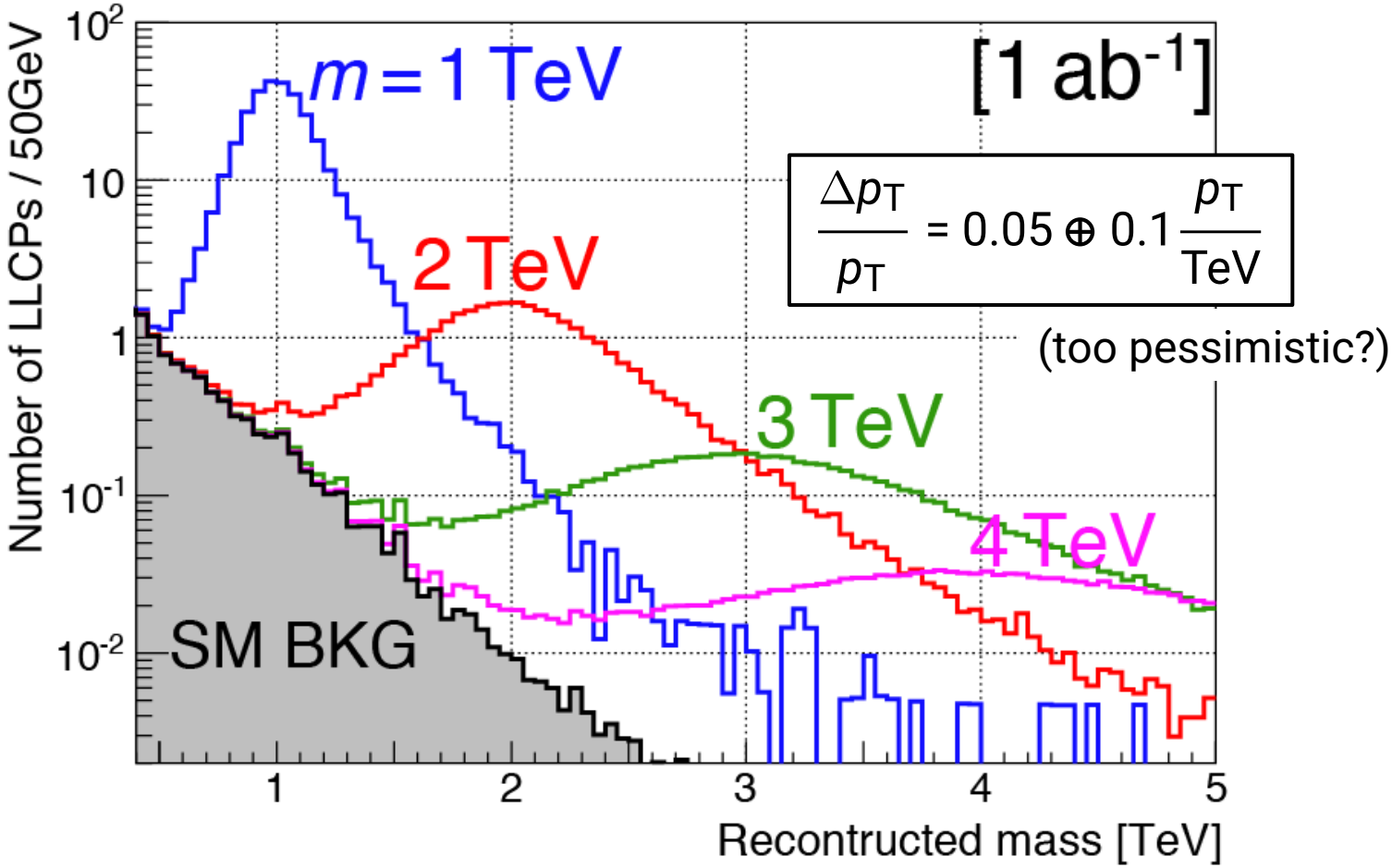
Result: Expected exclusion limit

Feng, Sl, Shadmi, Tarem [1505.02996]



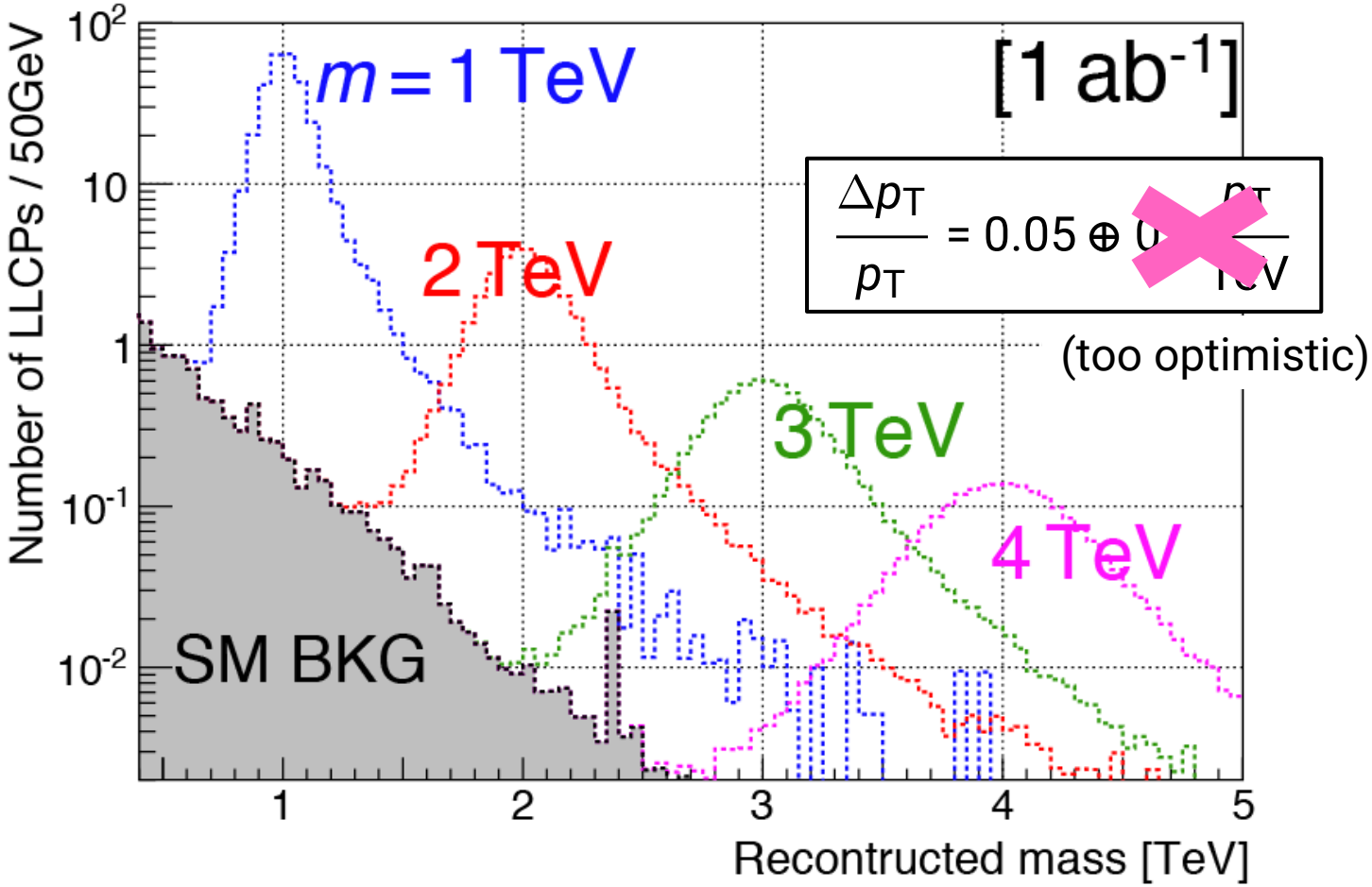

Cross section [ab]
10^3
10^2
10
1
1
2
3
4
5
Slepton mass [TeV]
mixing-angle dependence
$m^{\text{exp}}_{\text{excl.}} = 1.8\text{–}2.3\,\text{TeV}$
2.4–3.1 TeV
3.2–4.0 TeV
expected σ_{UL}
$\sigma_{\text{LO}}(pp \to \tilde{e}_L\, \tilde{e}_L^*)$
$\sigma_{\text{LO}}(pp \to \tilde{e}_R\, \tilde{e}_R^*)$
$\sigma_{\text{LO}}(pp \to \tilde{\tau}_1\, \tilde{\tau}_1^*)$ min.
$\int L = 0.3\,\text{ab}^{-1}$
$\int L = 1\,\text{ab}^{-1}$
$\int L = 3\,\text{ab}^{-1}$

