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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）

24 Aug. 2015

SUSY 2015 @ Lake Tahoe

Based on

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

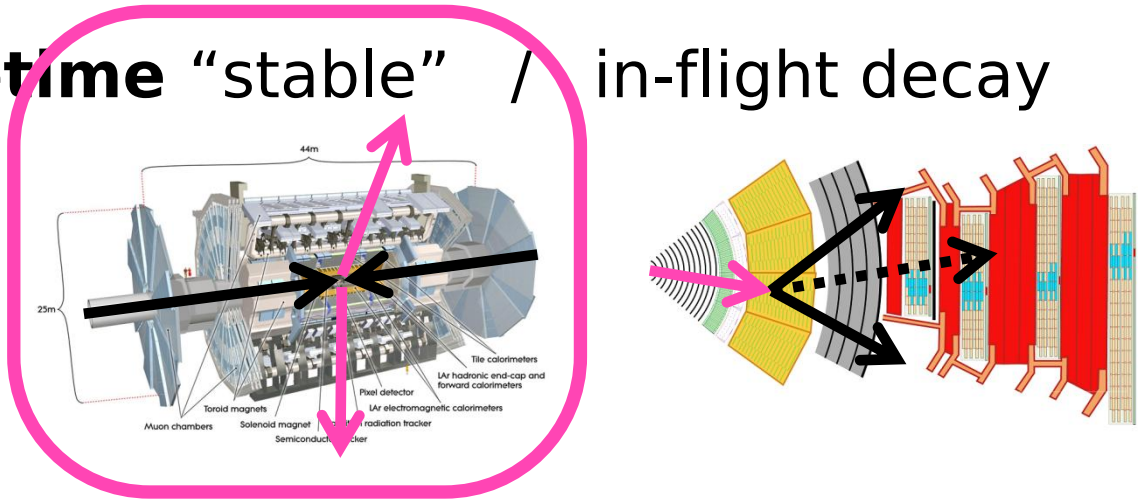
Mass “Heavy” / “light”

O(100) GeV $\ll$ 100 GeV

Charge colored / EM charged / neutral

→ Hadronize → charged track → Missing

Lifetime “stable” / in-flight decay



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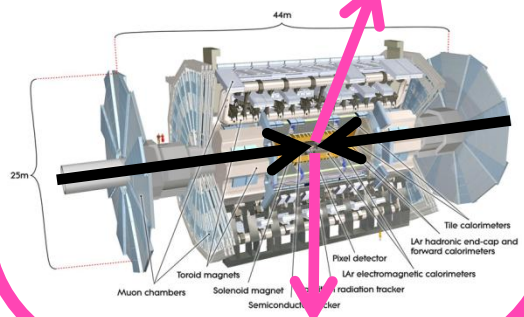

"long-lived charged particles"

- long-lived sleptons $\tilde{e}, \tilde{\mu}, \tilde{\tau}$
- long-lived charginos $\tilde{\chi}^{\pm}$
- ...

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

  at 100 TeV pp collider

- New phenomenon

  at 100 TeV pp collider

  "Muon radiative energy loss"

Sushi picture (c) Paylessimages, inc.

1. How searched at the LHC?

2. at 100 TeV collider?

