הטכניון
מכון טכנולוגי
לישראל
TECHNION
Israel Institute
of Technology

Long-lived sleptons at a 100 TeV pp collider

(and at the 14 TeV LHC)

Sho IWAMOTO（岩本　祥）

13 Dec. 2015

IPS 61st annual meeting @ Bar Ilan University

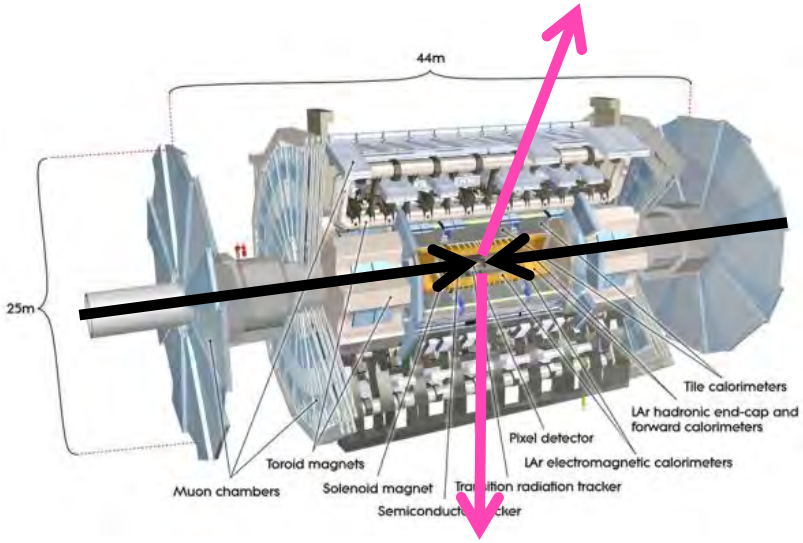
Based on

J. L. Feng (UC Irvine), SI, Y. Shadmi, S. Tarem (Technion) [1505.02996]

Sleptons $\tilde{l}$: a particle predicted in SUSY

[SUSY-partner of leptons]

- Mass $\gtrsim 100\,\mathrm{GeV}$ (LEP)
- Charge: EM-charged
- Lifetime: ?????
  - If long-lived (“stable”) $\Longrightarrow$ charged track



- Expected reach "$m_{\tilde{l}}$"

  at 100 TeV pp collider

- New phenomenon

  at 100 TeV pp collider

  "Muon radiative energy loss"

1. Motivation for long-lived $\tilde{l}$

2. searches at the **LHC**

3. at **100 TeV collider?**

- Muon radiative energy loss for BKG reduction

4. Results

- Expected reach: $m_{\tilde{l}}$

1. **Motivation** for long-lived $\tilde{l}$

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4. **Results**

- Expected reach: $m_{\tilde{l}}$

$$\Omega_{\rm DM} h^2 = 0.12$$ ... how to realize?

- A hypothesis: "superWIMP scenario"

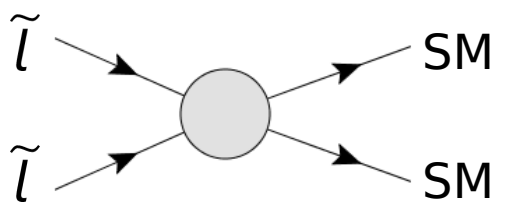
LSP = $\tilde{G}$, NLSP = $\tilde{l}$ ... long-lived $\tilde{l}$

$$\tau(\tilde{l} \to l\tilde{G}) = \underbrace{5.7 \times 10^{-7}\,\mathrm{sec}}_{\equiv 170\,\mathrm{m}} \cdot \left(\frac{m_{\tilde{l}}}{1\,\mathrm{TeV}}\right)^{-5} \left(\frac{m_{\tilde{G}}}{1\,\mathrm{MeV}}\right)^{2}$$

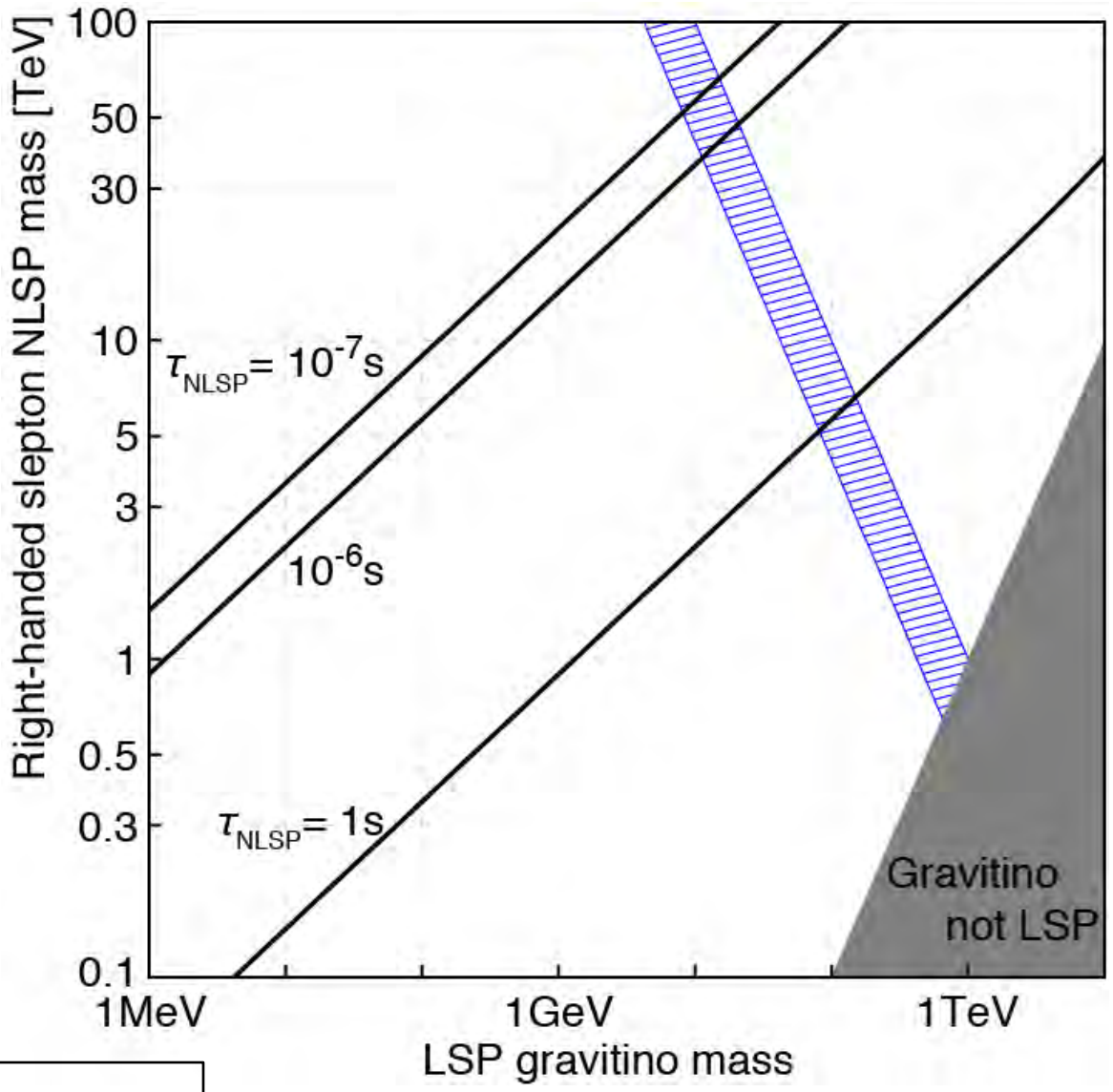
$\Rightarrow$ $\tilde{l}$: freeze-out with $\Omega_{\rm slepton} h^2 \gg 0.12$,

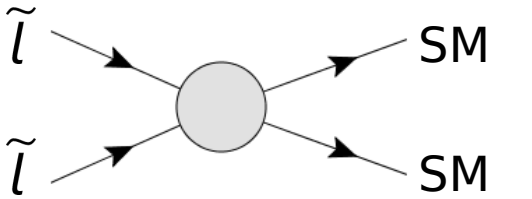
and then decay.

$$\Omega_{\tilde{G}} h^2 = \frac{m_{\tilde{G}}}{m_{\tilde{l}}} \Omega_{\rm slepton} h^2$$



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





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1. Motivation for long-lived $\tilde{l}$ $= \Omega_{\rm DM} h^2$

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

2. searches at the **LHC**

3. at **100 TeV collider?**

➢ Muon radiative energy loss for BKG reduction

4. Results

➢ Expected reach: $m_{\tilde{l}}$

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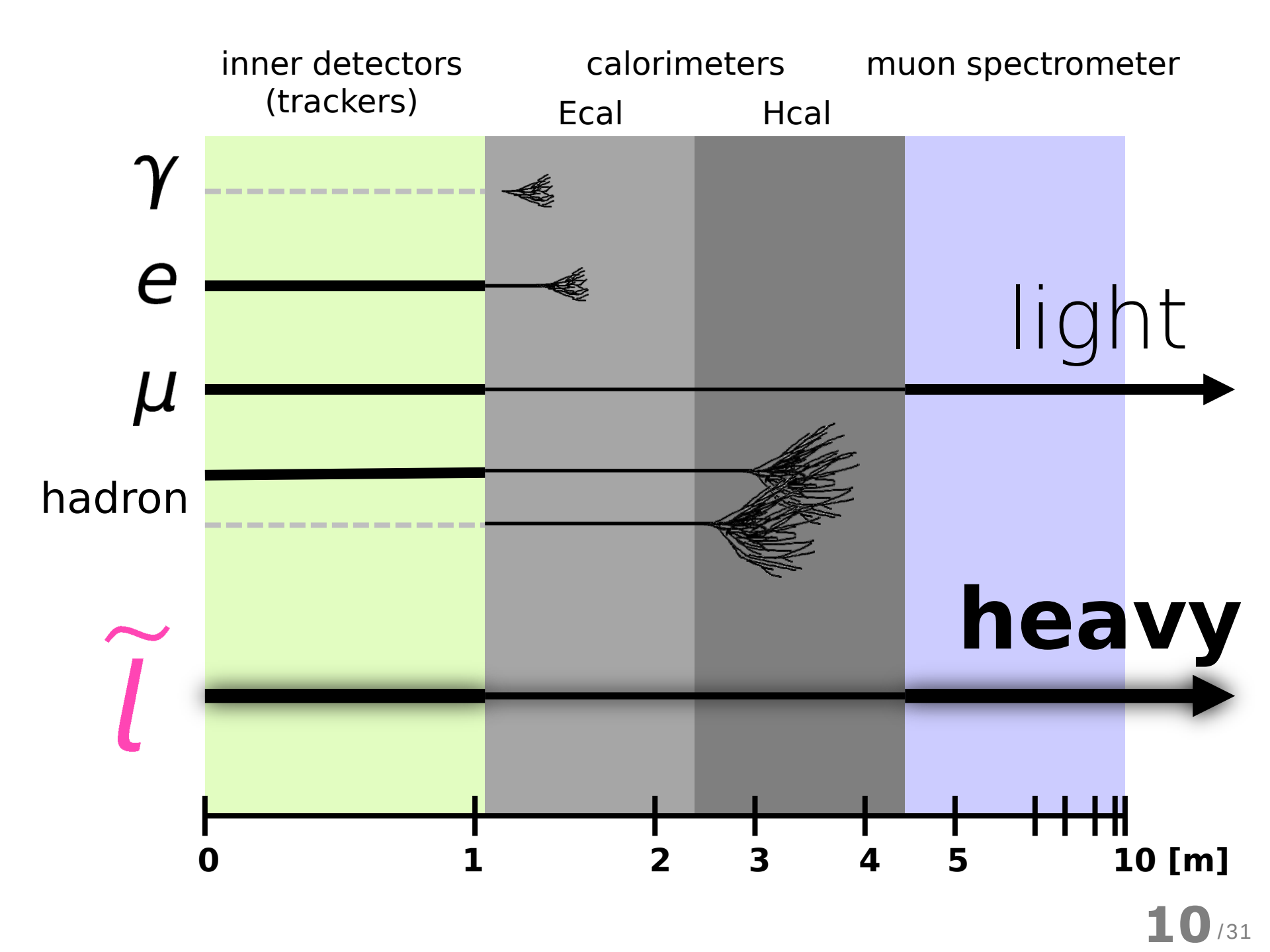

inner detectors
(trackers)
calorimeters
Ecal
Hcal
muon spectrometer
γ
e
μ
hadron
light
heavy
0
1
2
3
4
5
10 [m]

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

momentum & velocity

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

  - TOF [time-of-flight]

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

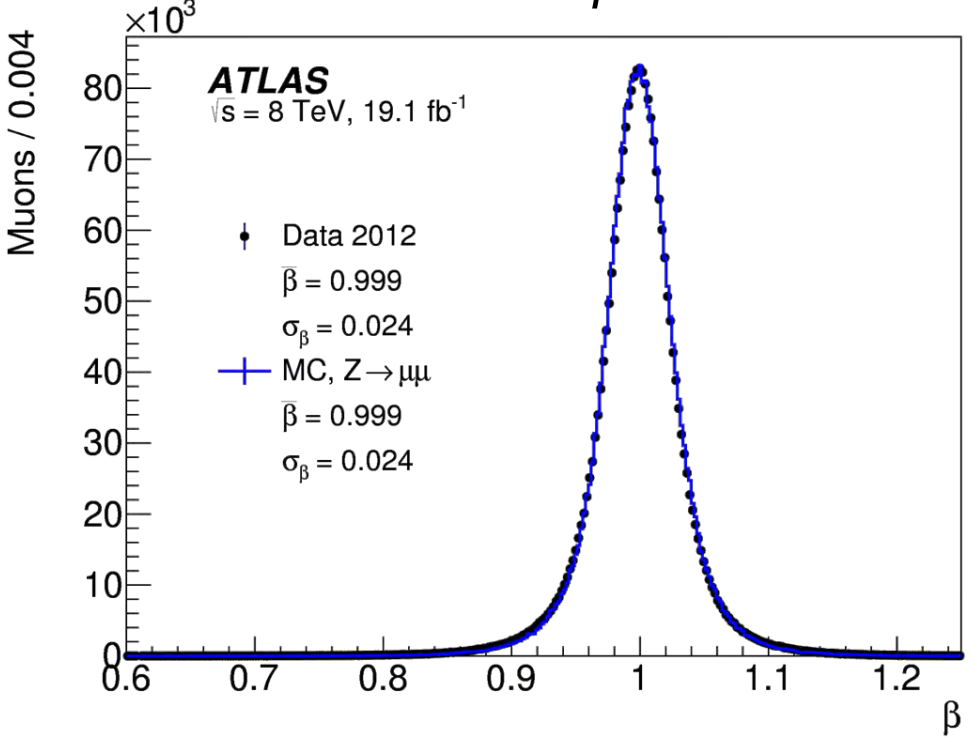
  - dE/dx [ionization energy loss]