Feng, SI, Shadmi, Tarem [1505.02996]



FCC-hh trk. goal: 10–20% @ 10 TeV (Michele Selvaggi's talk) $\left(= \frac{p}{\beta\gamma} = \frac{p_T \cosh\eta}{\beta\gamma}\right)$

cf. ATLAS 7 TeV commissioning:
(ID-barrel, MS-barrel, MS-extbarrel) = (38%, 14%, 6%) @ 1 TeV



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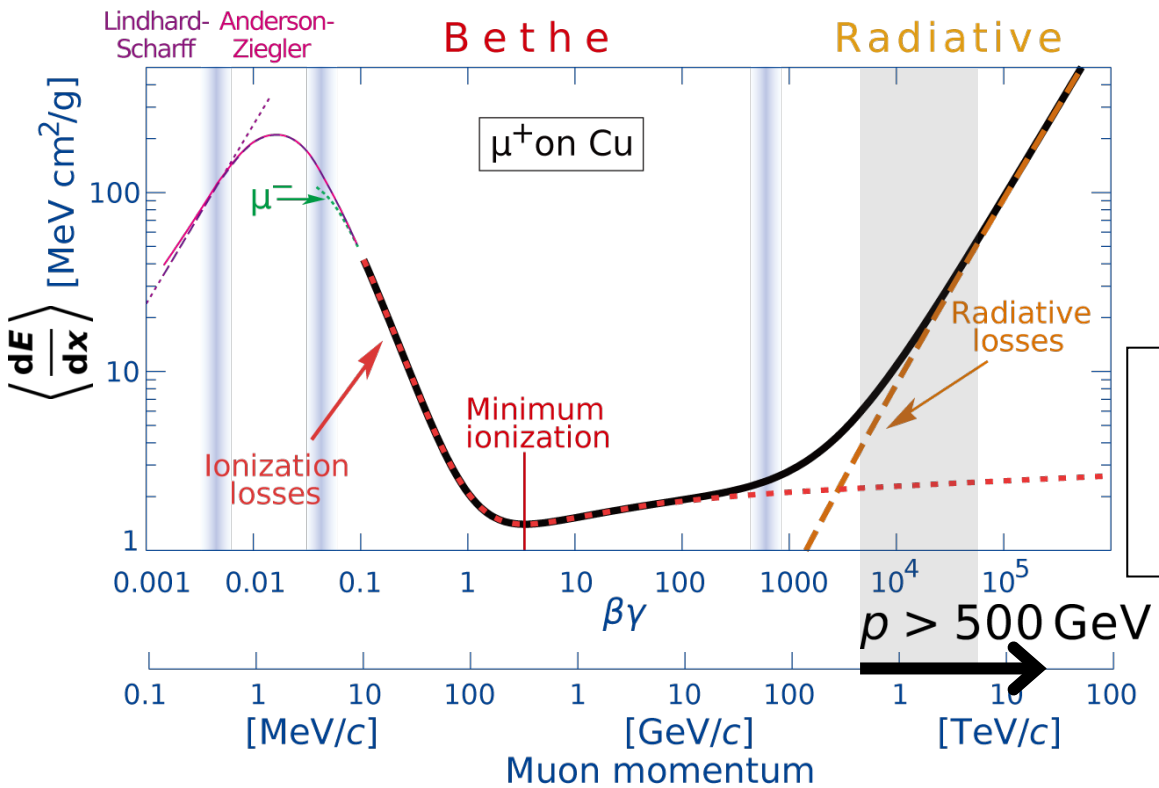
1. Motivations: Why LLCP?
2. Searches at (HL-)LHC
3. Searches at FCC-hh
   - Muon radiative energy loss for BKG rejection
   - Our simulation
4. **Summary: FCC-hh prospects**

- 100 TeV FCC-hh mass reach (Drell–Yan $\tilde{l}$ or $\tilde{\tau}$)

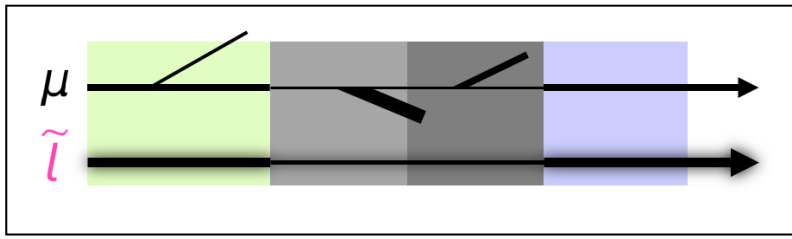
	$0.3ab^{-1}$	$1ab^{-1}$	$3ab^{-1}$
Exclusion	1.8–2.3	2.4–3.1	3.2–4.0
Discovery	1.6–2.2	2.3–3.0	3.1–4.0

in TeV

- **"Muon radiative energy loss"**



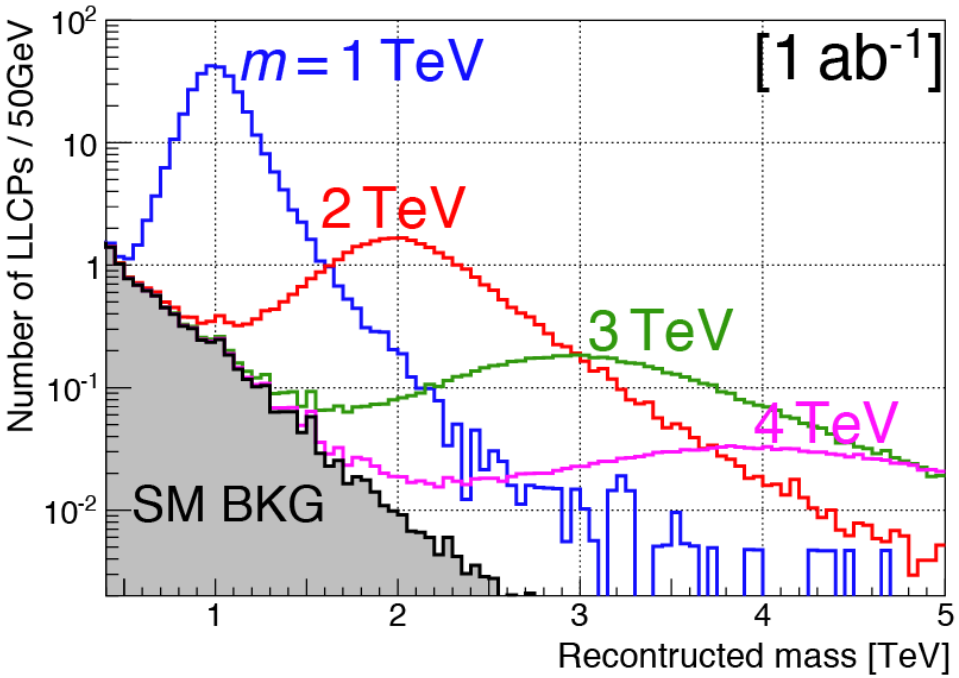
- Bremsstrahlung
- Photonuclear interaction
- e^+-e^-pair-production