- Muon radiative energy loss for BKG reduction

3. Our simulation

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

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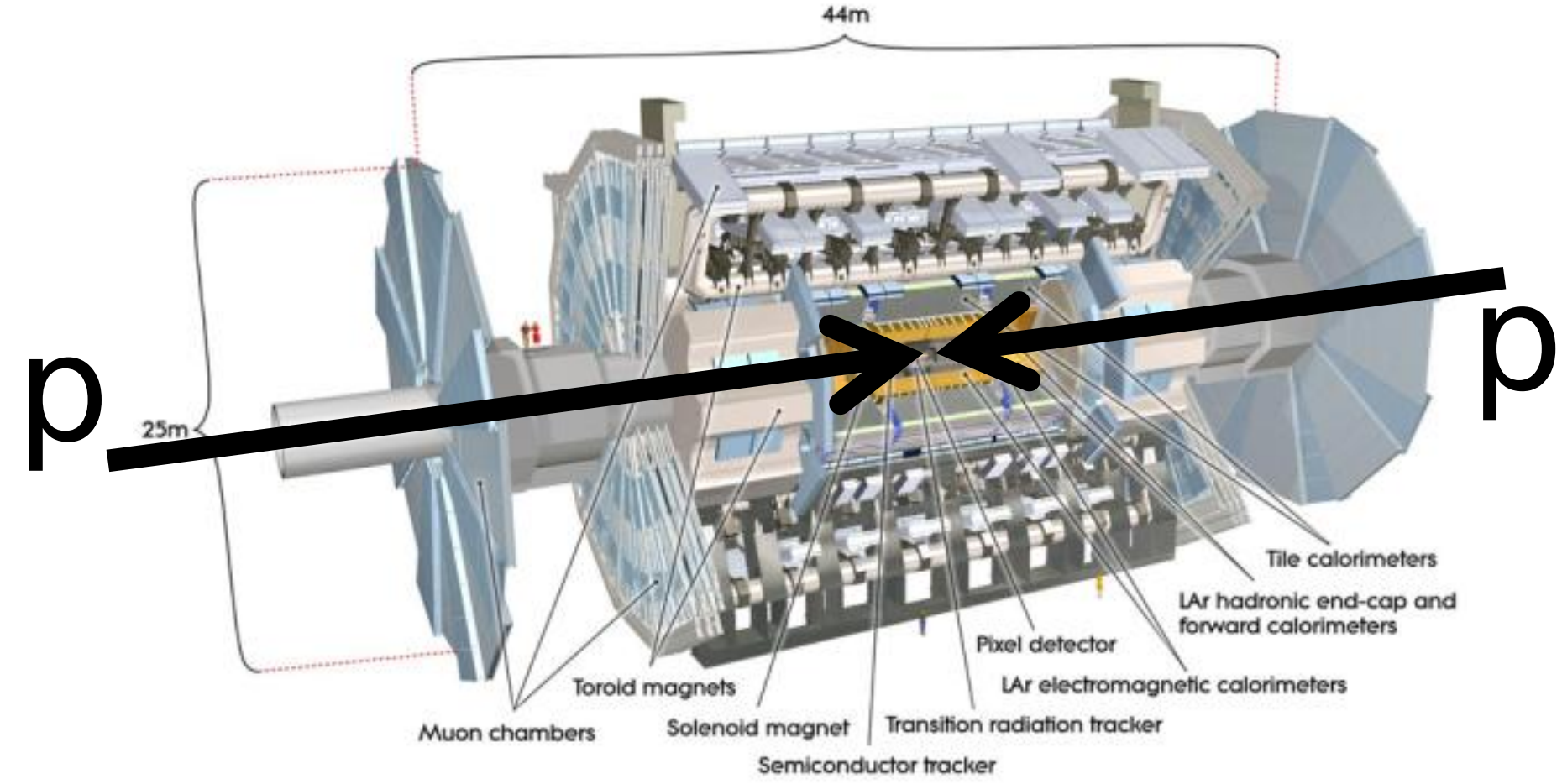
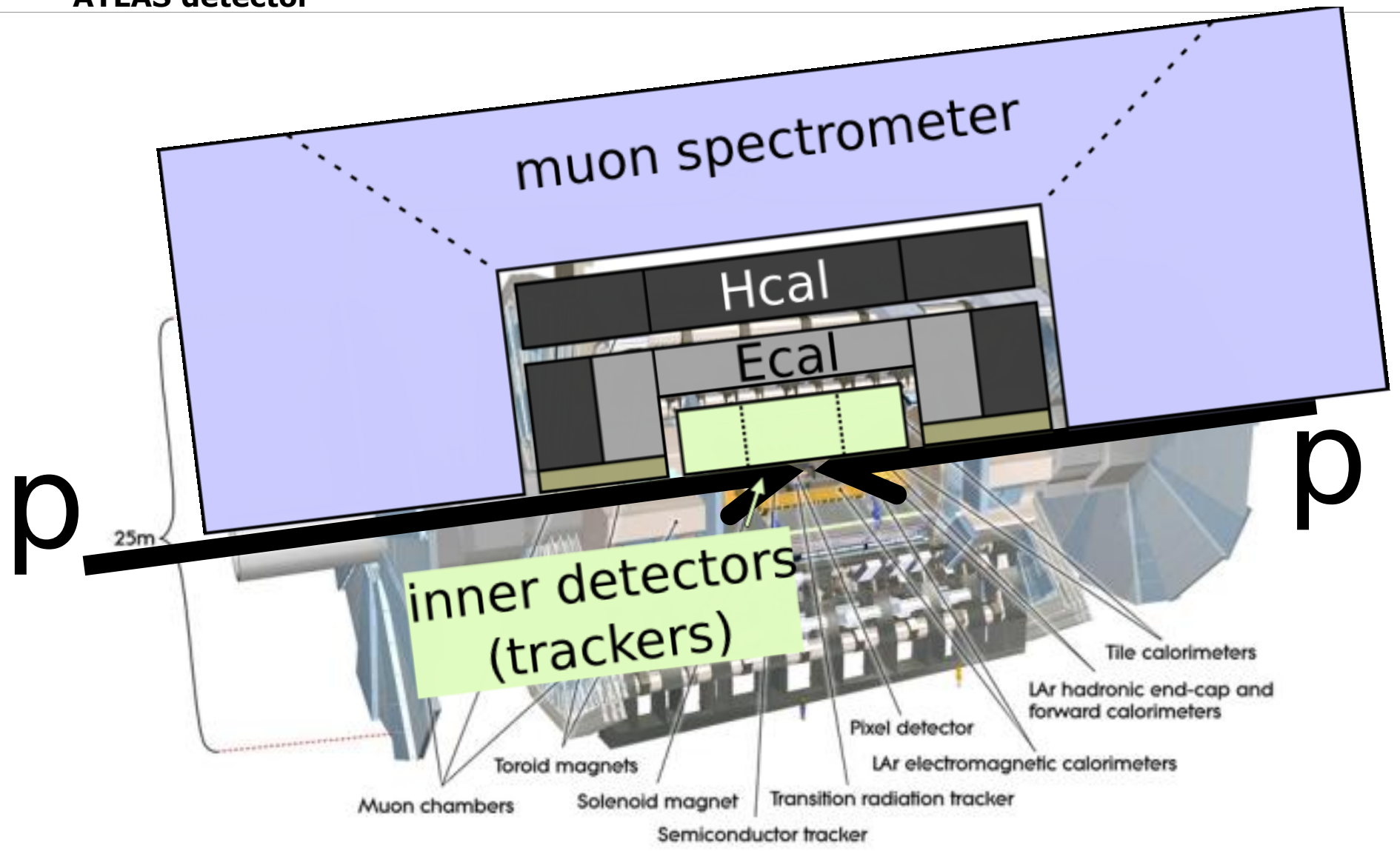