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

momentum & velocity

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

ATLAS: **muon** β resolution



- TOF [time-of-flight]

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

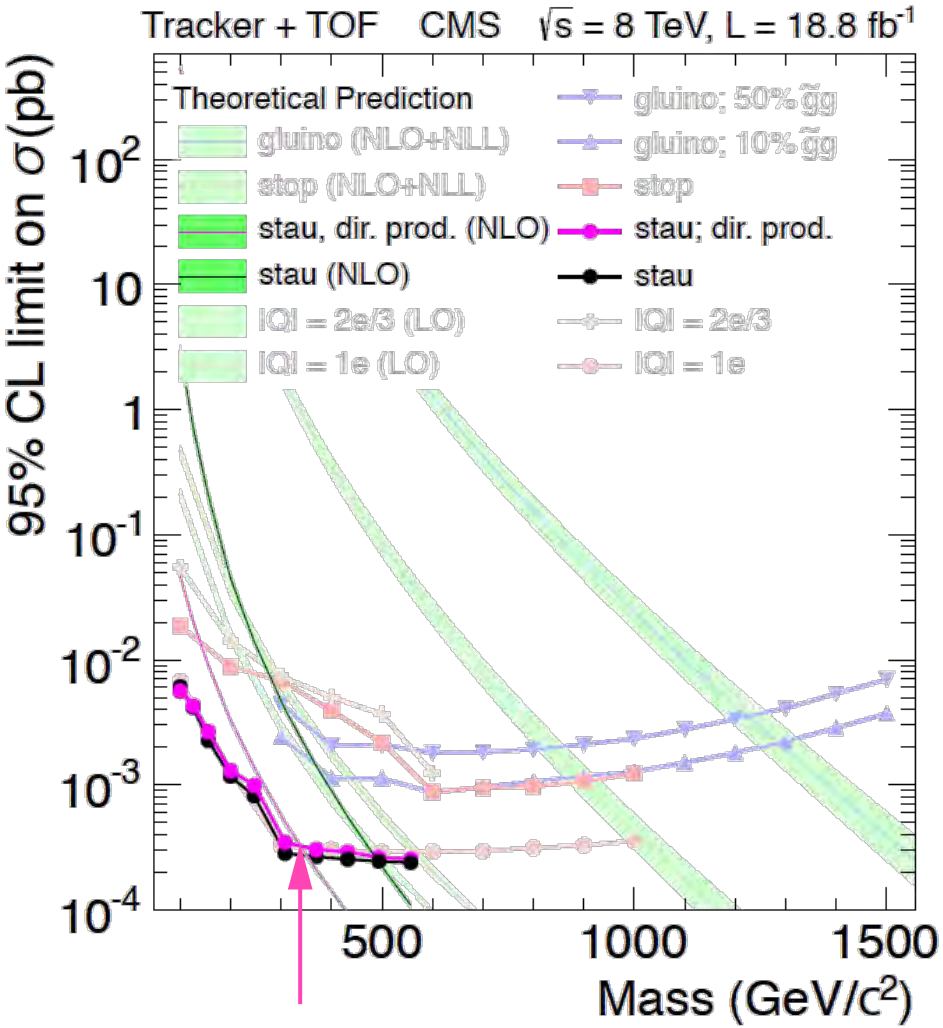
- d*E*/d*x* [ionization energy loss]

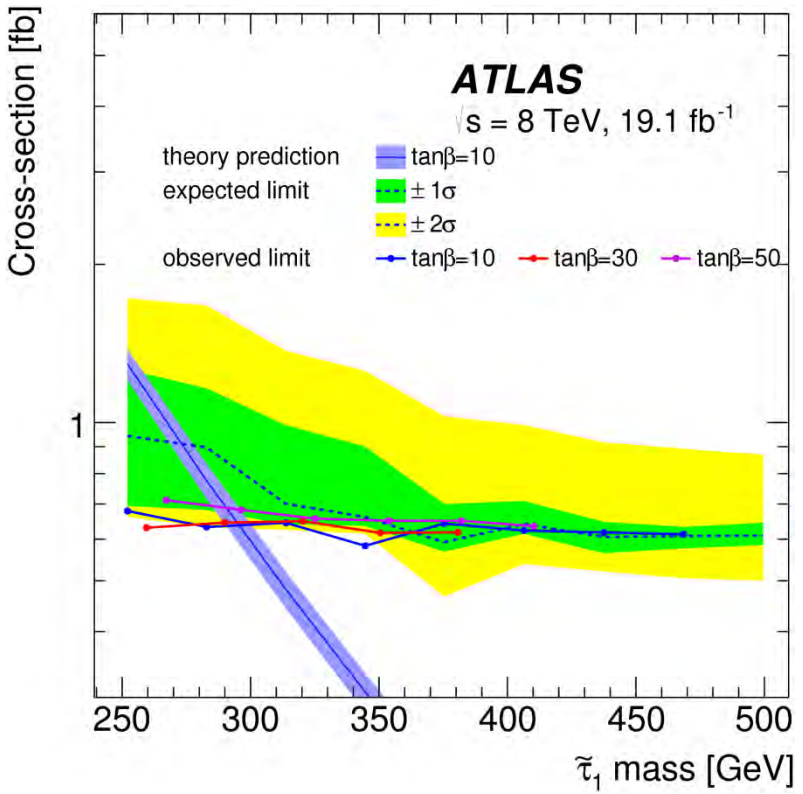
See also: LHCb collaboration [1506.09173]

For p $p \to \gamma, Z \to \tilde{\tau}_1(\tilde{\tau}_R)\ \tilde{\tau}_1$

(**direct** production)

$$m(\tilde{\tau}_1) > \begin{cases} 339\ \text{GeV [CMS]} \\ [1305.0491] \\ 286\ \text{GeV [ATLAS]} \\ [1411.6795] \end{cases}$$





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ATLAS @8TeV [1411.6795]

$\tilde{l}$ selection flow:

- observed as a muon
- $p_T > 70\,\mathrm{GeV}$
- $|\eta| < 2.4$
- $0.2 < \hat{\beta} < 0.95$

Our 100TeV simulation

$\tilde{l}$ selection flow:

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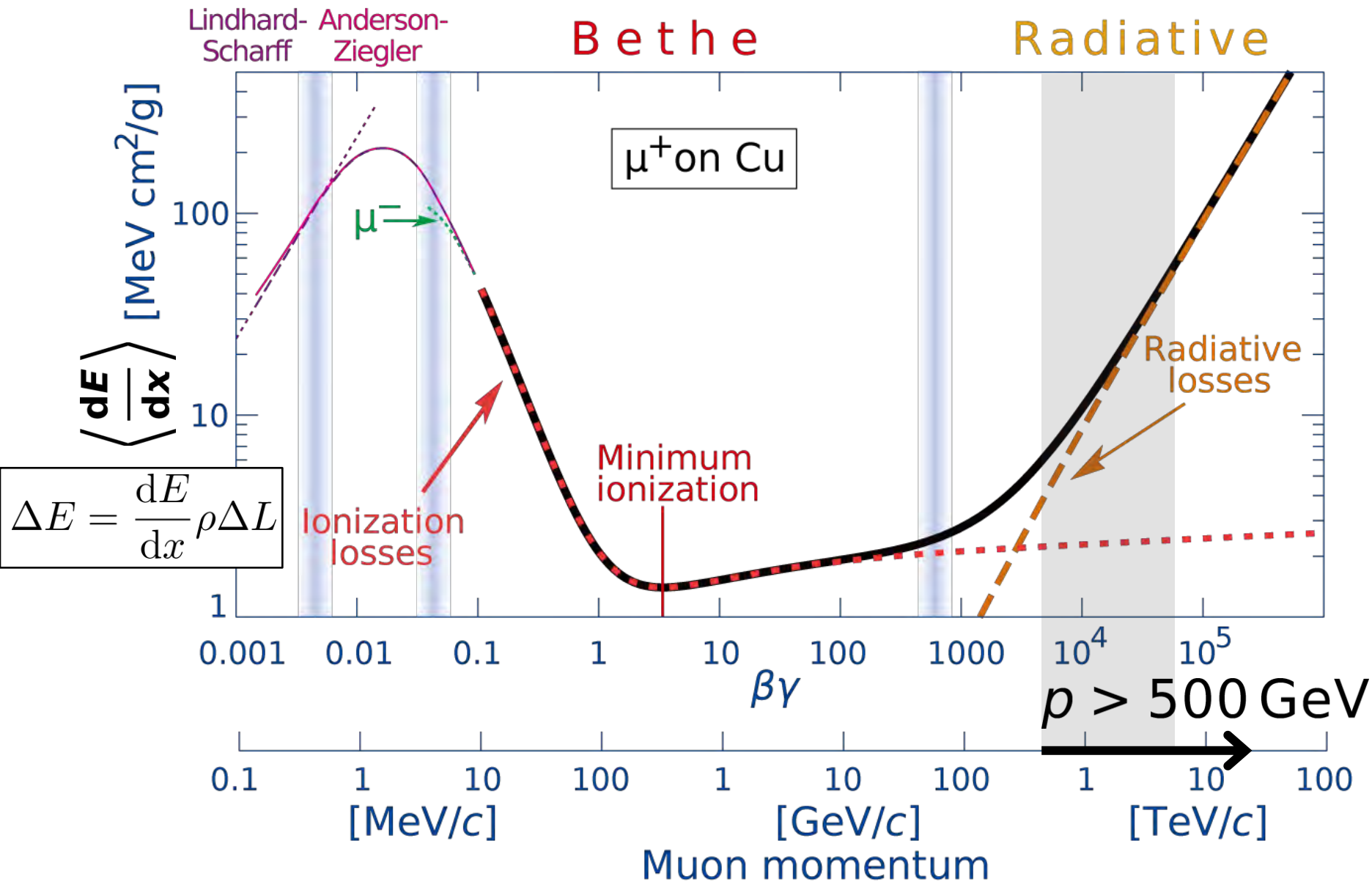
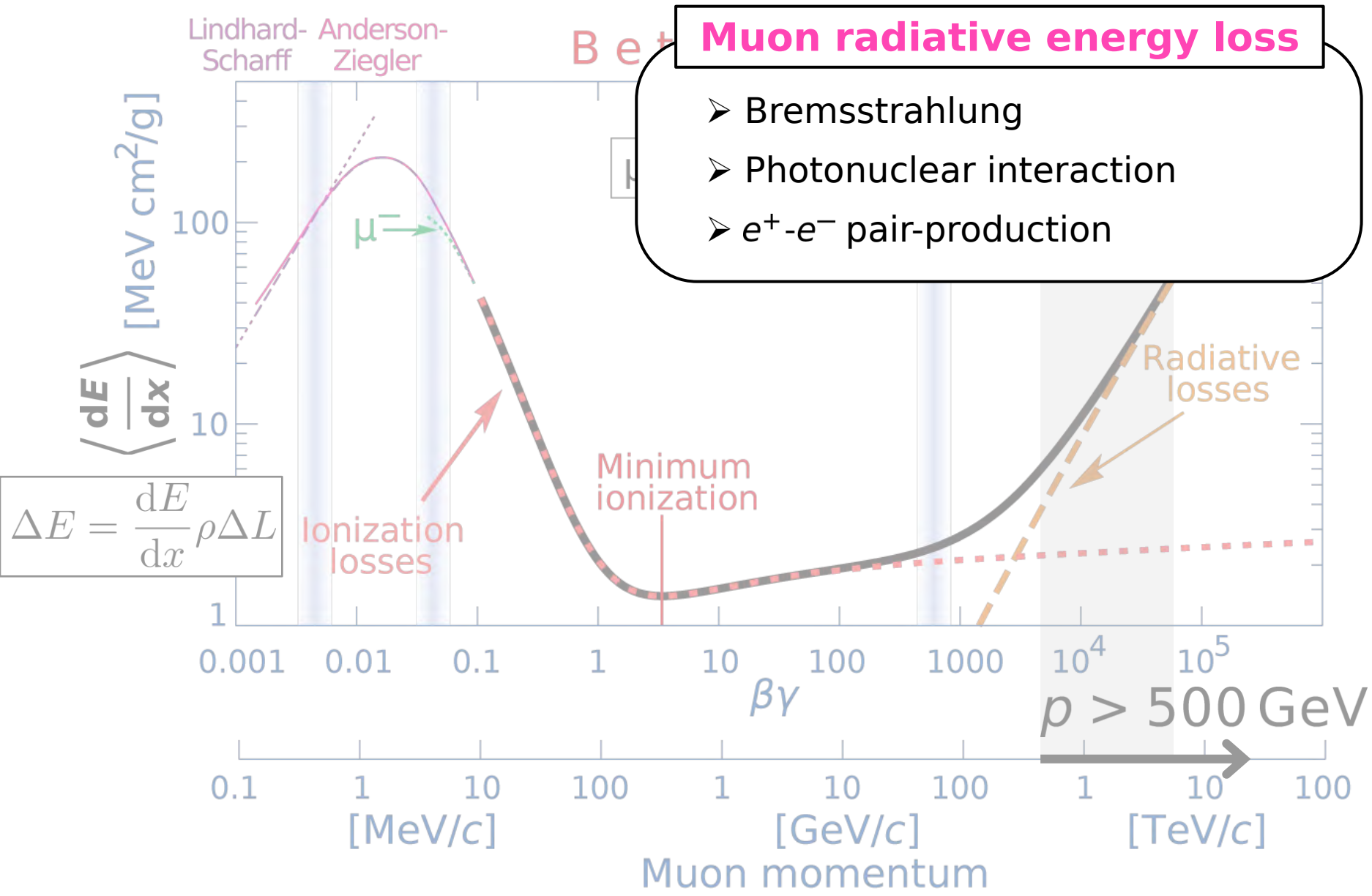


Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]



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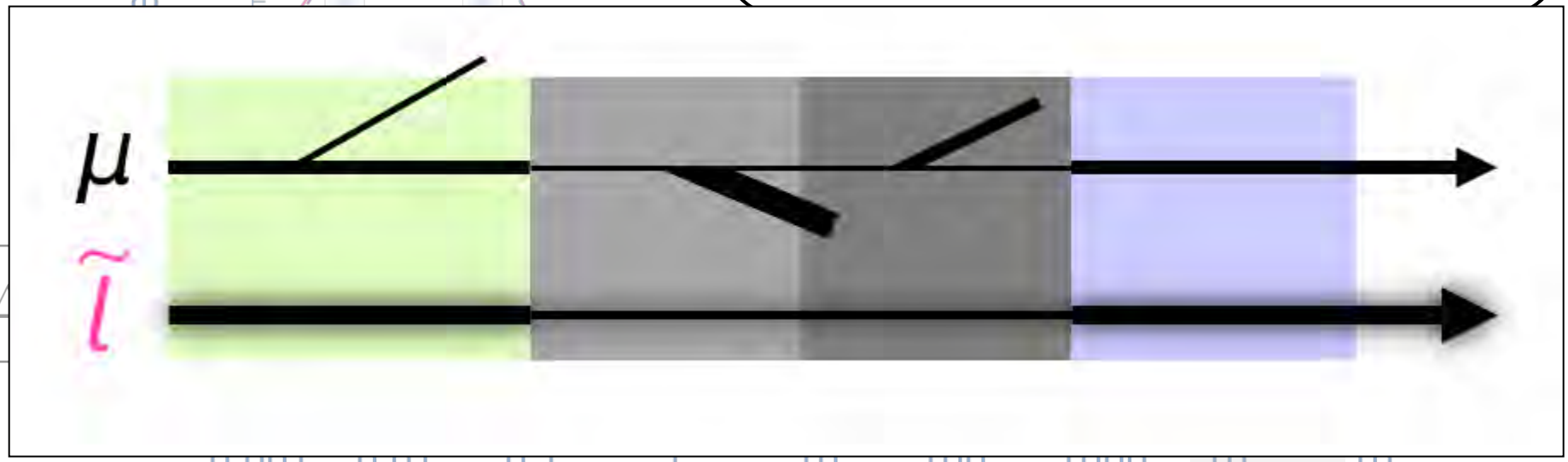
Muon radiative energy loss

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



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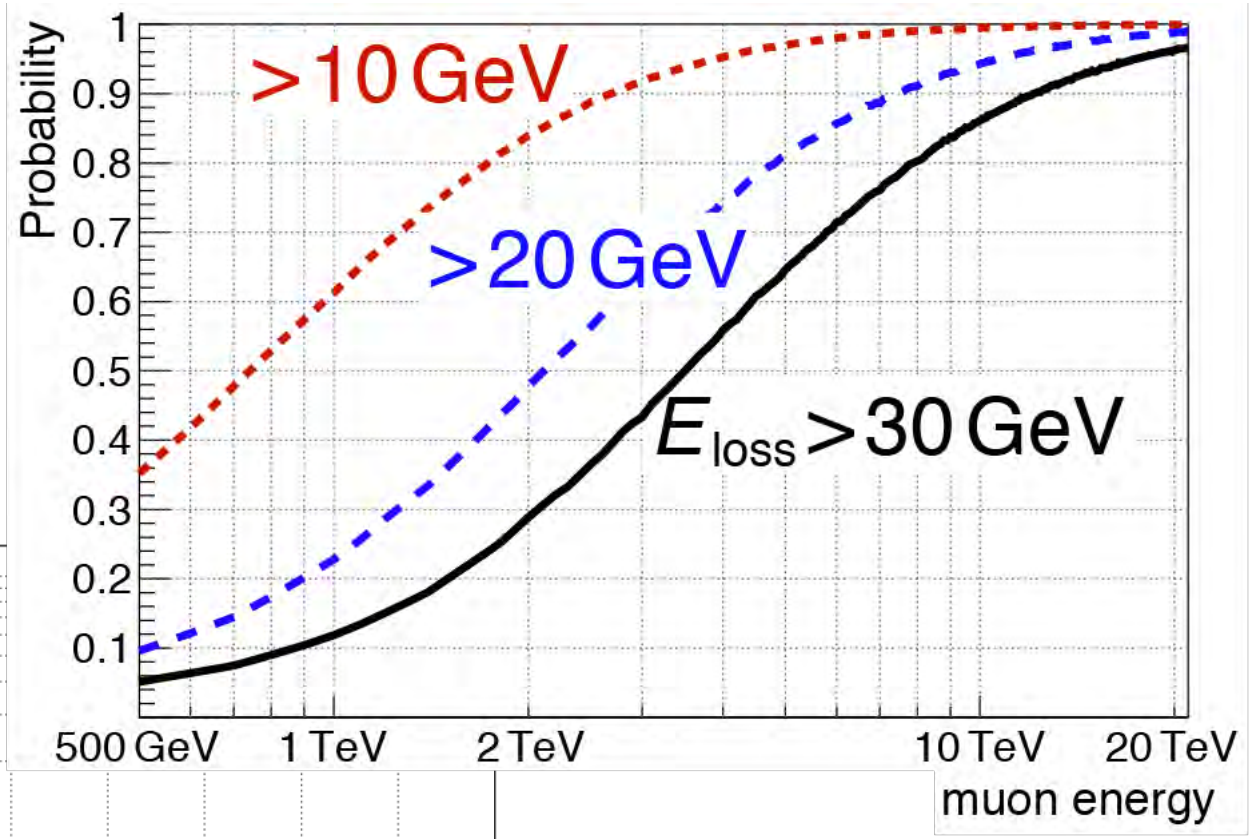

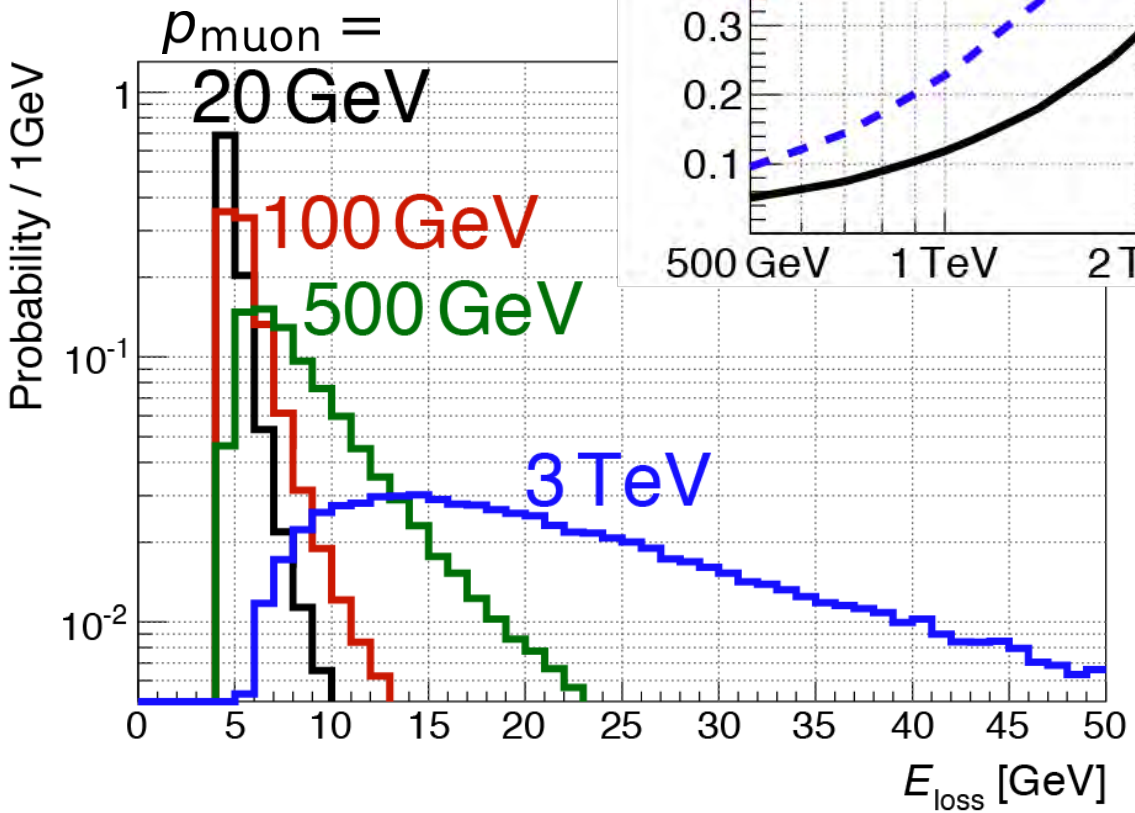

[Simulated with GEANT 4]

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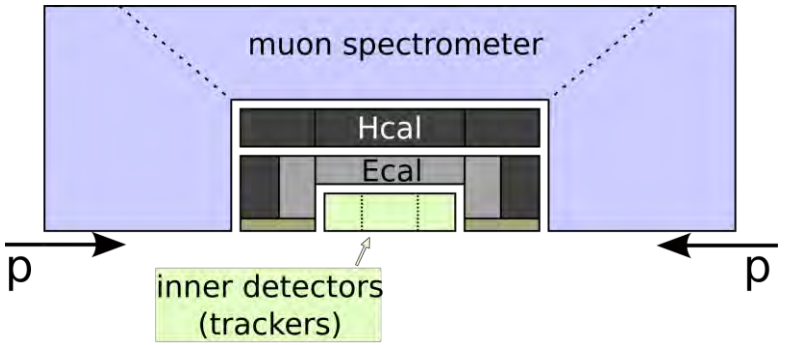
- Detector
  - similar to ATLAS/CMS
  - β-resolution same as ATLAS (resolution: 2.4%)



- Signal: Madgraph5 + Pythia6 + Delphes3
  (calculated at the LO)
- BKG: “Snowmass 2013” BKG set for 100TeV
  (publicly available)
- Pile-up not considered

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- $\tilde{l}$ -selection flow

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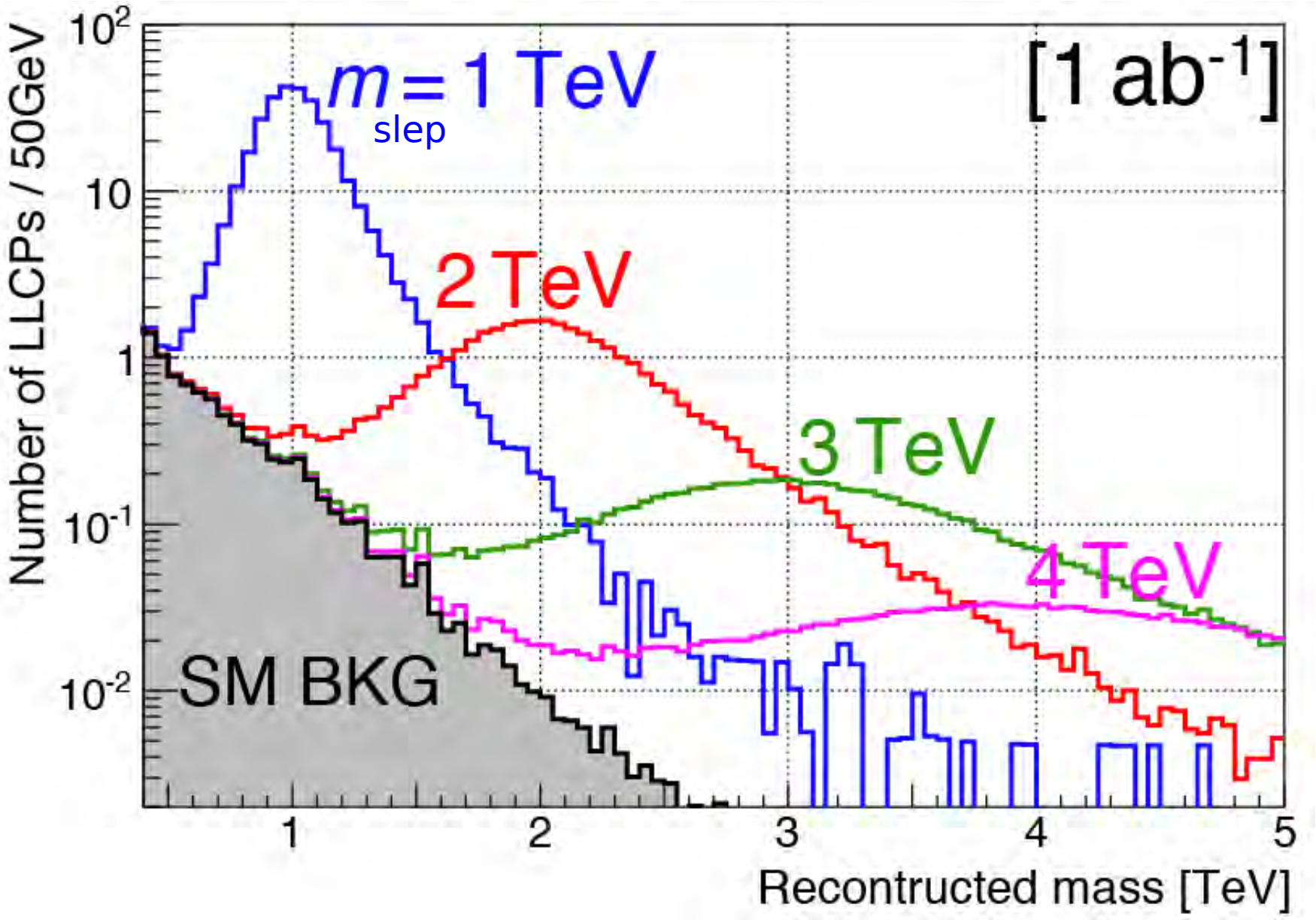
  - $E_{\mathrm{loss}} < 30\,\mathrm{GeV}$
- Event selection
  - two $\tilde{l}$-candidates


$m = 1$ TeV
slep
[1 ab^{-1}]
2 TeV
3 TeV
4 TeV
SM BKG
Number of LLCPs / 50GeV
10^2
10
1
10^{-1}
10^{-2}
1
2
3
4
5
Recontructed mass [TeV]