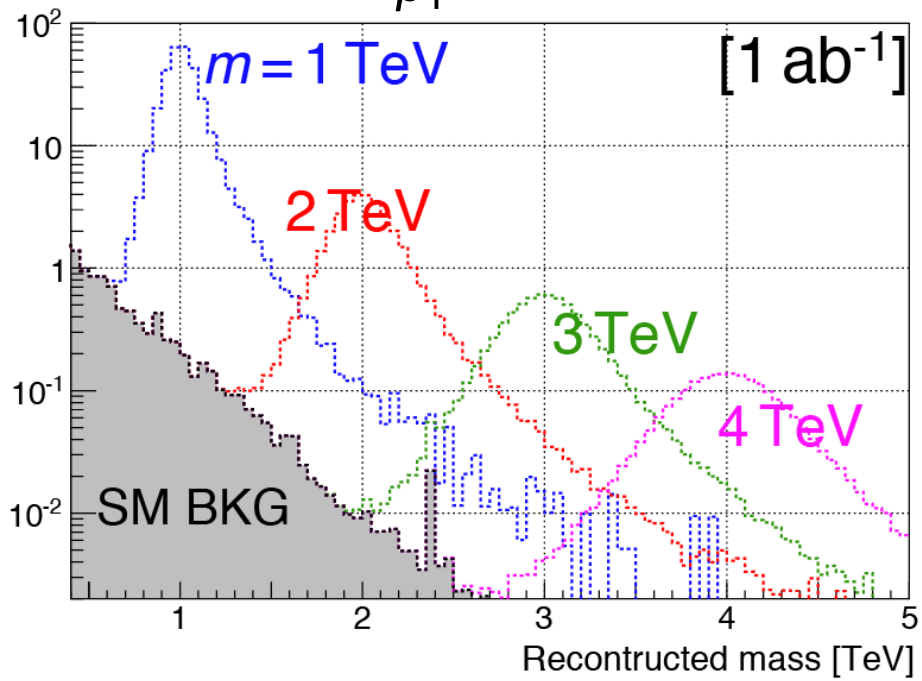
→ **34%** of BKG reduction

100 TeV FCC-hh muon momentum resolution

$$\frac{\Delta p_T}{p_T} = 0.05 \oplus 0.1 \frac{p_T}{\mathrm{TeV}}$$



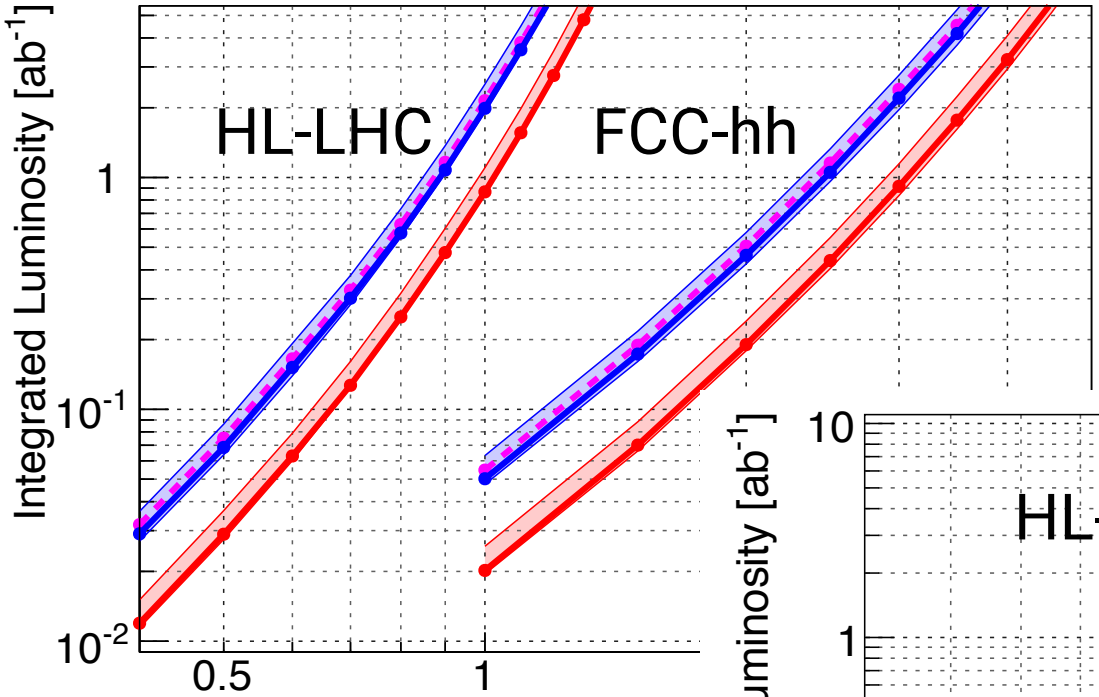
$$\frac{\Delta p_T}{p_T} = 0.05$$



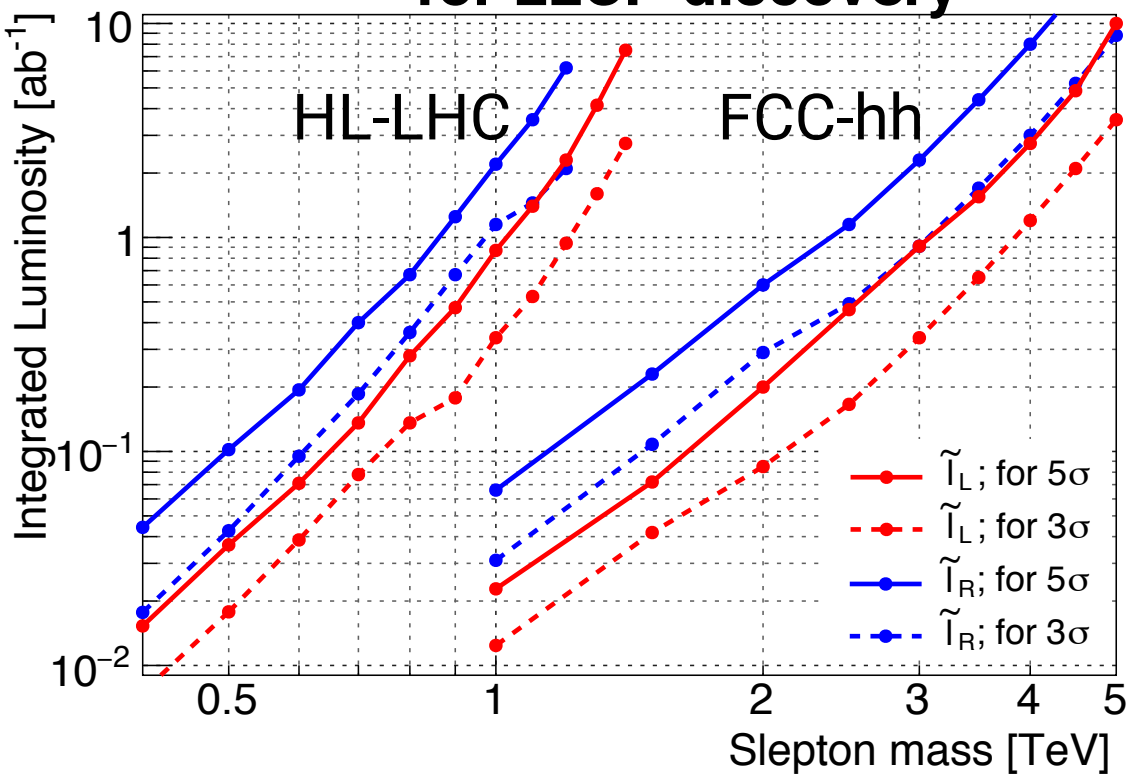
(FCC-hh trk. goal: $\frac{\Delta p_T}{p_T} = (\mathrm{const}) \oplus \frac{0.01-0.02}{\mathrm{TeV}}$ **)**