44m
25m
p
p
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker


muon spectrometer
Hcal
Ecal
p
p
25m
inner detectors
(trackers)
Tile calorimeters
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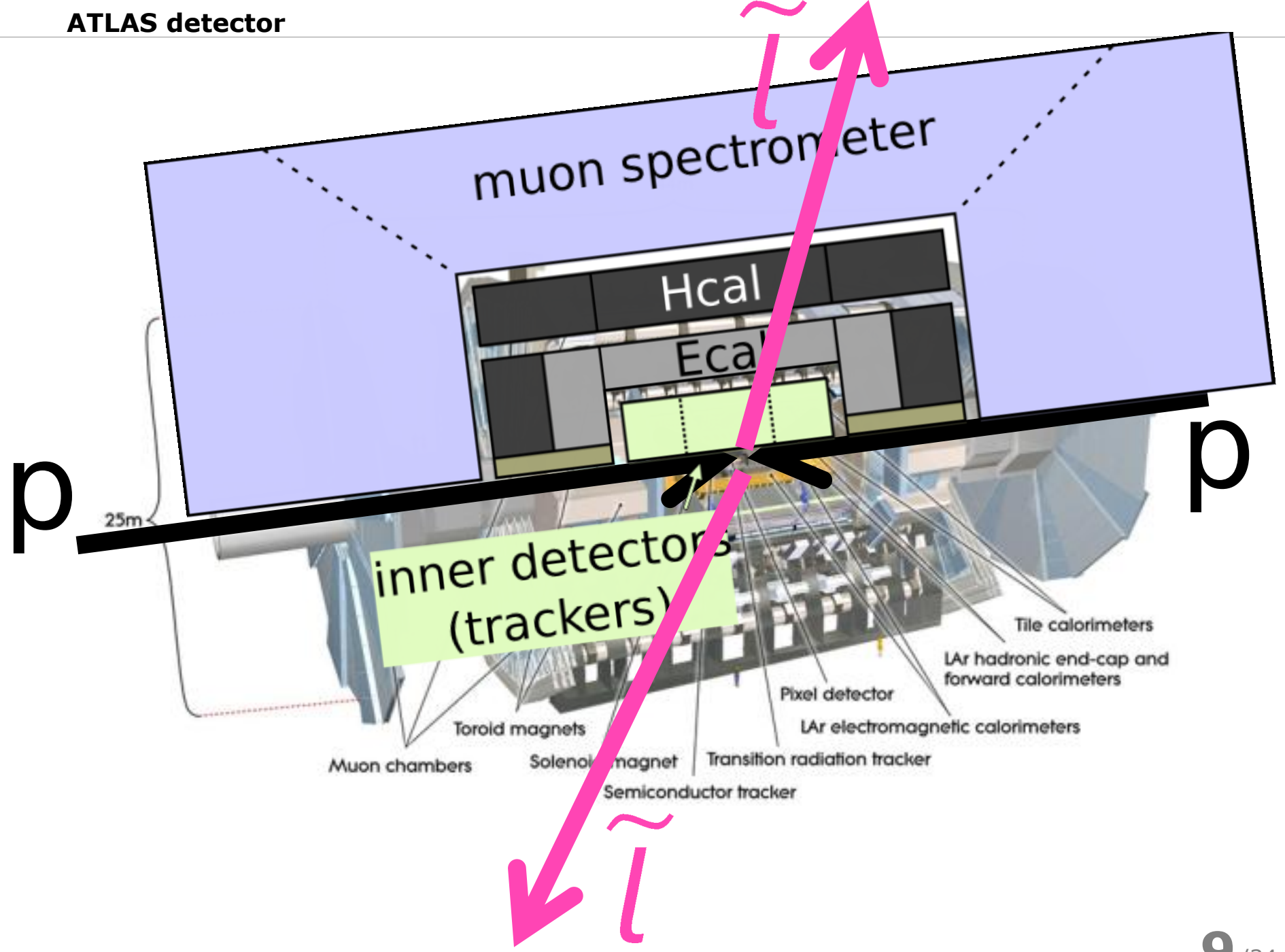
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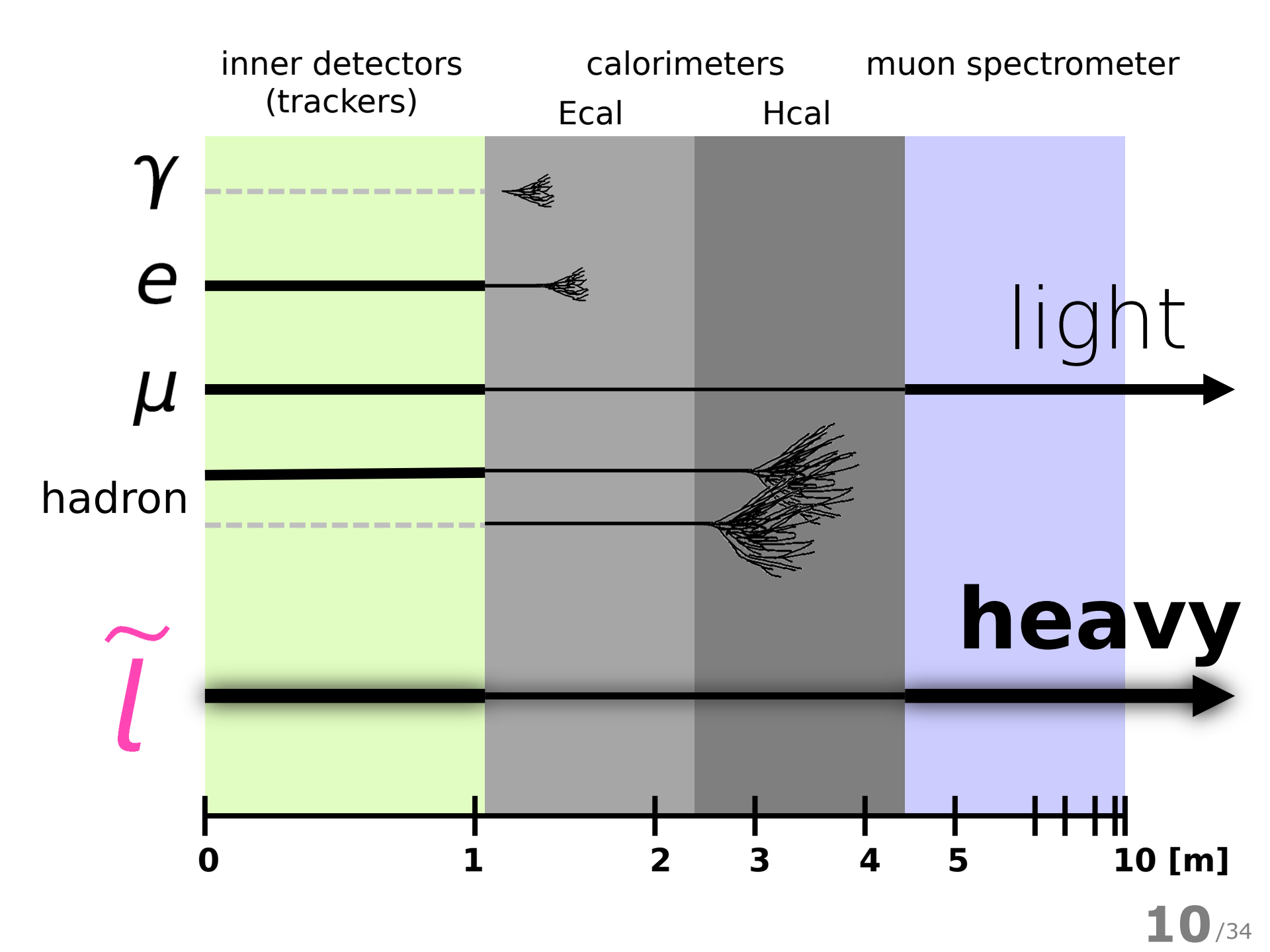

inner detectors
(trackers)
calorimeters
Ecal
Hcal
muon spectrometer
γ
e
μ
hadron
light
heavy
0
1
2
3
4
5
10 [m]

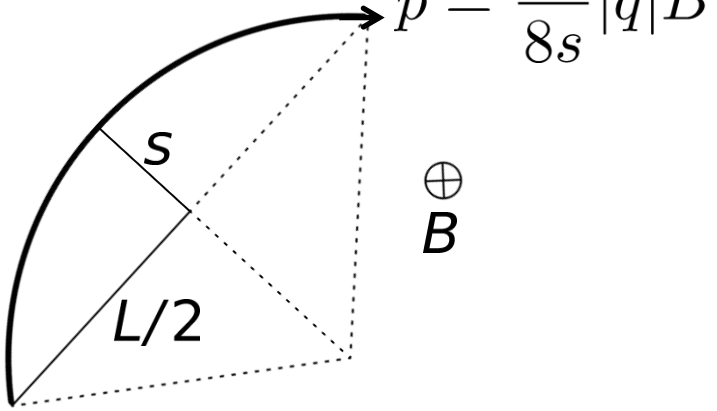
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

momentum & velocity

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

➢ momentum

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



➢ velocity

- TOF [time-of-flight]