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

	signal $\tilde{l} = 1\,\text{TeV}$	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
$\epsilon_{\text{acc}}\epsilon_{\text{eff}}$	48%	77%	—

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

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

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Feng, SI, Shadmi, Tarem [1505.02996]

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$\times 0.82$

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

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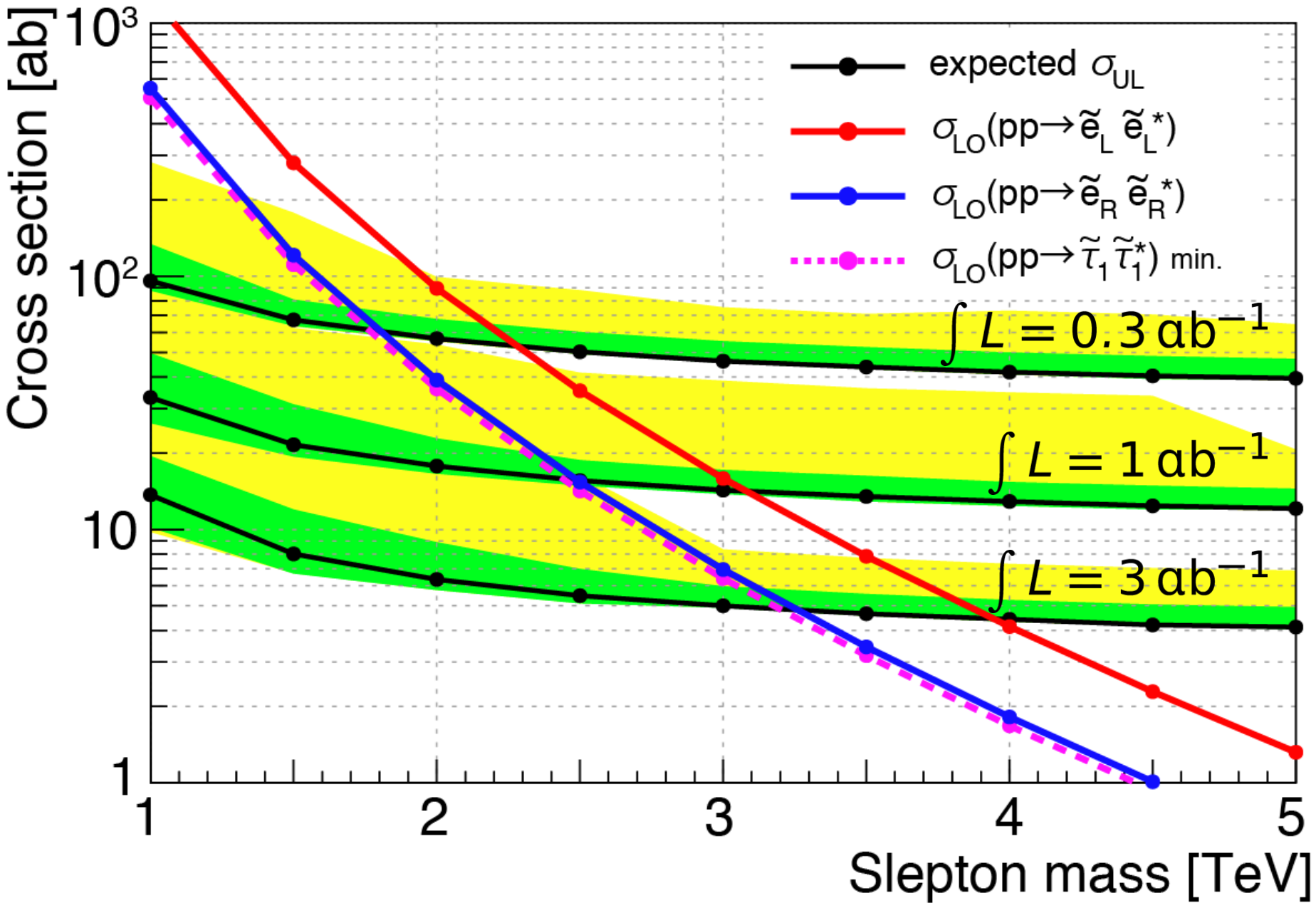
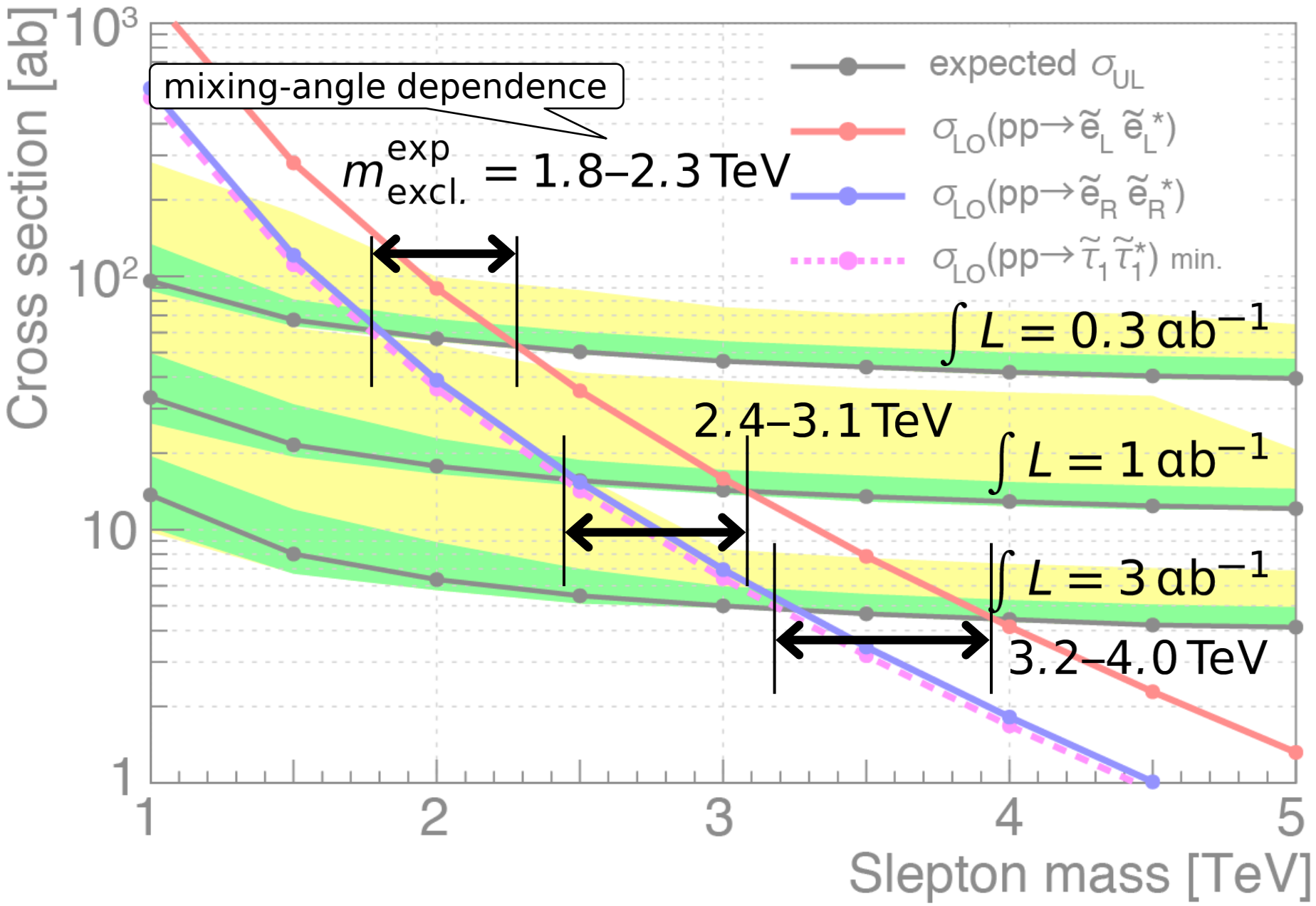
■ Event selection

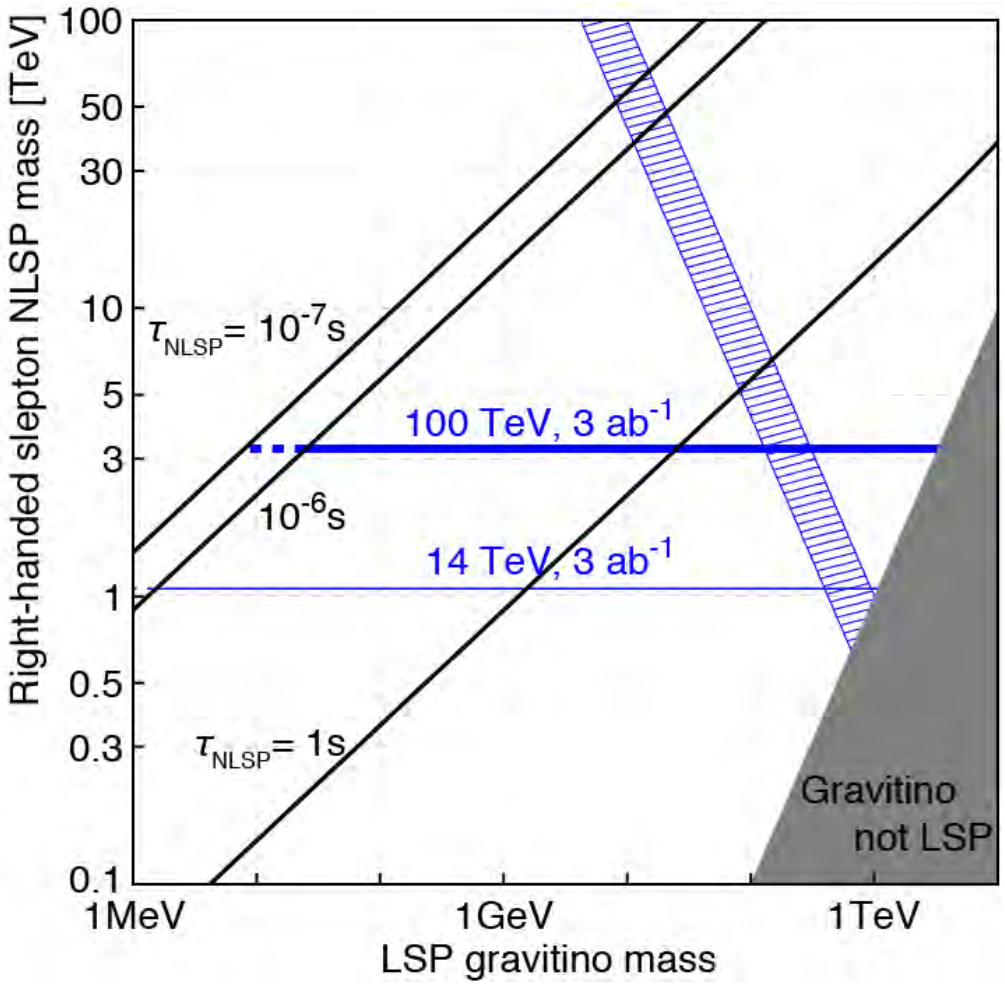
- two $\tilde{l}$-candidates


Cross section [ab]
10^3
10^2
10
1
1
2
3
4
5
Slepton mass [TeV]
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.
$\int L = 0.3\,ab^{-1}$
$\int L = 1\,ab^{-1}$
$\int L = 3\,ab^{-1}$

Feng, SI, Shadmi, Tarem [1505.02996]



- SuperWIMP scenario



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

  … $m_{\tilde{l}} \lesssim 600\,\mathrm{GeV}$

covered @ LHC

$\tilde{l}$ -selection flow

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N_{LLCP}	1 TeV	3 TeV	BKG
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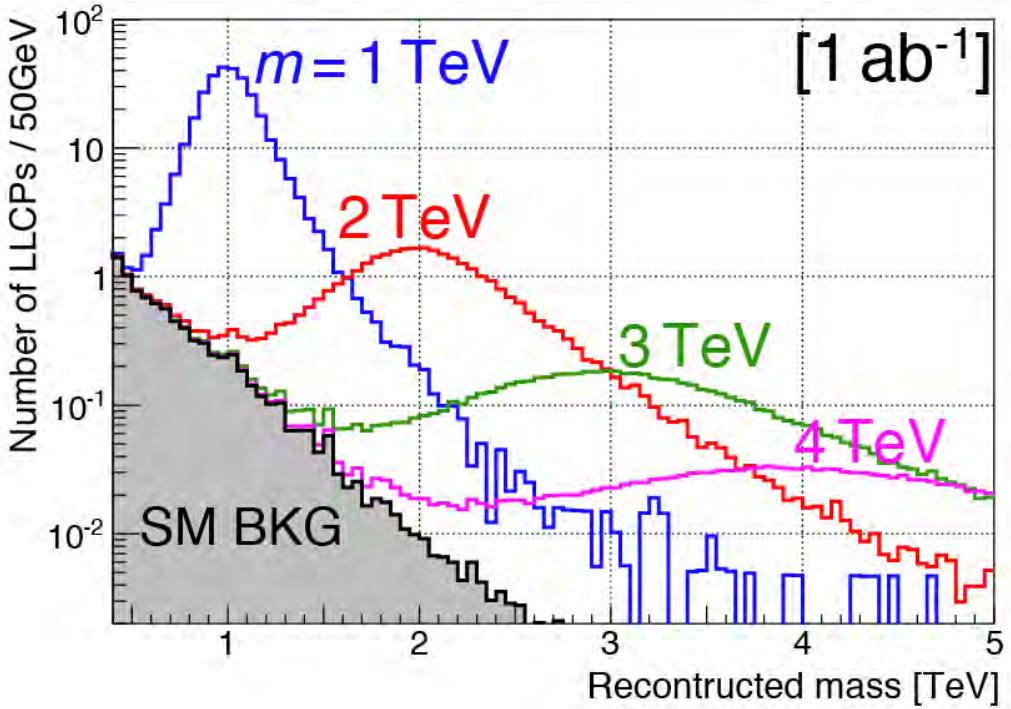
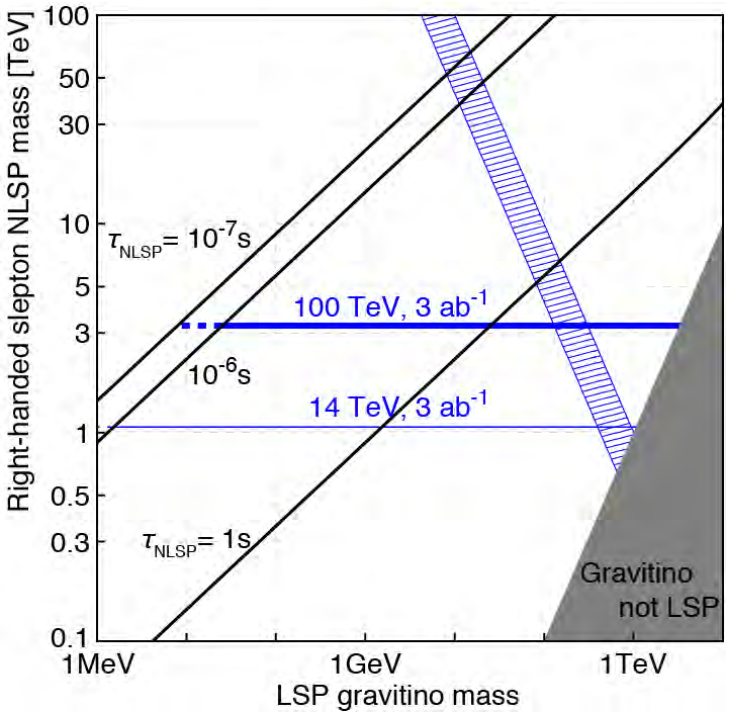
SR