Exclusion & Discovery Reach

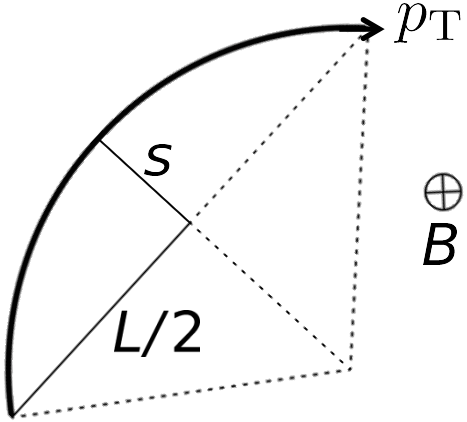
for LLCP exclusion



for LLCP discovery



Momentum resolution

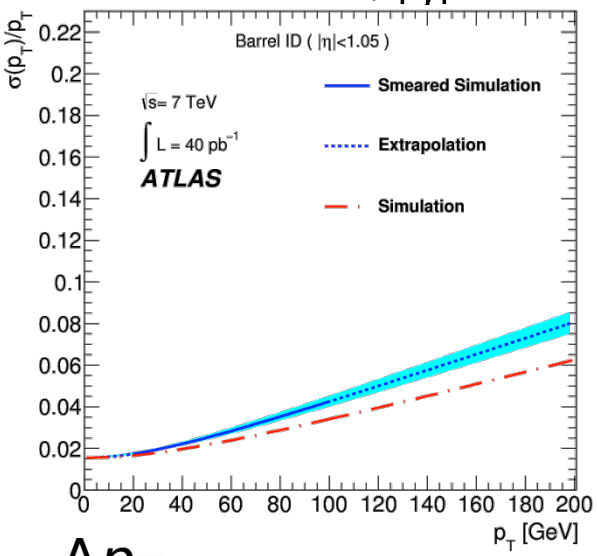


$$p_{\mathrm{T}} = \frac{L^2}{8s}|q|B \Longrightarrow \Delta p_{\mathrm{T}} = \frac{L^2|q|B}{8}\frac{\Delta s}{s^2} = \frac{8\Delta s}{L^2|q|B}\cdot p_{\mathrm{T}}^2$$

$$\therefore \Delta p_{\mathrm{T}} \propto p_{\mathrm{T}}^2$$

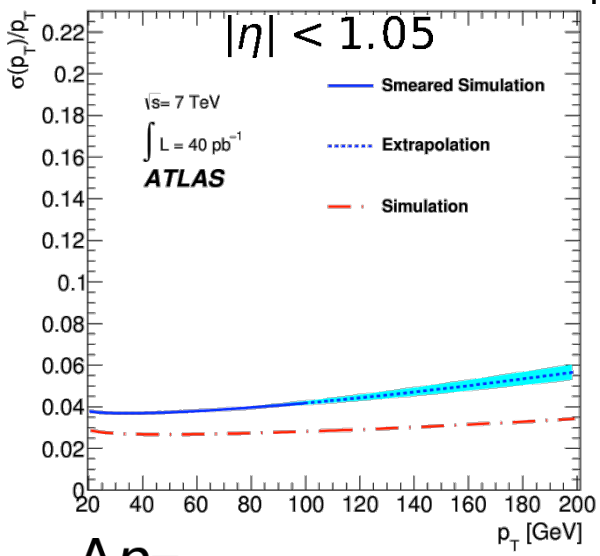
ATLAS 7 TeV results on muon momentum resolution

Inner Detector, $|\eta| < 1.05$

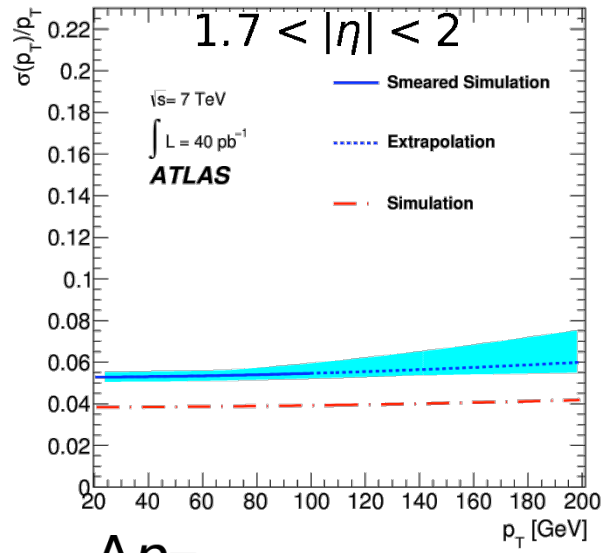


$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.38 p_{\mathrm{T}}/\mathrm{TeV}$$

Muon spectrometer



$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.14 p_{\mathrm{T}}/\mathrm{TeV}$$



$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.06 p_{\mathrm{T}}/\mathrm{TeV}$$