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

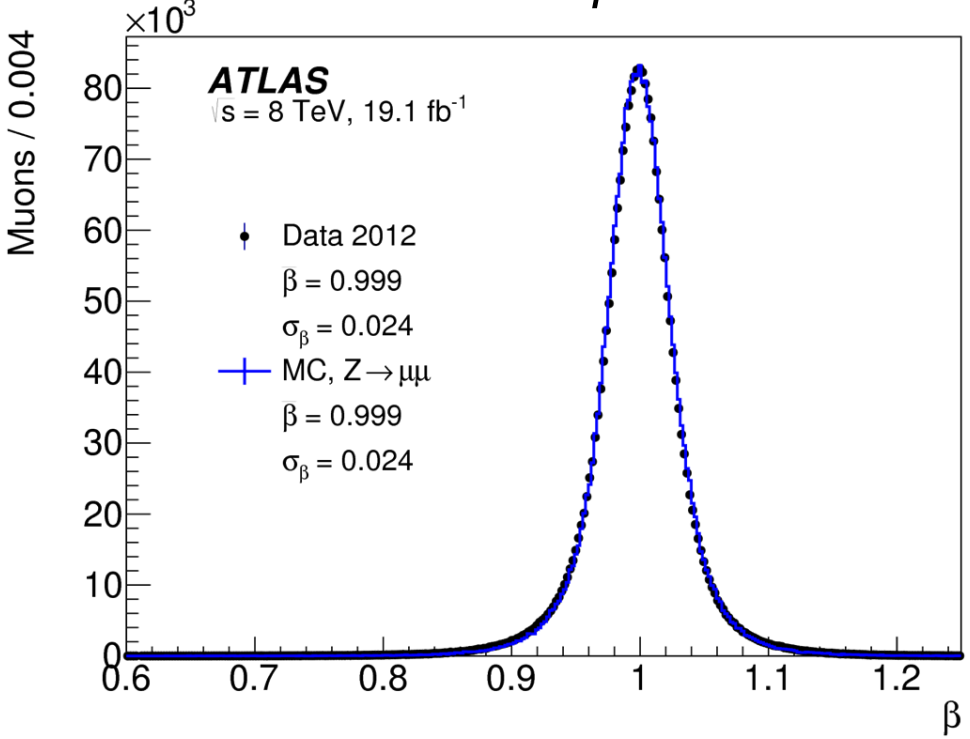
- d*E*/d*x* [ionization energy loss]

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

momentum & velocity

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

ATLAS: **muon** β resolution



➢ velocity

- TOF [time-of-flight]

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

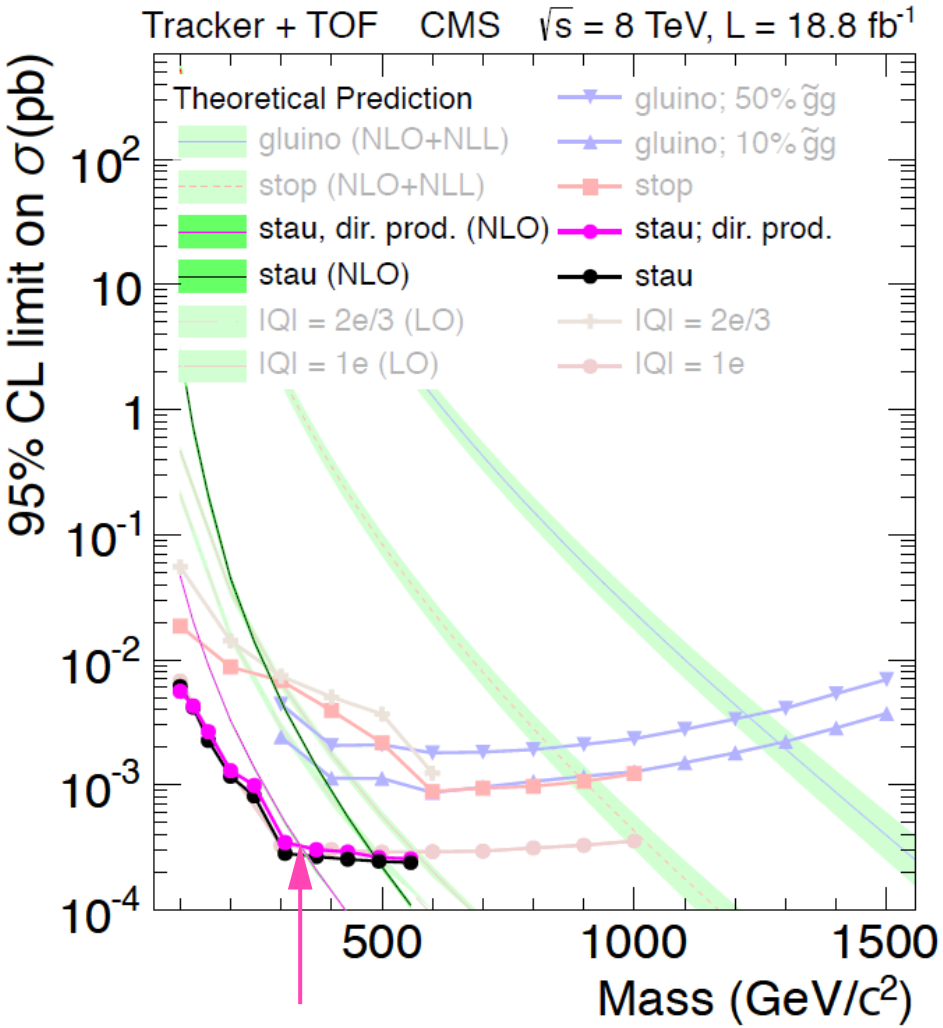
- d*E*/d*x* [ionization energy loss]

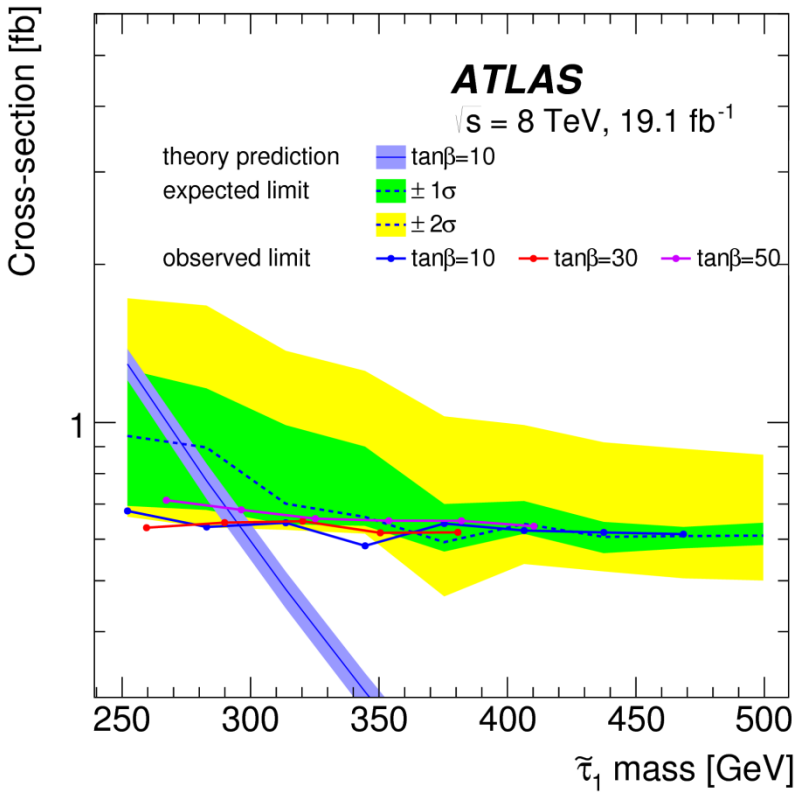
See also: LHCb-CONF-2014-001

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

(**direct** production)