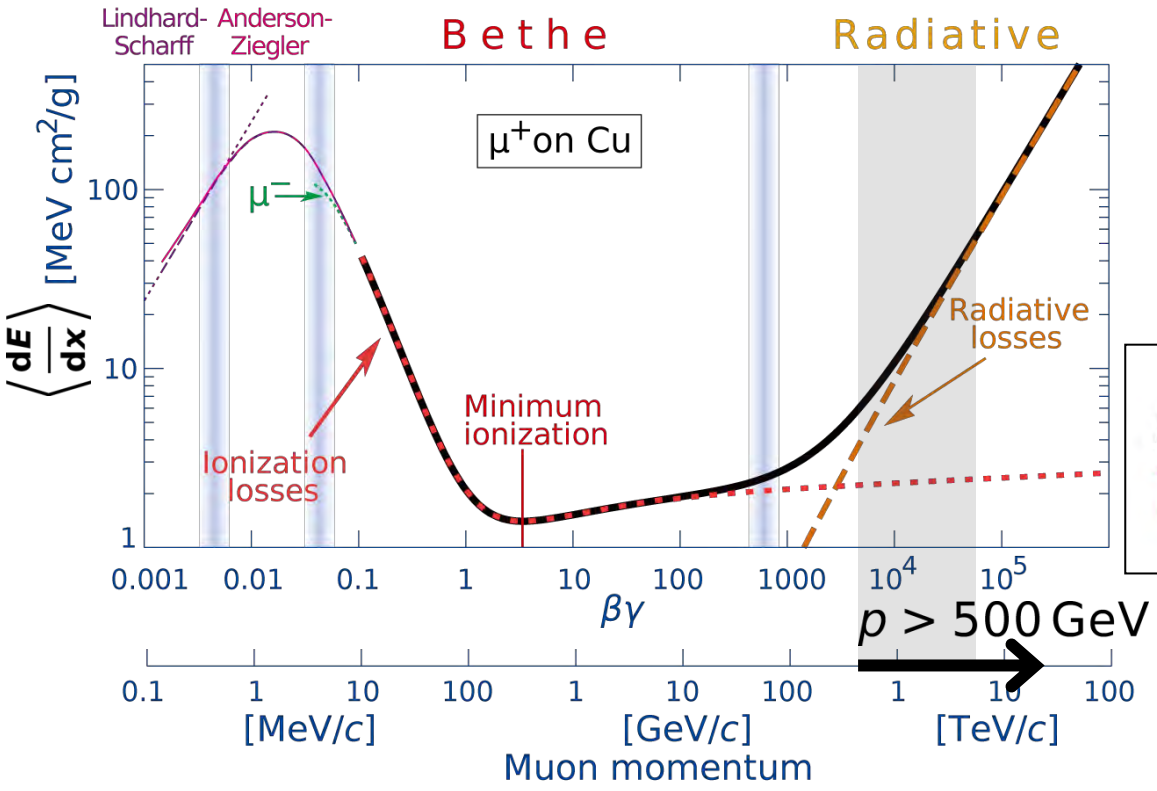




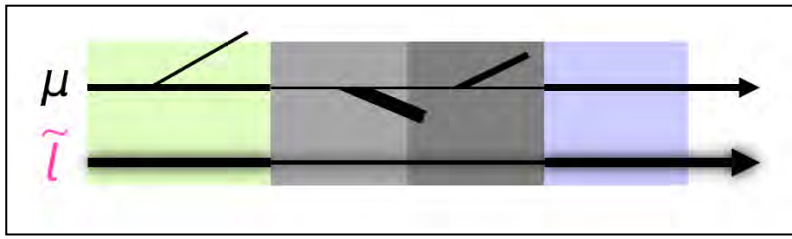
- Expected exclusion reach @100 TeV

$$m_{\text{excl.}}^{\text{exp}} = \begin{cases} 1.8\text{–}2.3\,\text{TeV} & (0.3\,\text{ab}^{-1}) \\ 2.4\text{–}3.1\,\text{TeV} & (1.0\,\text{ab}^{-1}) \\ 3.2\text{–}4.0\,\text{TeV} & (3.0\,\text{ab}^{-1}) \end{cases}$$

- **"Muon radiative energy loss"**



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



→ **34%** of BKG reduction

Appendix: LHC Run 2

1. How searched at the LHC?

2. at 100 TeV collider?