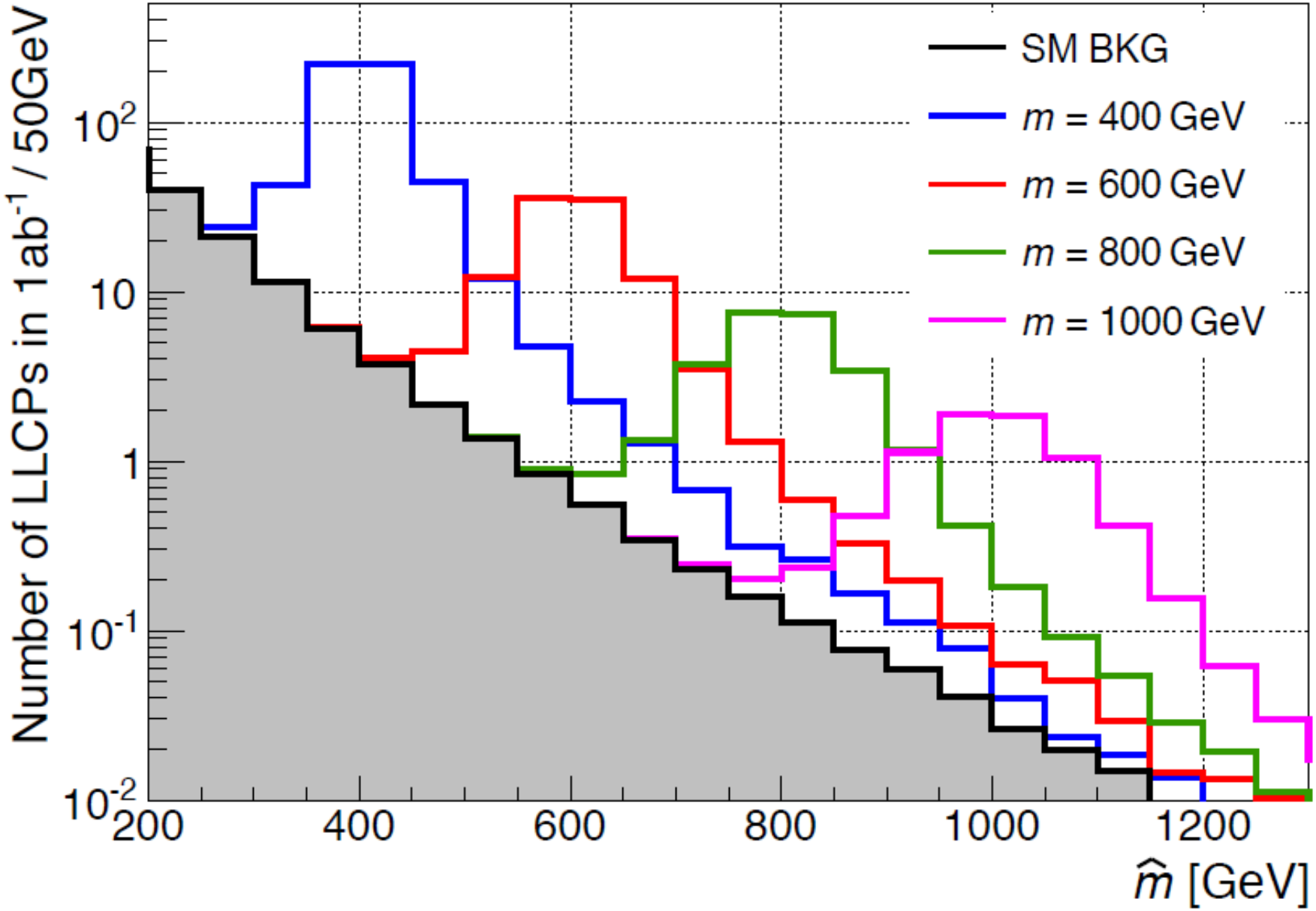
HL-LHC: our simulation

- 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

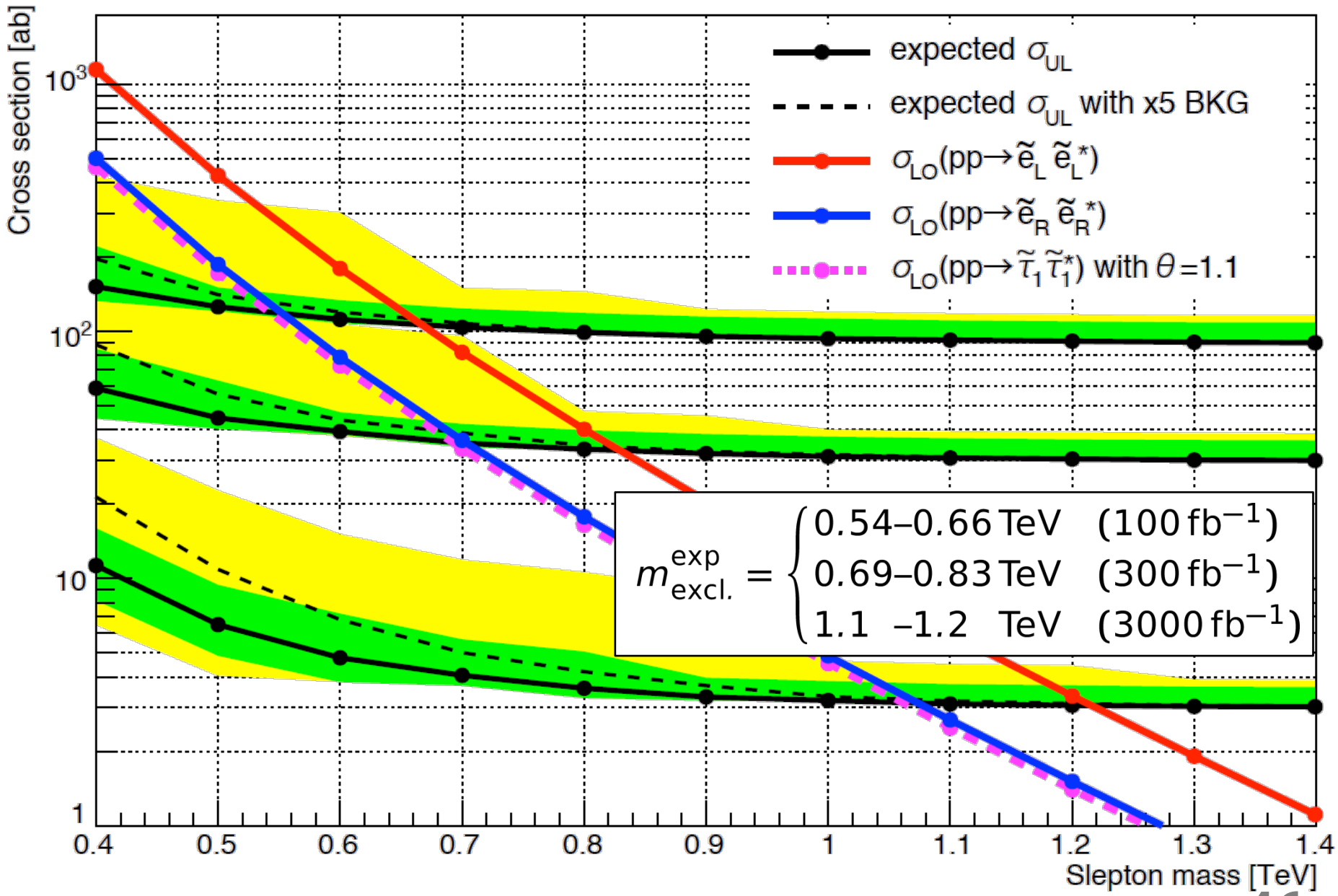
  reconstructed "muon" w.
  - $p_T > \mathbf{100}$ GeV
  - $|\eta| < 2.4$
  - $0.3 < \hat{\beta} < 0.95$
  - ~~$E_{loss} < 30$ GeV~~
- Event selection
  - two $\tilde{l}$-candidates