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





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2. at 100 TeV collider?

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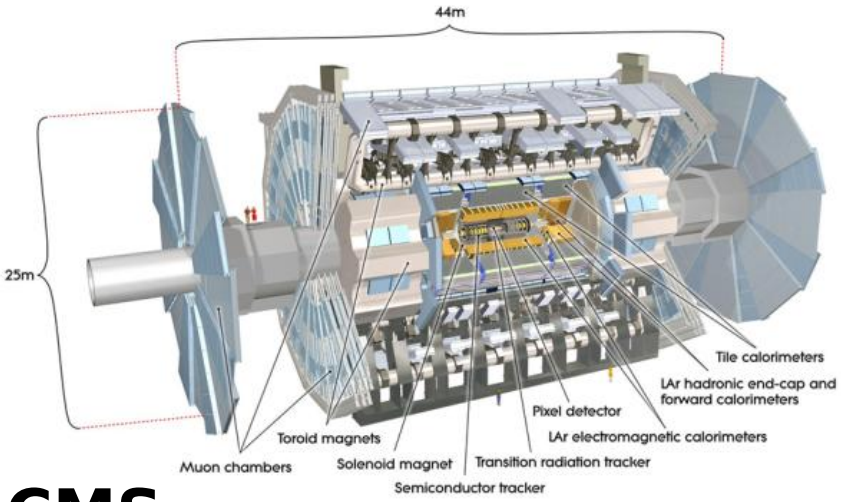
3. Our simulation

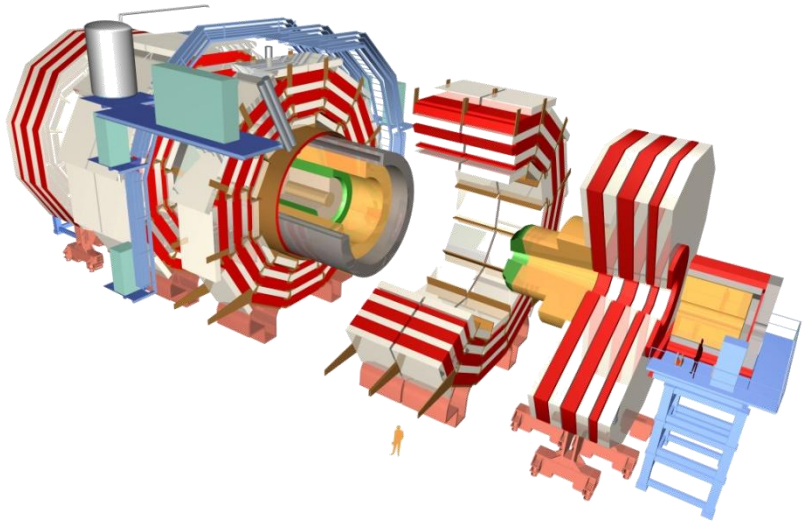
- Expected reach: $m_{\tilde{l}}$

- LHC

ATLAS



CMS



- 100 TeV Collider

HectoLAS

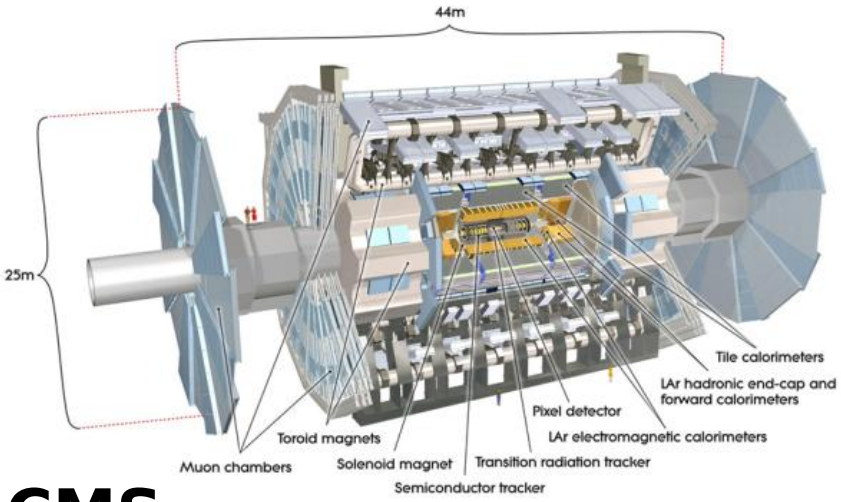
?

₵MS

?