   - Muon radiative energy loss for BKG reduction

3. Our simulation

   - Expected reach: $m_{\tilde{l}}$

A. Note on momentum resolution

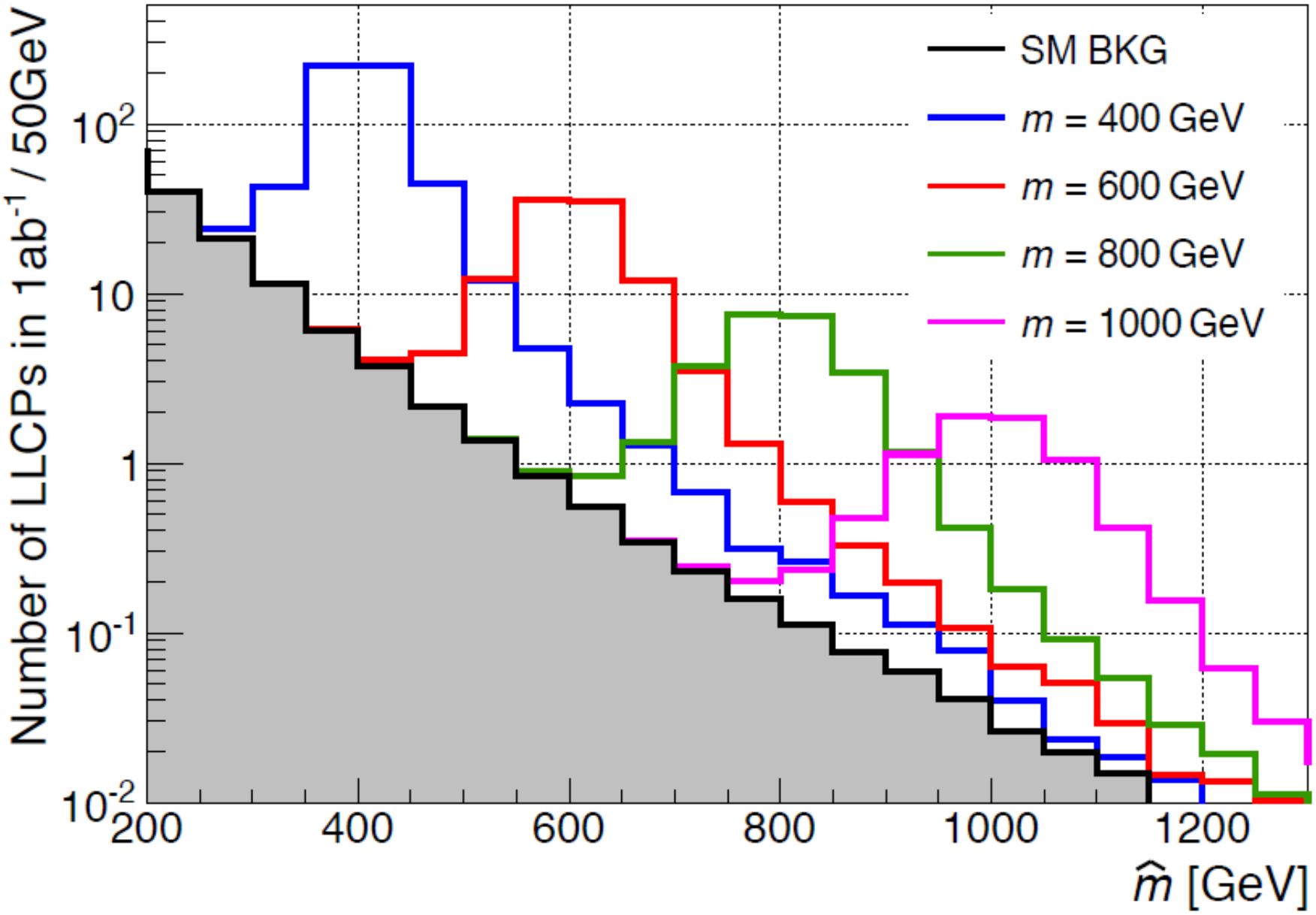
B. 14 TeV LHC

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

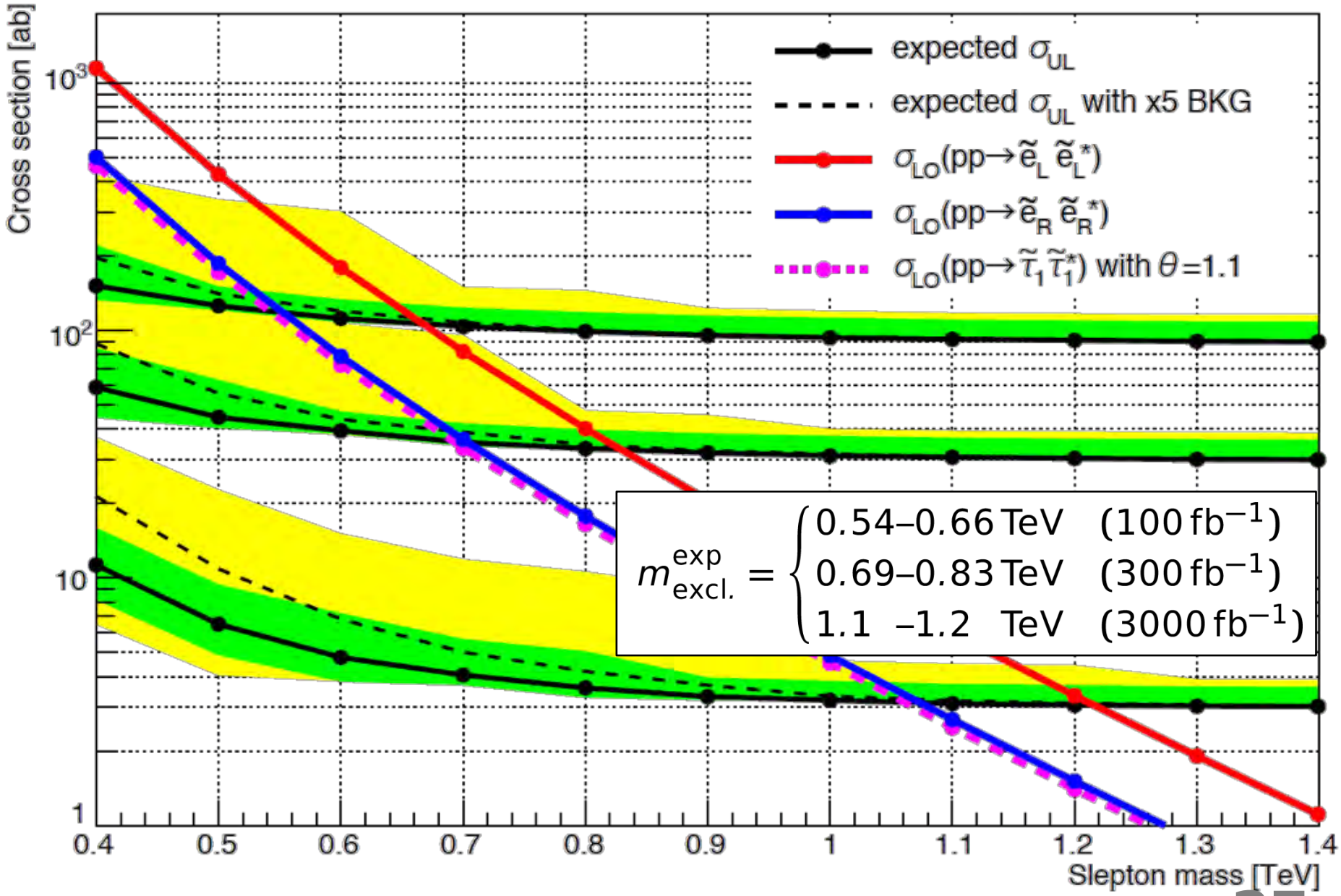
- $\tilde{l}$ -selection flow

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

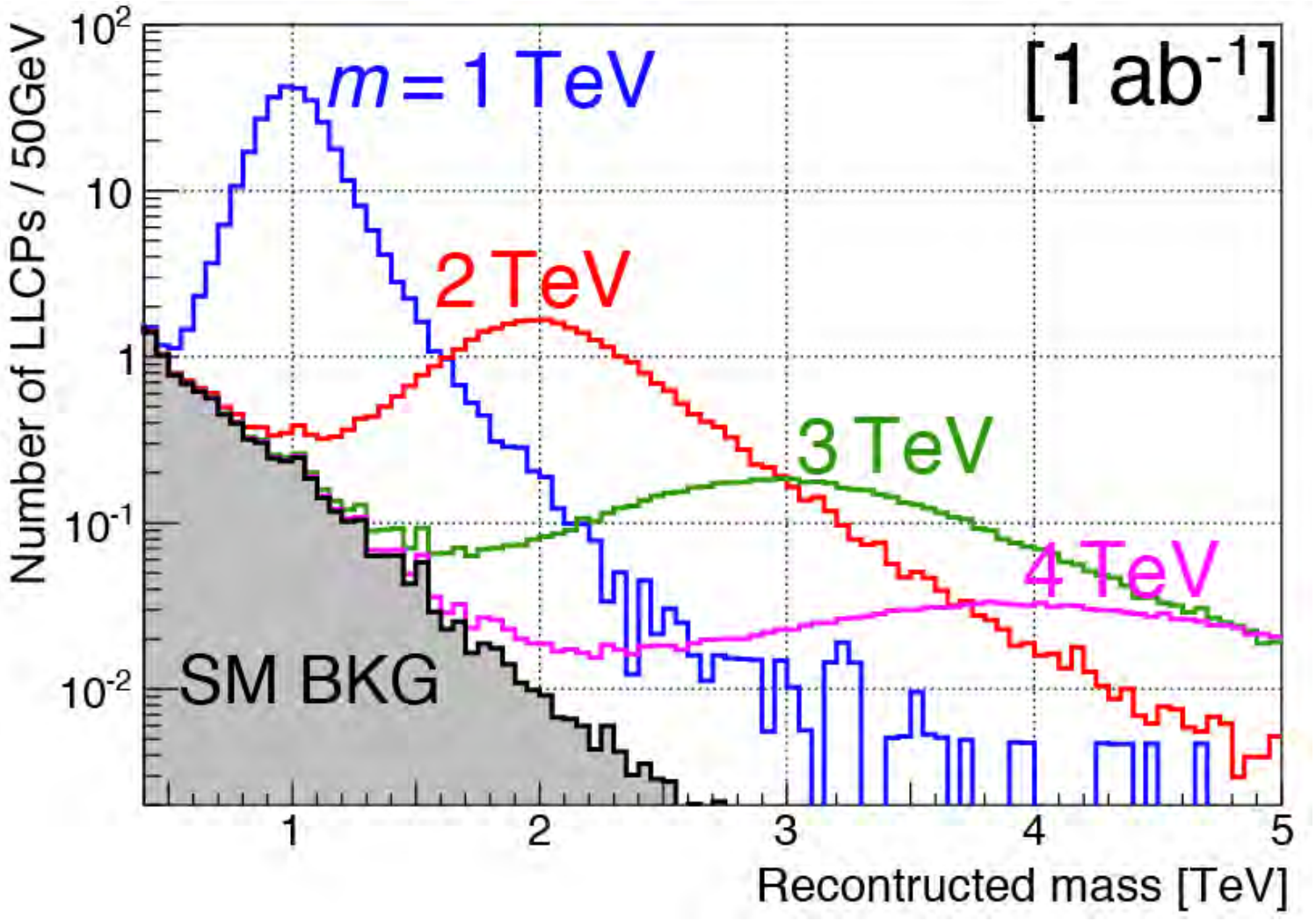

SM BKG
m = 400 GeV
m = 600 GeV
m = 800 GeV
m = 1000 GeV
Number of LLCPs in 1ab-1 / 50GeV
10^2
10
1
10^-1
10^-2
200
400
600
800
1000
1200
m̂ [GeV]

14 TeV LHC expectation

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

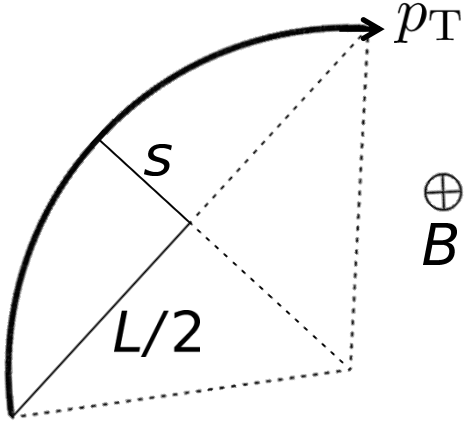


The mass resolution is very bad?



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

Appendix: Momentum resolution @100TeV

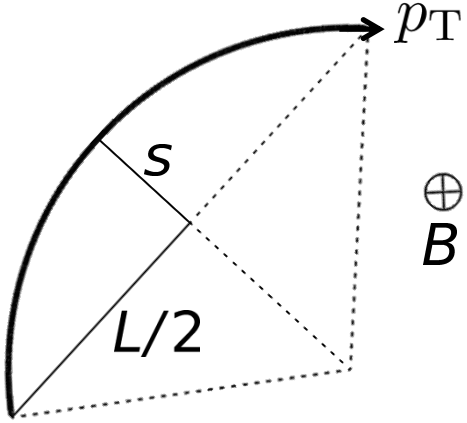


$$p_{\mathrm{T}} = \frac{L^2}{8s}|q|B \Rightarrow \Delta p_{\mathrm{T}} = \frac{L^2|q|B}{8}\frac{\Delta s}{s^2}$$

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

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

ATLAS [1404.4562]; see also [1201.4704]



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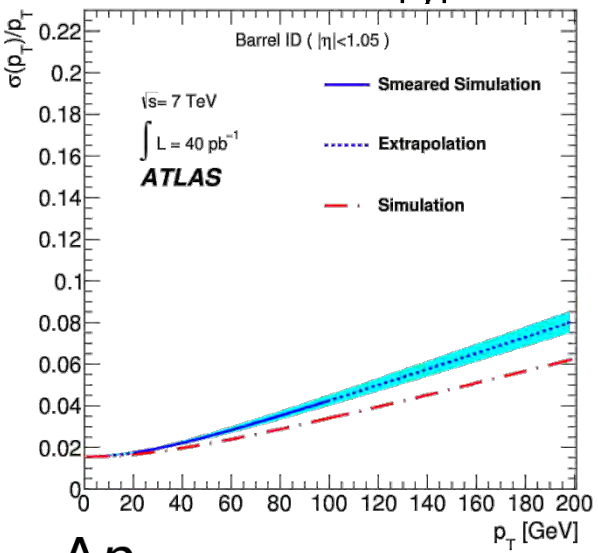
$$\therefore \Delta p_{\mathrm{T}} \propto p_{\mathrm{T}}^2$$

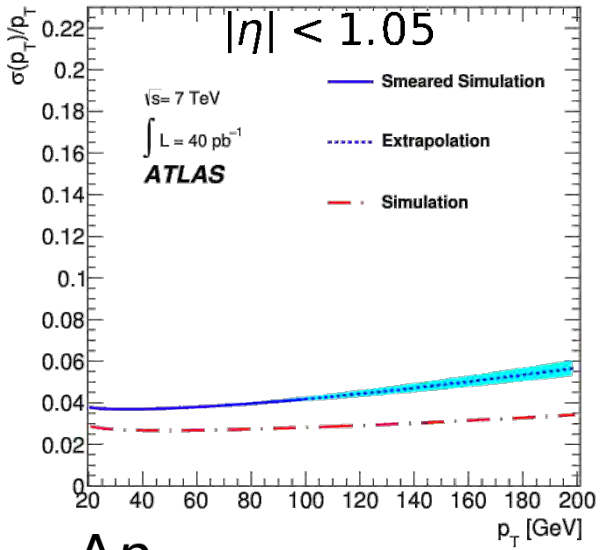
ATLAS 7 TeV results on muon momentum resolution

Inner Detector, $|\eta| < 1.05$

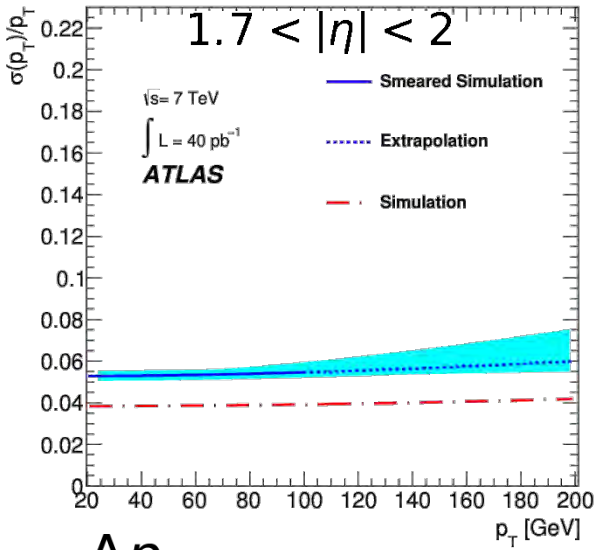


$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.38 p_{\mathrm{T}}/\mathrm{TeV}$$

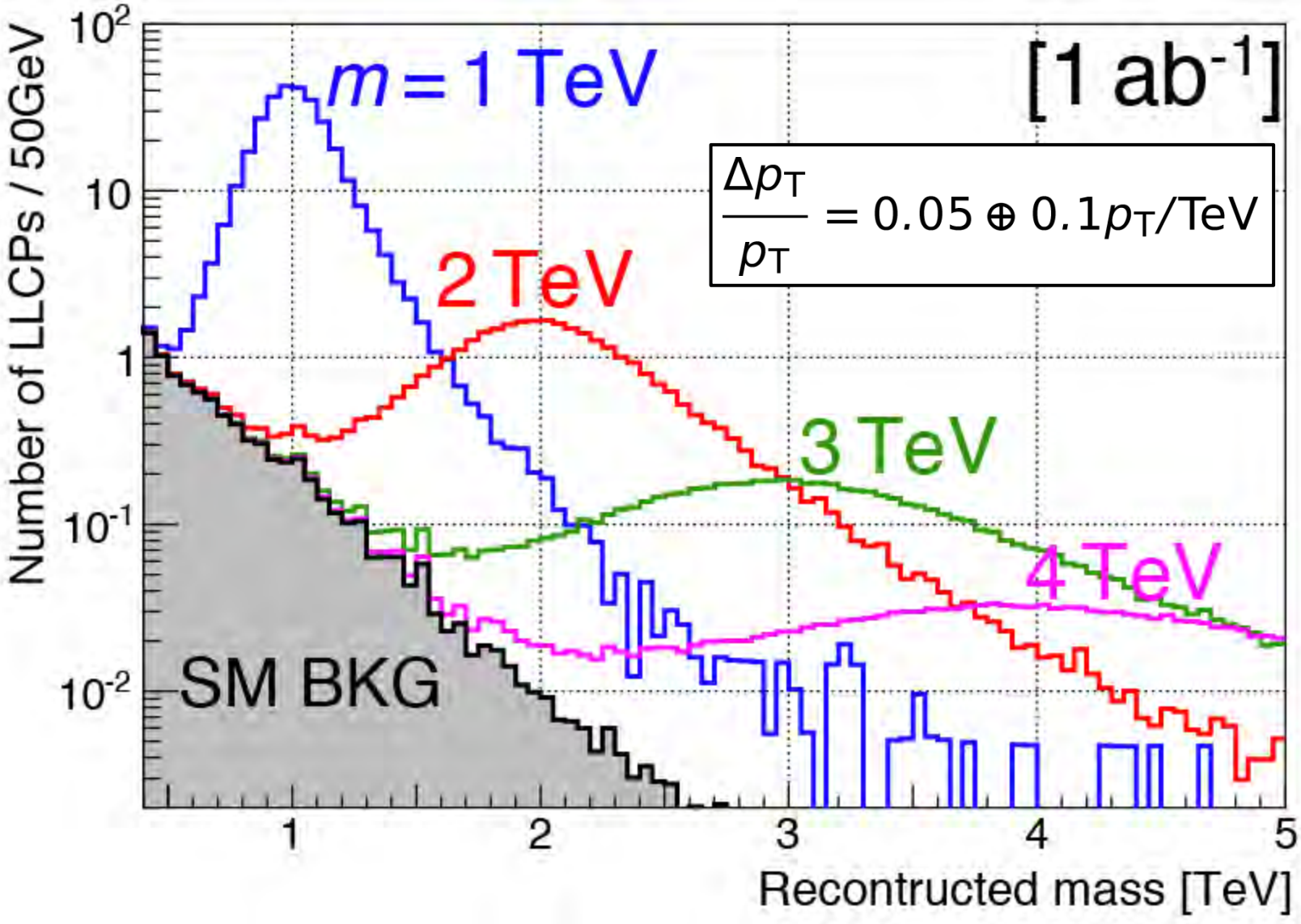
Muon spectrometer

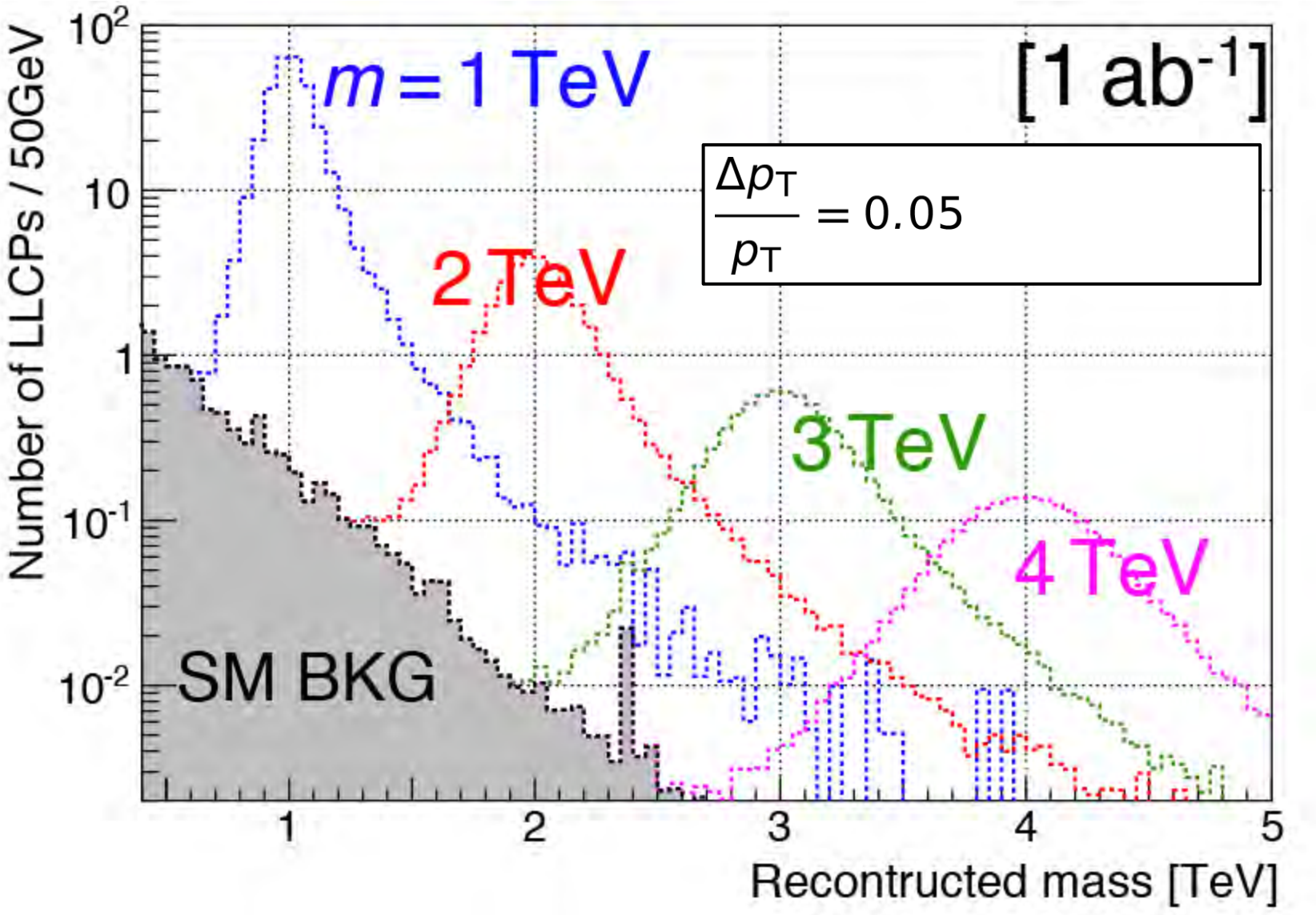


$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.14 p_{\mathrm{T}}/\mathrm{TeV}$$