14 TeV LHC expectation



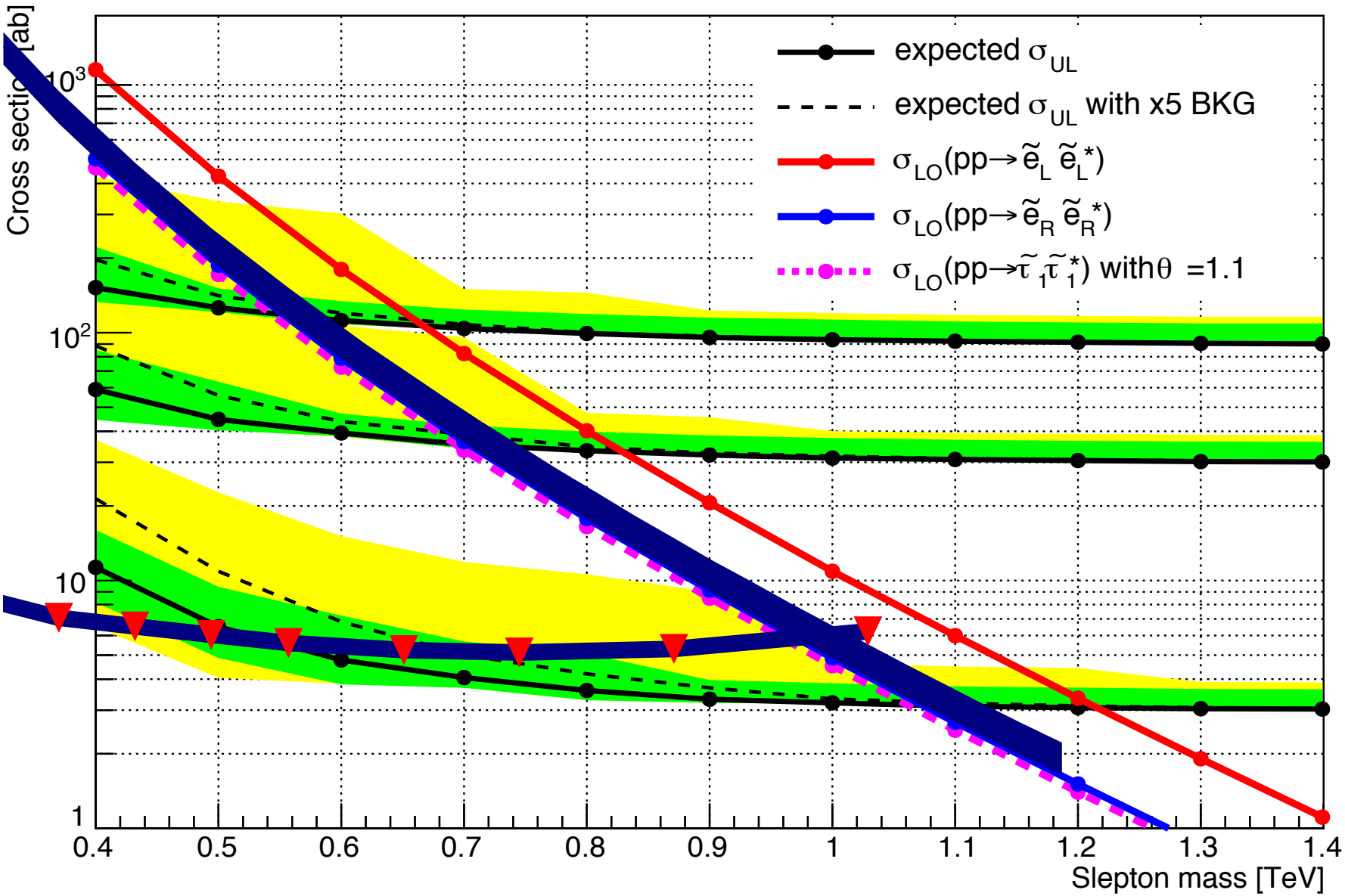
14 TeV LHC expectation

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



Compare with CMS official

CMS-PAS-EXO-14-007 (sept. 2016)



Why β>0.4? (slepton dE/dx)

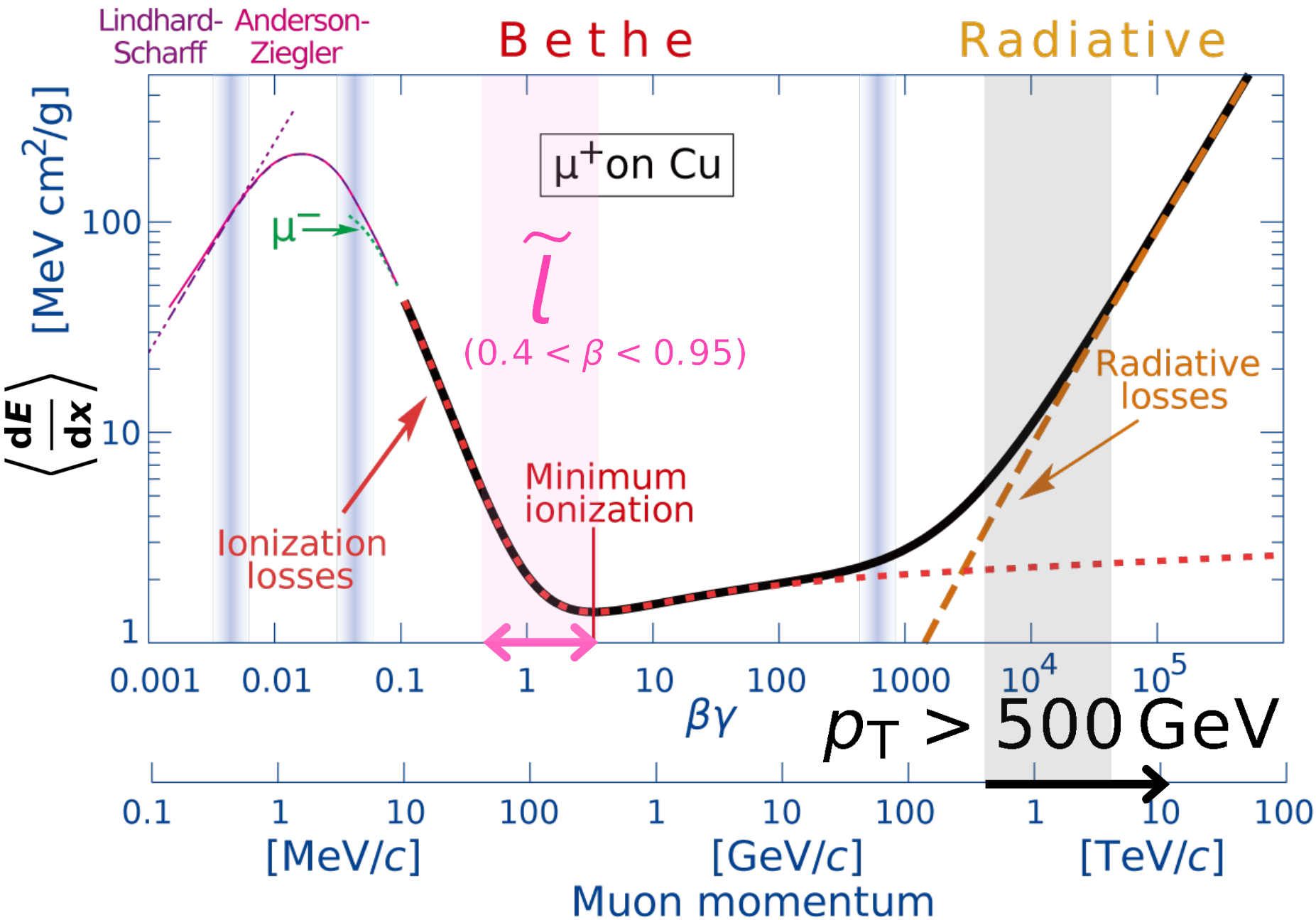
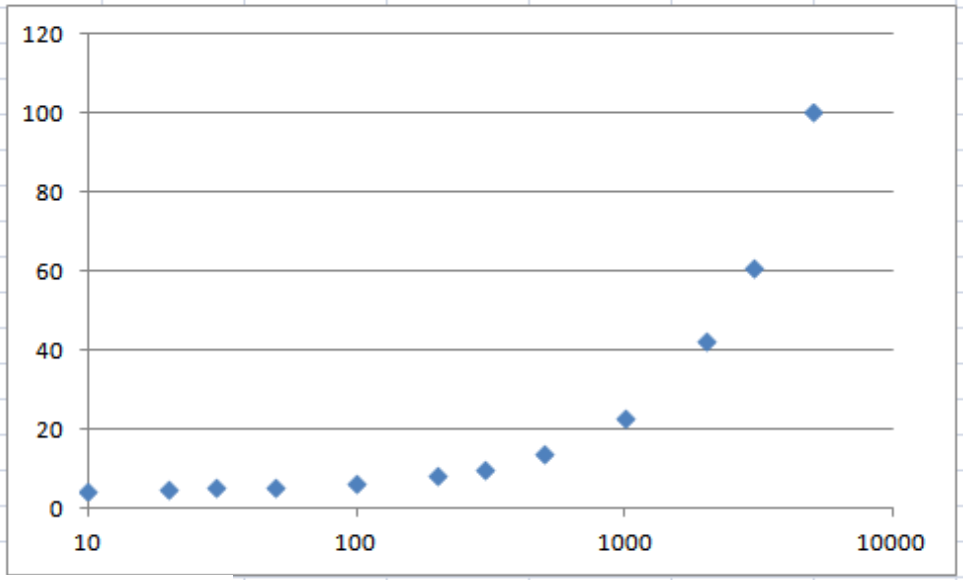