LHC

ATLAS



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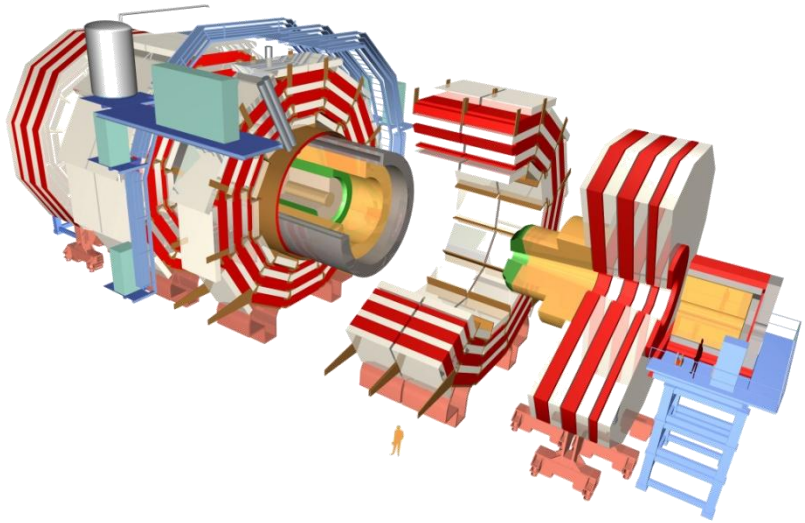
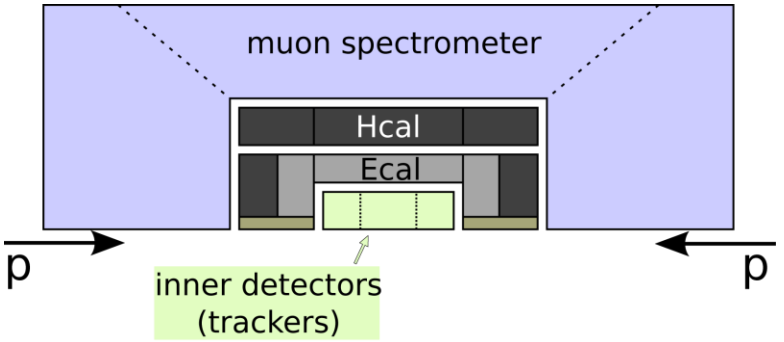
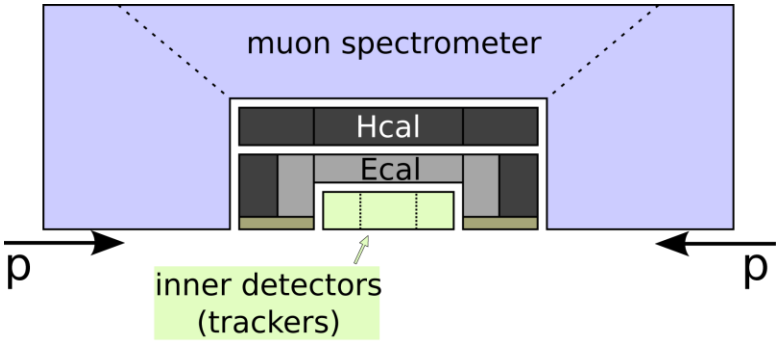


100 TeV Collider

HectoLAS



¢MS



our selection flow

$\widetilde{l}$ = reconstructed “muon” with

- $p_T > 500\,\mathrm{GeV}$
- $|\eta| < 2.4$
- $0.4 < \hat{\beta} < 0.95$ (from TOF)
-

Cf.) ATLAS 8 TeV [1411.6795]

- $p_T > 70\,\mathrm{GeV}$
- $|\eta| < 2.5$
- $0.2 < \hat{\beta} < 0.95$

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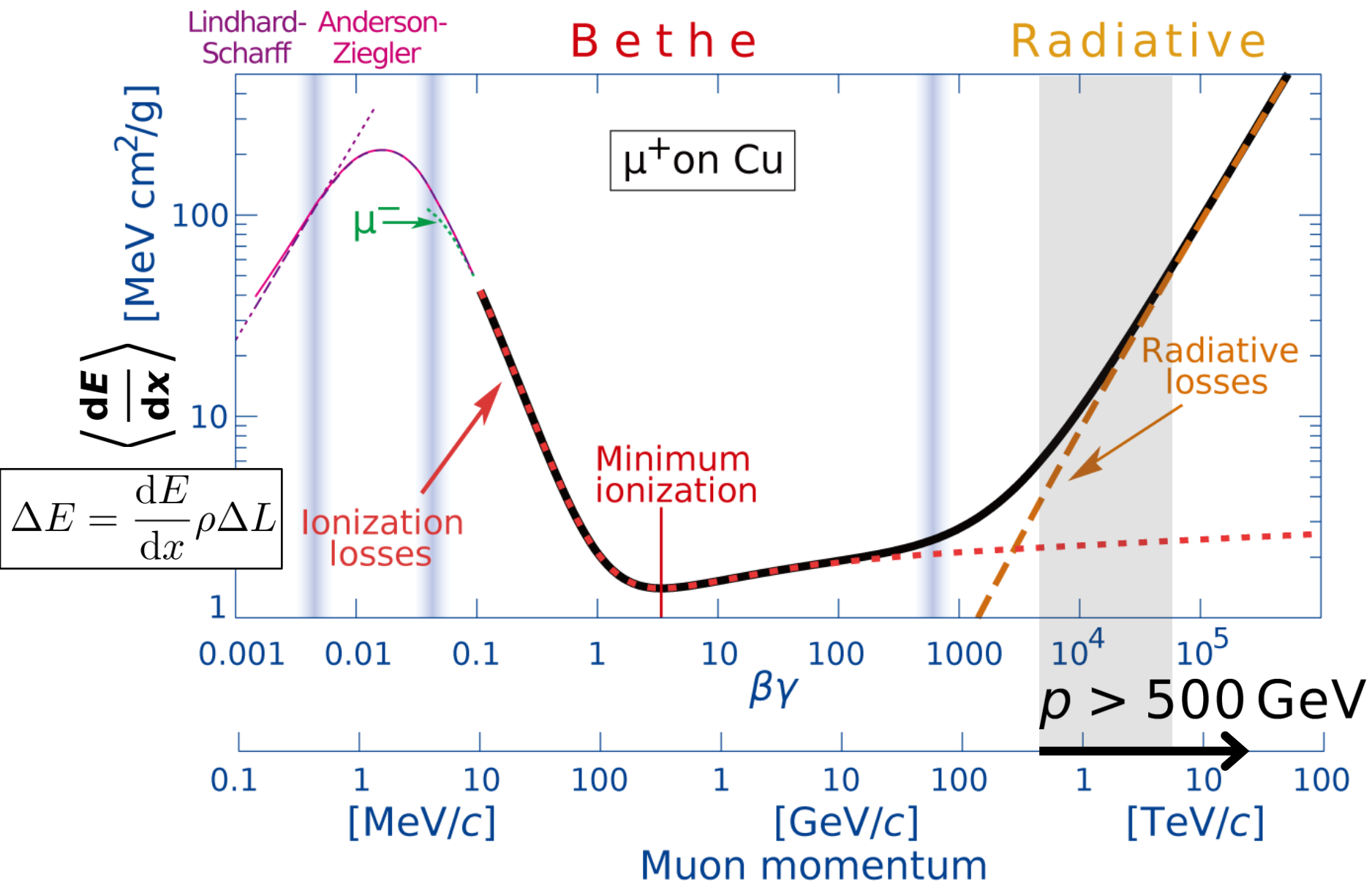
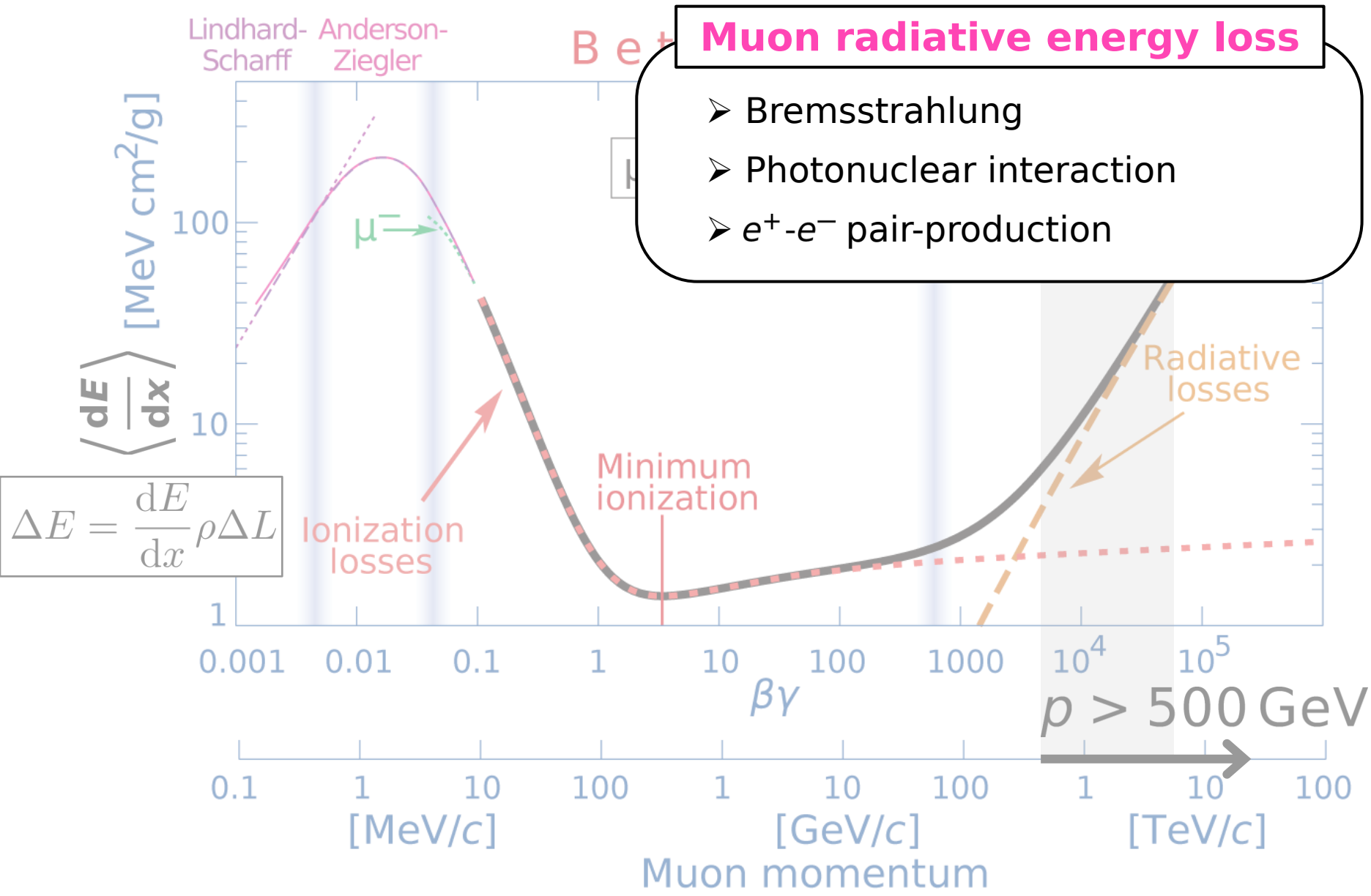


Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]



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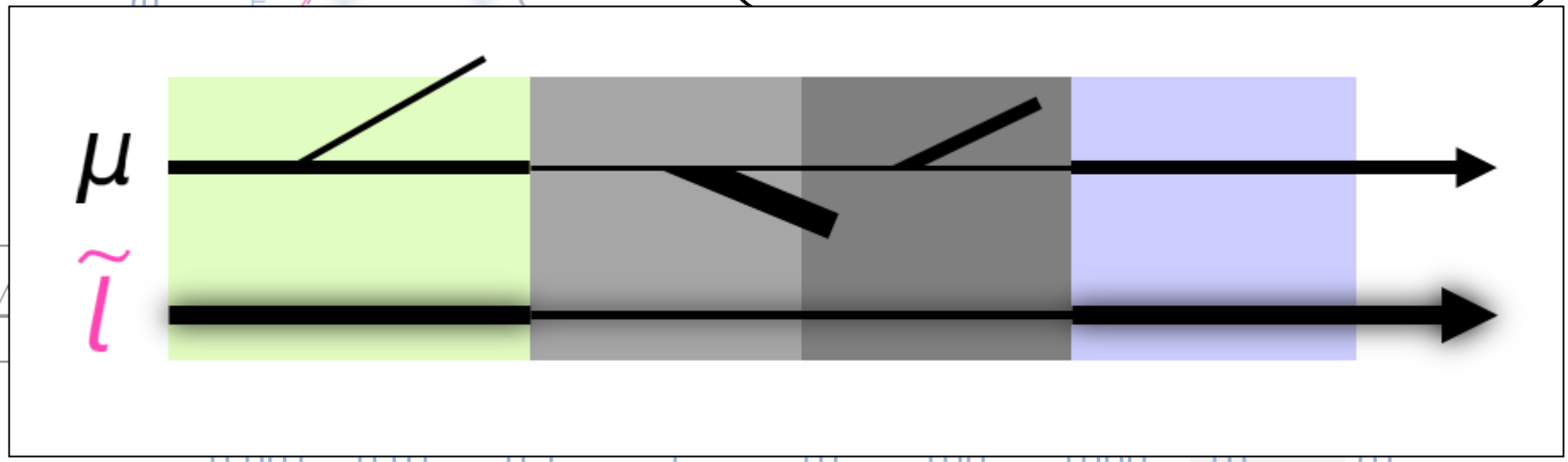
Muon radiative energy loss