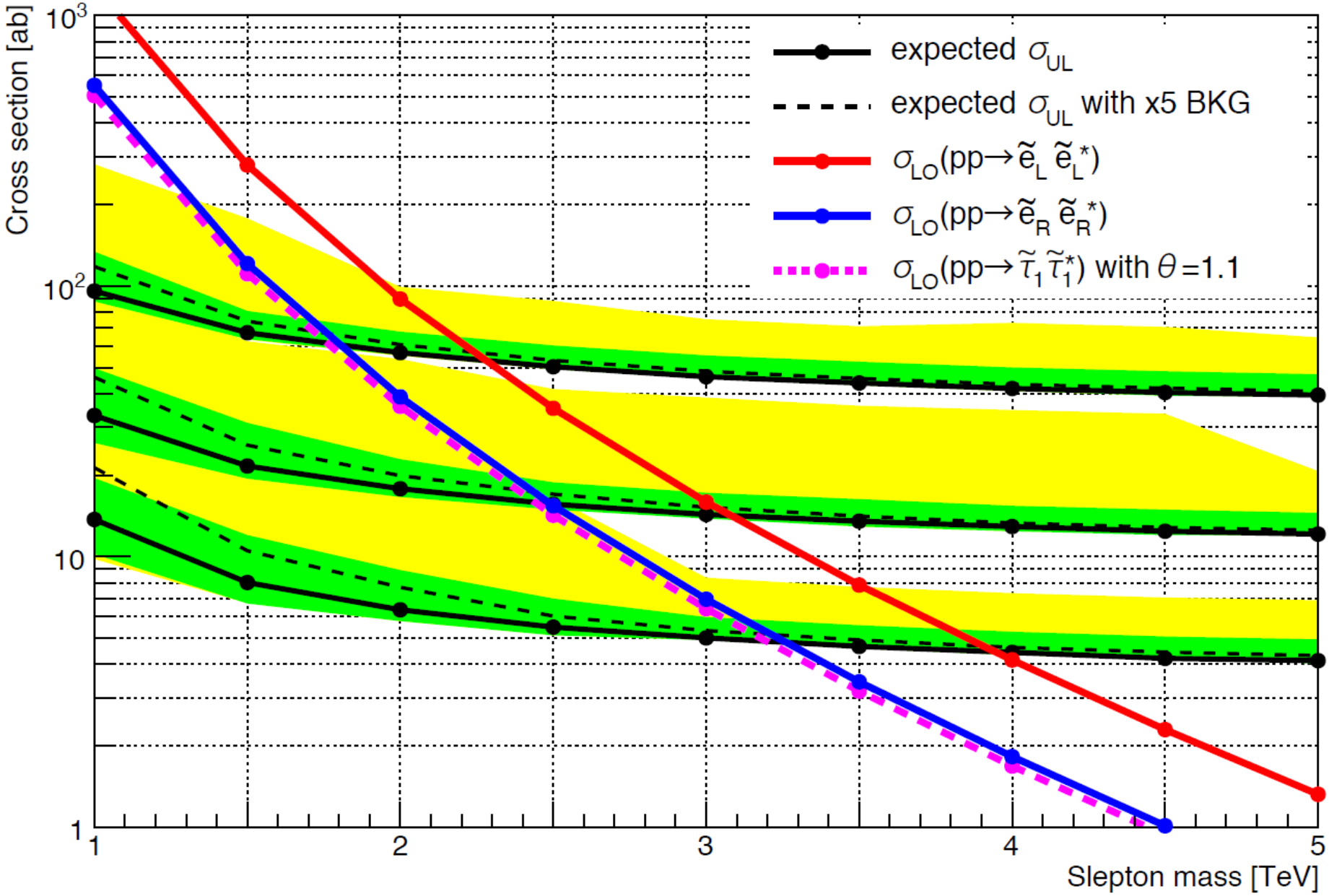


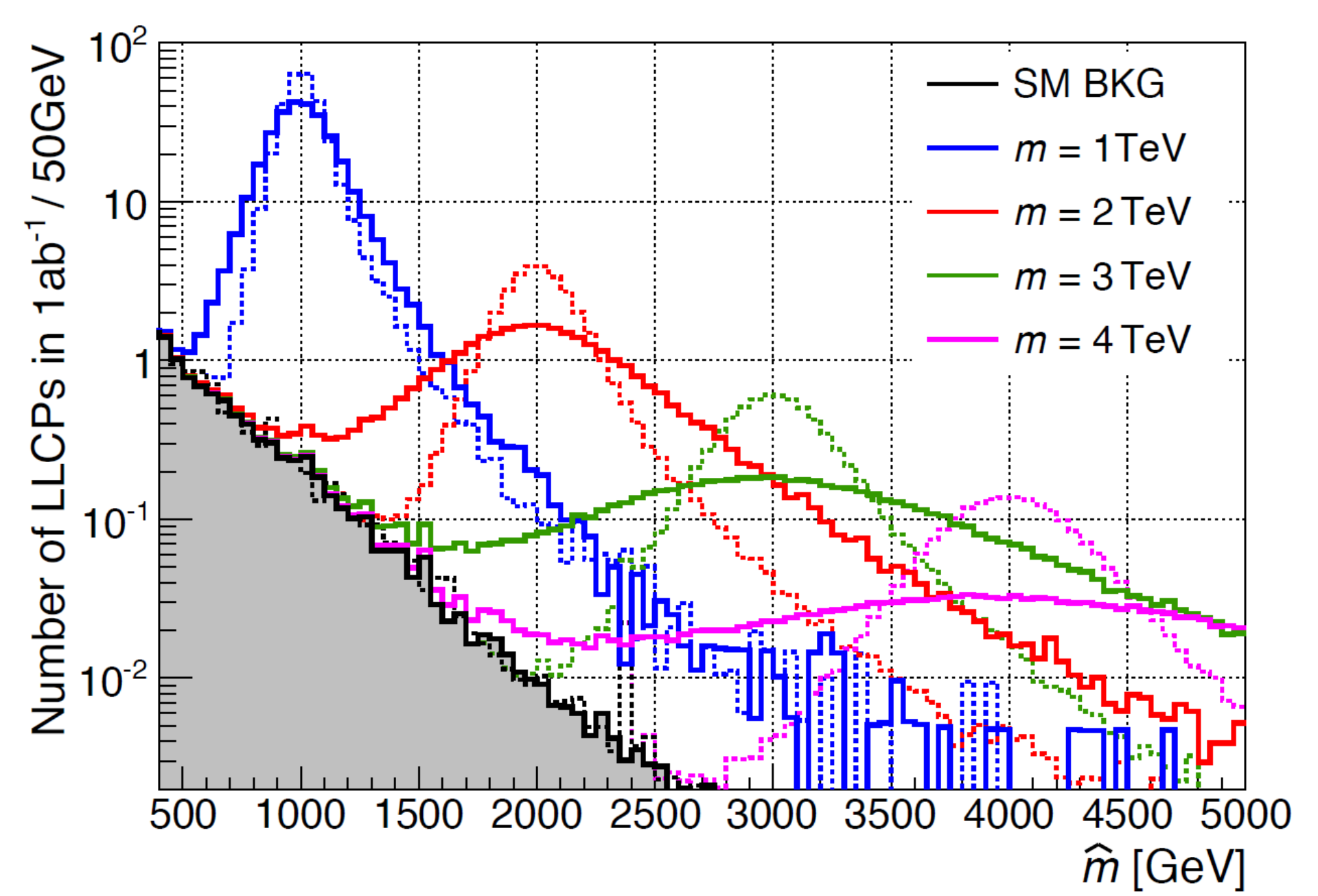
$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.06 p_{\mathrm{T}}/\mathrm{TeV}$$

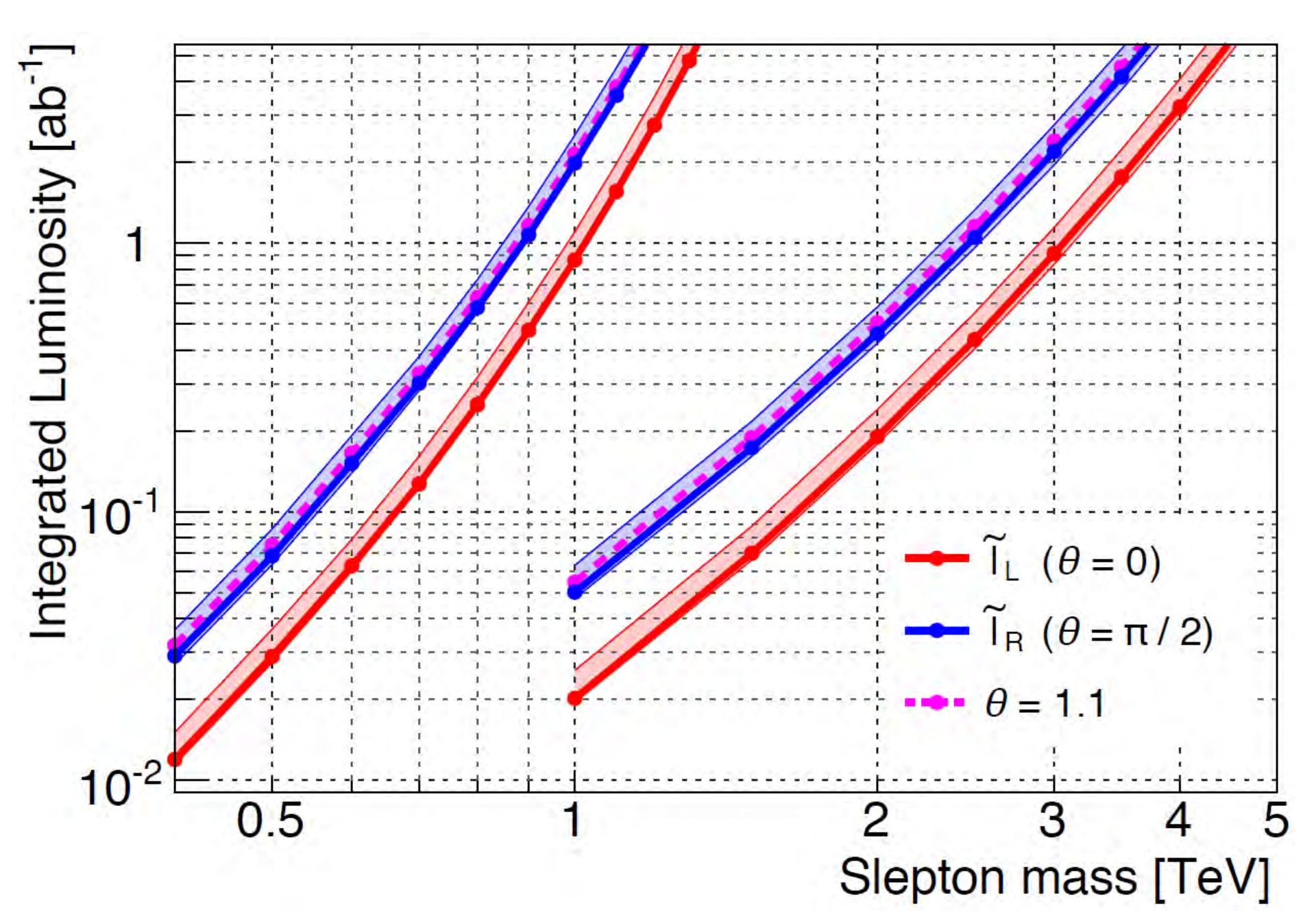

$m = 1$ TeV
[1 ab^{-1}]
$\frac{\Delta p_T}{p_T} = 0.05 \oplus 0.1 p_T/\text{TeV}$
2 TeV
3 TeV
4 TeV
SM BKG
Number of LLCPs / 50GeV
10^2
10
1
10^{-1}
10^{-2}
1
2
3
4
5
Recontructed mass [TeV]


$m = 1$ TeV
[1 ab^{-1}]
$\frac{\Delta p_T}{p_T} = 0.05$
2 TeV
3 TeV
4 TeV
SM BKG
Number of LLCPs / 50GeV
10^2
10
1
10^{-1}
10^{-2}
1
2
3
4
5
Recontructed mass [TeV]

Detailed Figures (100TeV)


Cross section [ab]
10^3
10^2
10
1
1
2
3
4
5
Slepton mass [TeV]
expected σ_{UL}
expected σ_{UL} with x5 BKG
$\sigma_{LO}(pp\rightarrow \tilde{e}_L \tilde{e}_L^*)$
$\sigma_{LO}(pp\rightarrow \tilde{e}_R \tilde{e}_R^*)$
$\sigma_{LO}(pp\rightarrow \tilde{\tau}_1 \tilde{\tau}_1^*)$ with θ=1.1