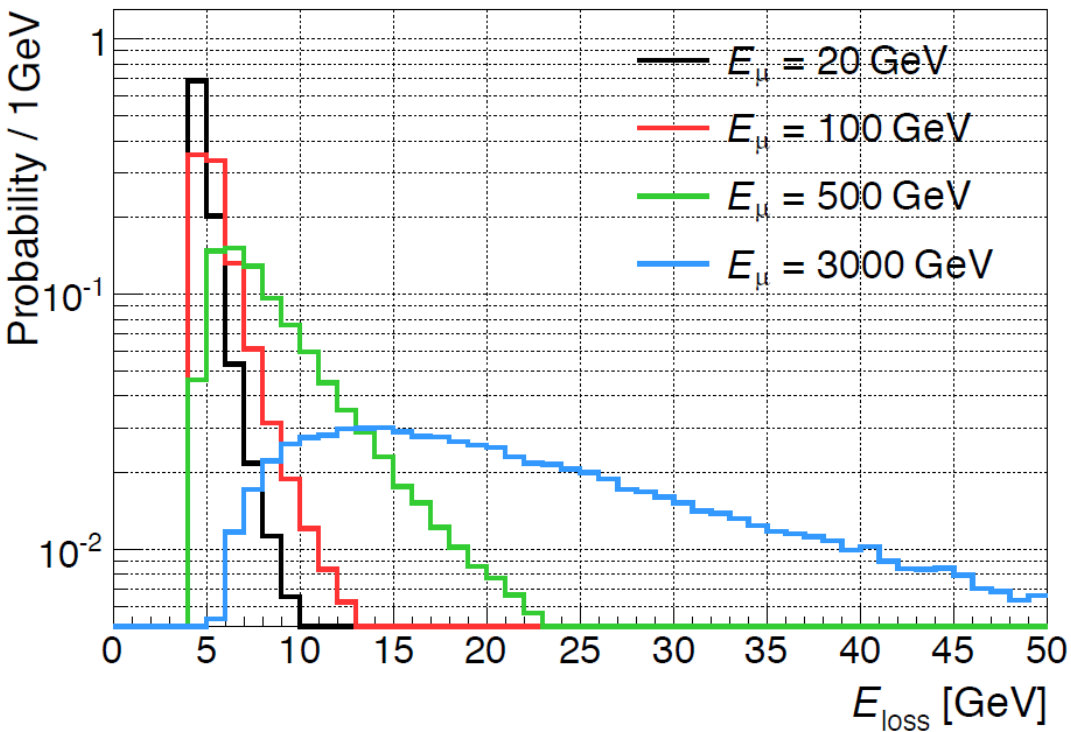
Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

Mean value of E_{loss}?

Averaged muon energy loss in 3m iron (internal)

10	4.64883
20	5.0253
30	5.27343
50	5.68943
100	6.60542
200	8.43546
300	10.2127
500	13.9577
1000	23.231
2000	42.3777
3000	61.1561
5000	100.336





Note that the mean is much larger than the median because of its long long long tail.

dE/dx to measure β

Mass measurement = Measurement of velocity β

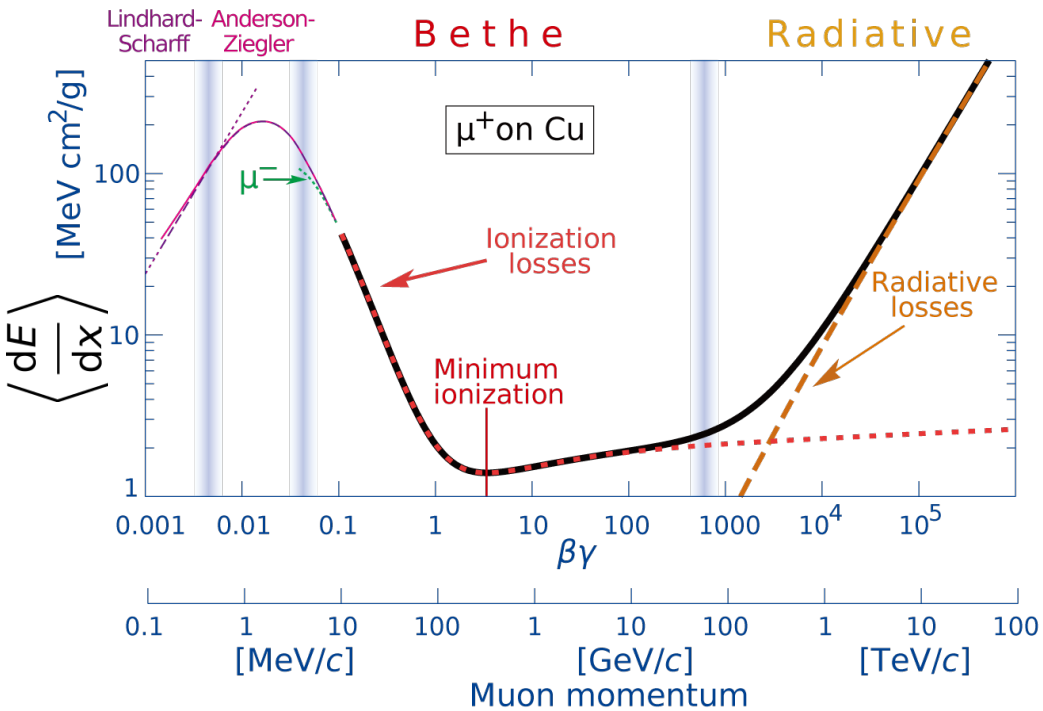
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

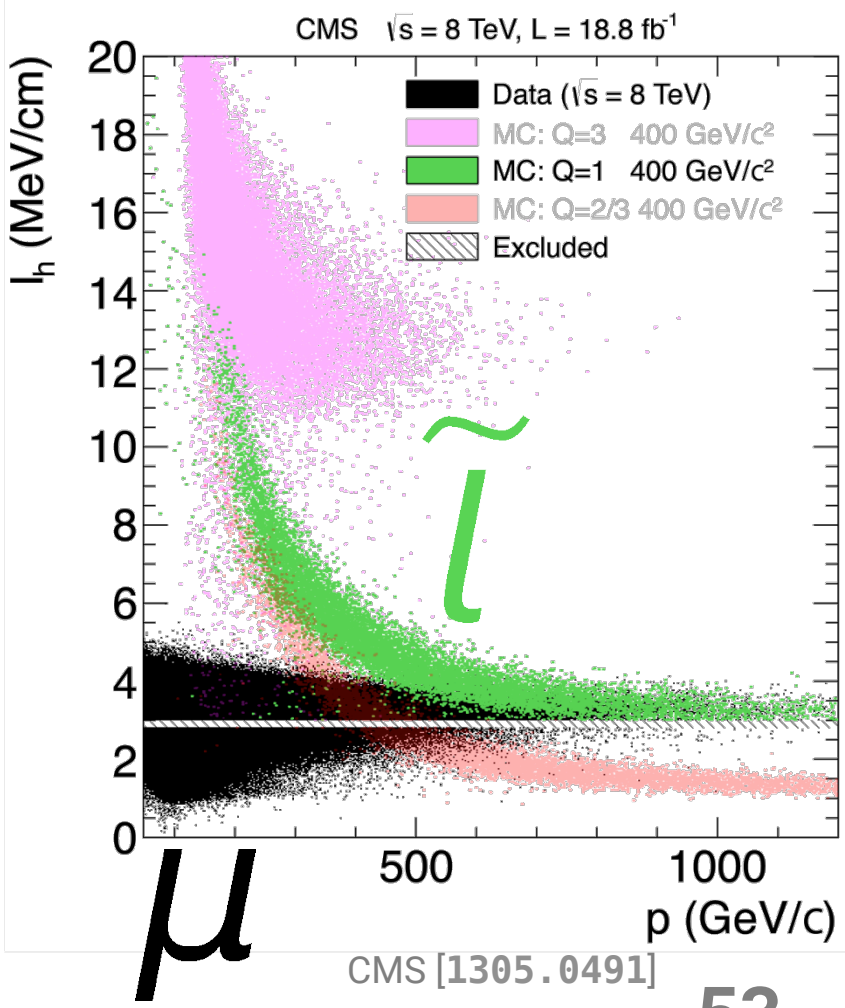
$$I_h = \rho \cdot \frac{\mathrm{d}E}{\mathrm{d}x}\Big|_{\text{estimated}}$$