SM BKG
m = 1TeV
m = 2TeV
m = 3TeV
m = 4TeV
Number of LLCPs in 1ab-1 / 50GeV
10^2
10
1
10^-1
10^-2
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
m̂ [GeV]


Integrated Luminosity [ab^{-1}]
1
10^{-1}
10^{-2}
0.5
1
2
3
4
5
Slepton mass [TeV]
$\tilde{l}_L$ ($\theta = 0$)
$\tilde{l}_R$ ($\theta = \pi / 2$)
$\theta = 1.1$

Why $\beta > 0.4$? (slepton dE/dx)

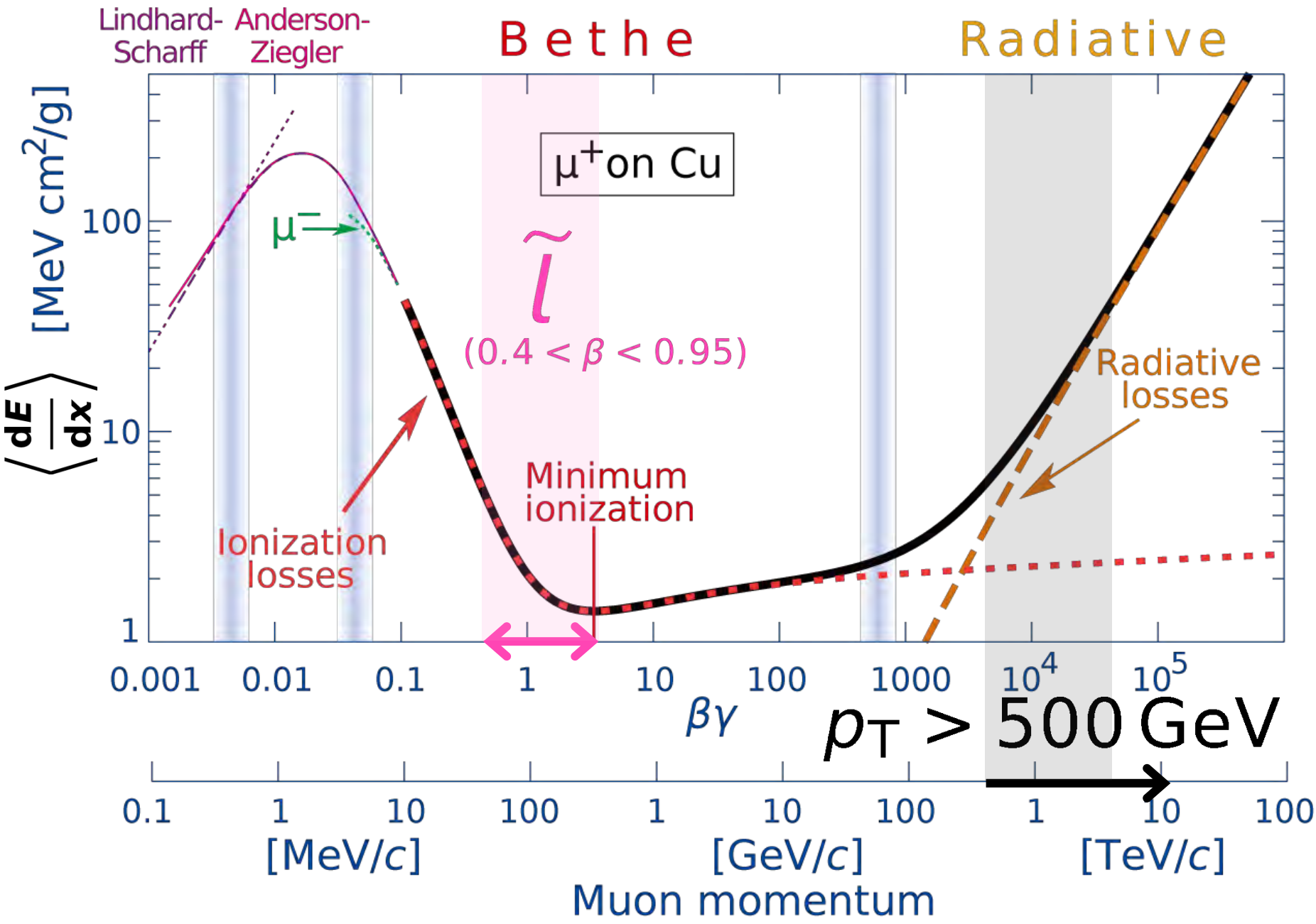
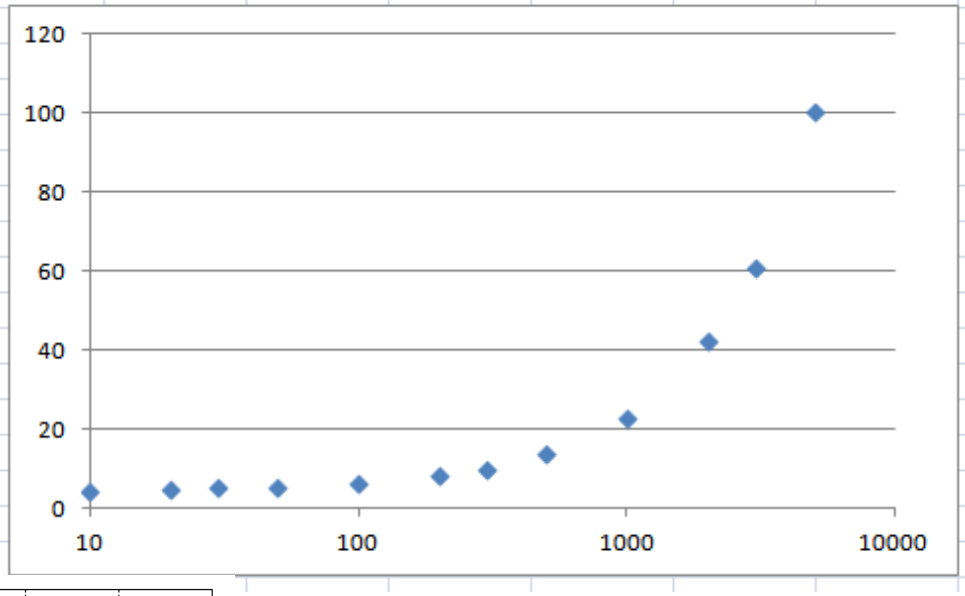


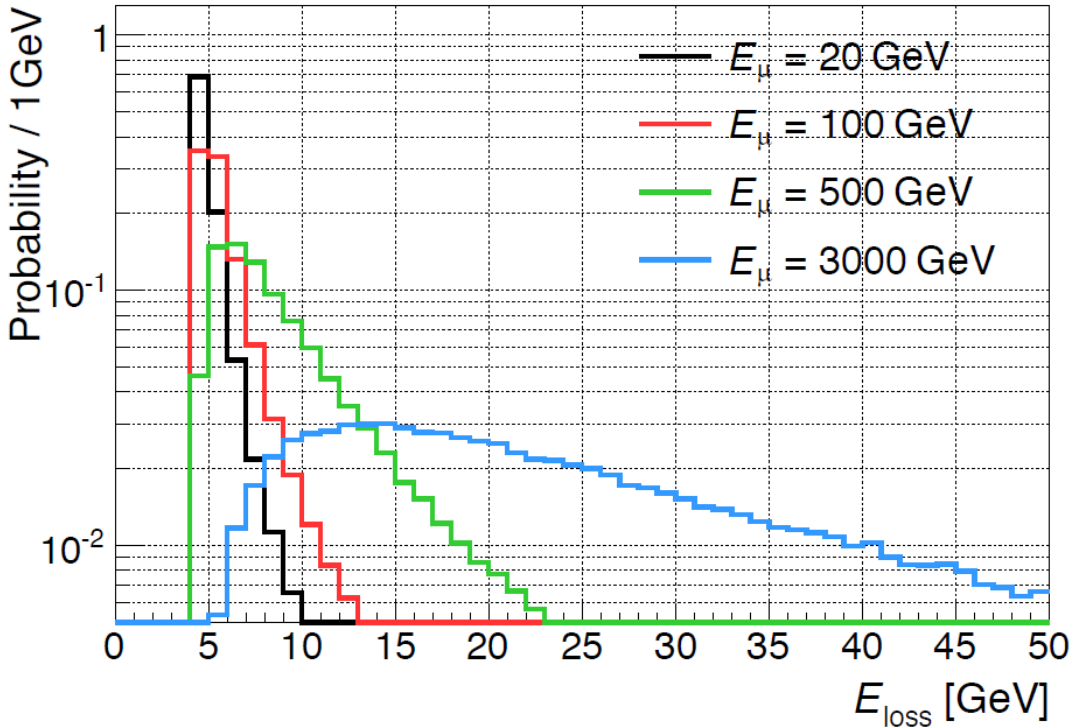
Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

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

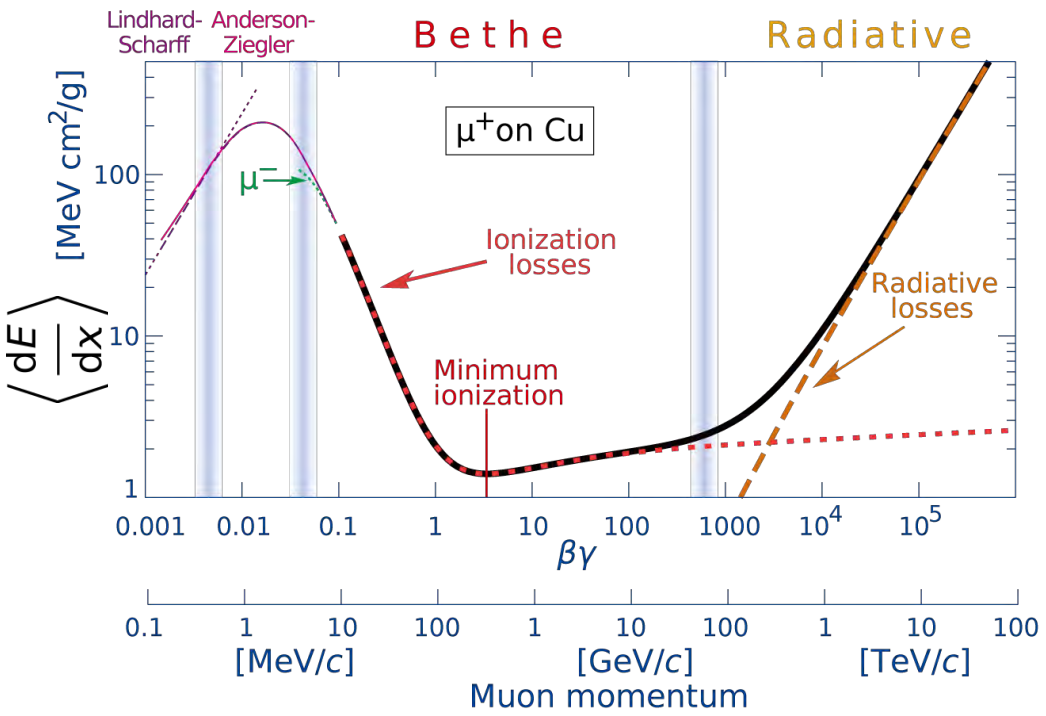
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

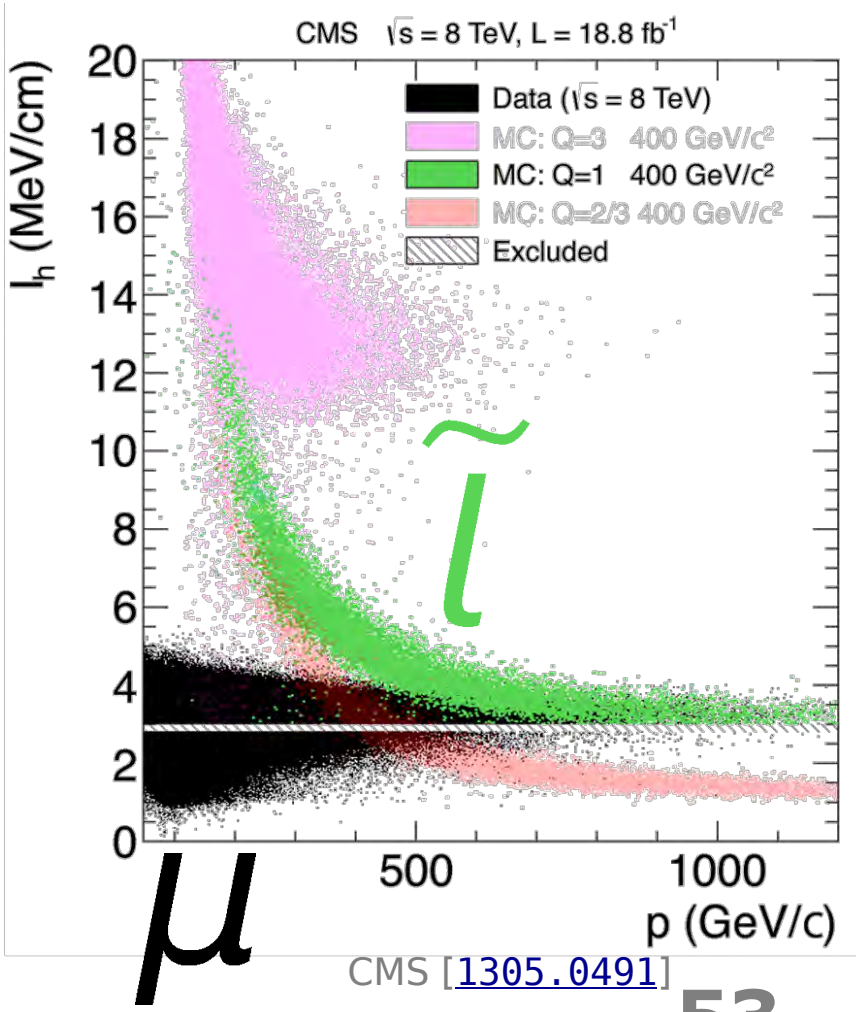
$$I_h = \rho \cdot \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{estimated}}$$

- TOF : time-of-flight

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

- d*E*/d*x* : ionization energy loss





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