- TOF : time-of-flight

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

- dE/dx : ionization energy loss





CMS [1305.0491]

Extra materials

$$\Gamma(\tilde{\chi}^{\pm} \to \tilde{\chi}^0 \pi^{\pm}) = \Gamma(\pi^{\pm} \to \mu^{\pm}\nu_{\mu}) \times \frac{16\delta m^3}{m_{\pi} m_{\mu}^2} \left(1 - \frac{m_{\pi}^2}{\delta m^2}\right)^{1/2} \left(1 - \frac{m_{\mu}^2}{m_{\pi}^2}\right)^{-2}$$

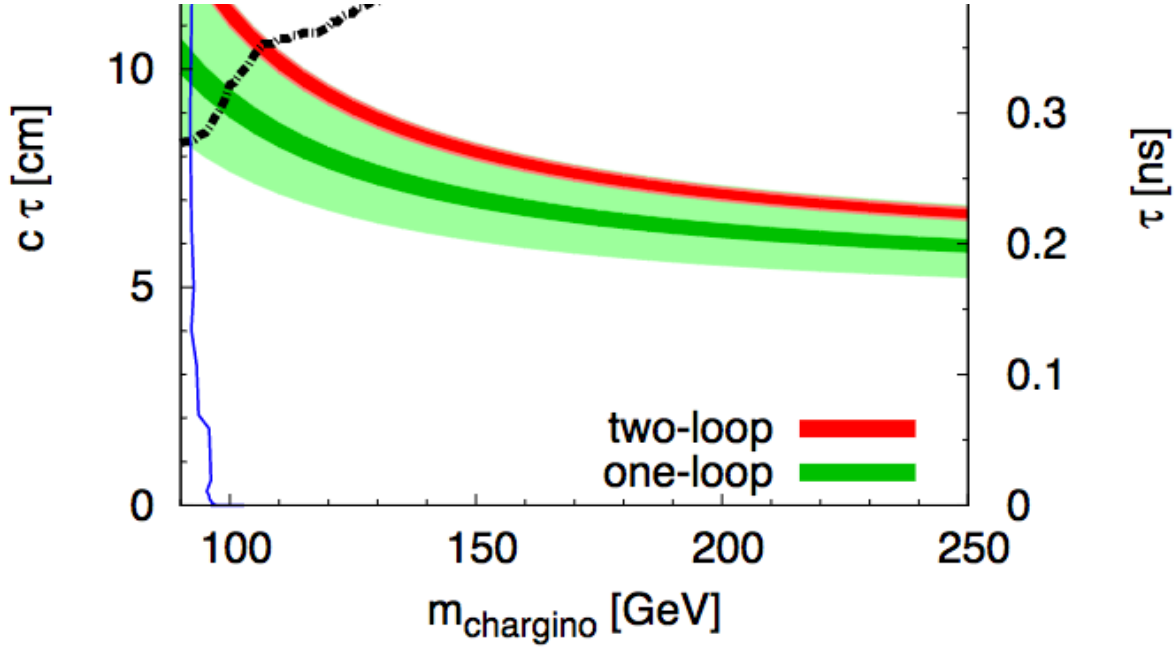


Figure 6: The lifetime of charged wino evaluated by using δm at the one-loop (green band) and two-loop (red band). We neglected the next-to-leading order corrections to the lifetime of the charged wino estimated in terms of the pion decay rate, which is expected to be a few percent correction. The black chain line is the upper limit on the lifetime for a given chargino mass by the ATLAS collaboration at 95 % CL ($\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7$ fb^{-1}) [28]. The blue line shows the constraints which are given by the LEP2 constraints [30]–[33].

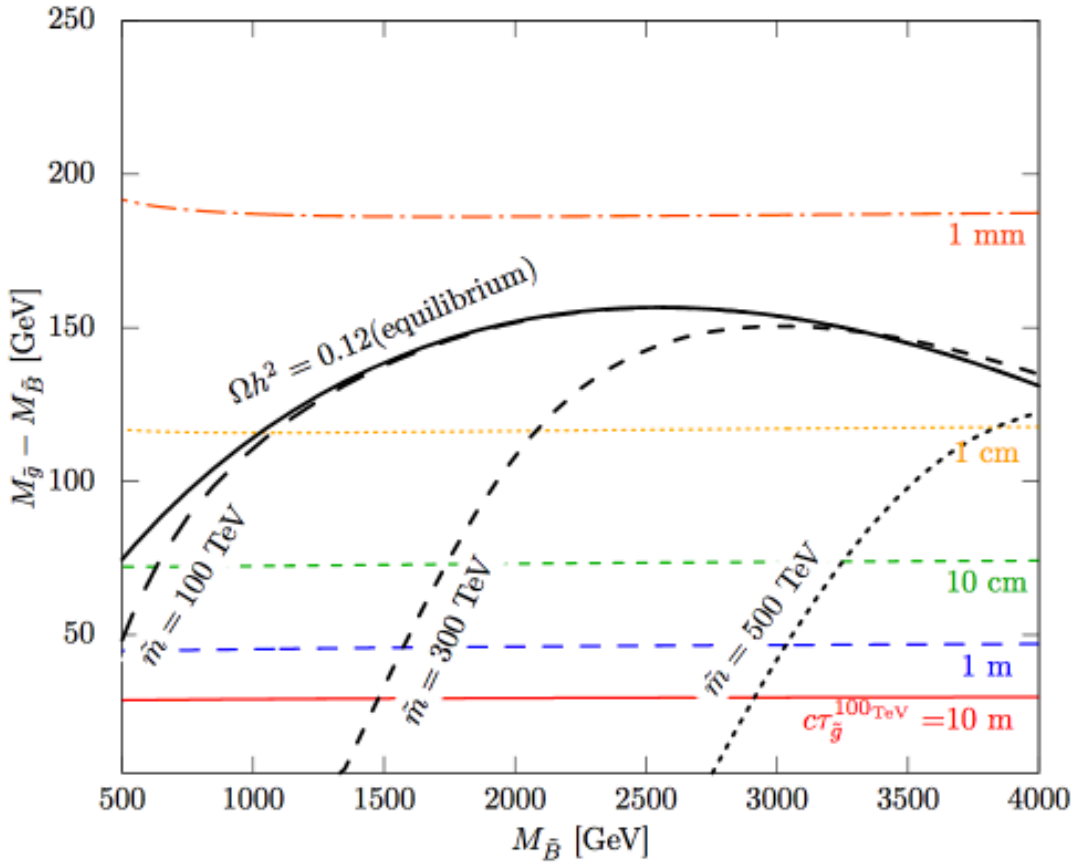


Figure 3: Decay length of the gluino $c\tau_{\tilde{g}}^{100\text{TeV}}$ with the squark mass $\tilde{m} = 100$ TeV in colored (almost horizontal) lines. Mass difference ΔM with which the thermal relic of the bino DM agrees to $\Omega_{\text{DM}}h^2 = 0.12$ is also shown in the black solid line for the case in which the bino-gluino chemical equilibrium is assumed, while the cases for $\tilde{m} = 100$, 300 and 500 TeV are given in the other black lines.