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



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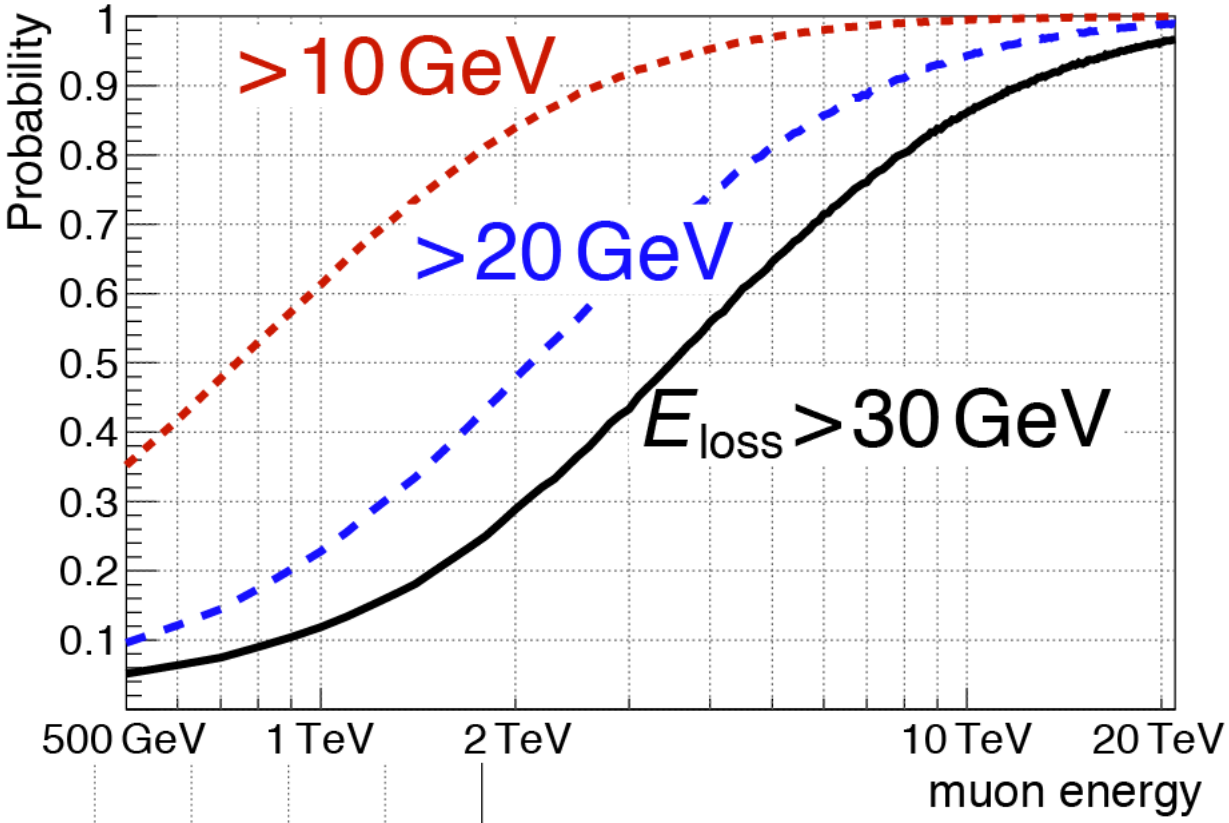

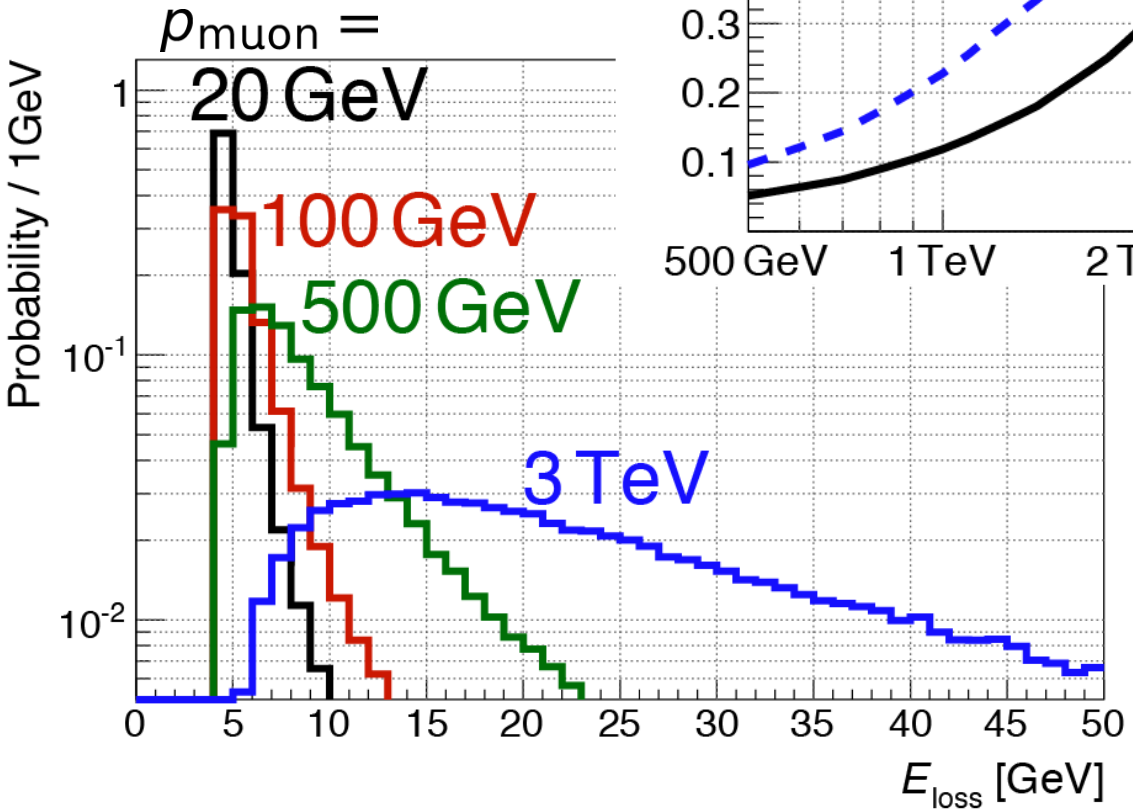

[Simulated with GEANT 4]

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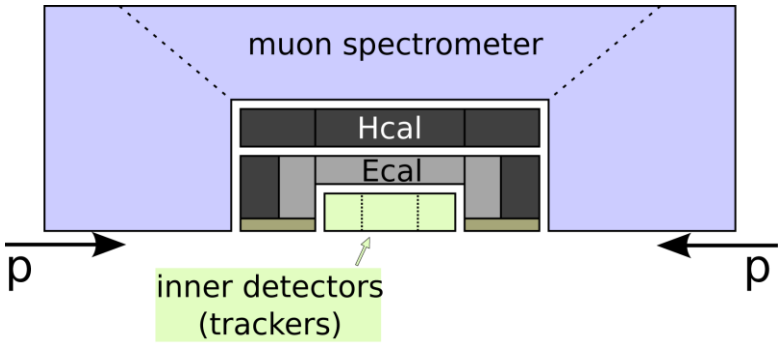
- Detector
  - similar to ATLAS/CMS
  - β-resolution same as ATLAS (resolution: 2.4%)



- 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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  - $E_{\mathrm{loss}} < 30\,\mathrm{GeV}$
- Event selection
  - two $\tilde{l}$-candidates

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

	signal		SM BKG
	$\tilde{l} = 1\,\text{TeV}$	$3\,\text{TeV}$	
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 ($\int L = 1\,\text{ab}^{-1}$)

	$1\,\text{TeV}$	$3\,\text{TeV}$	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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SR

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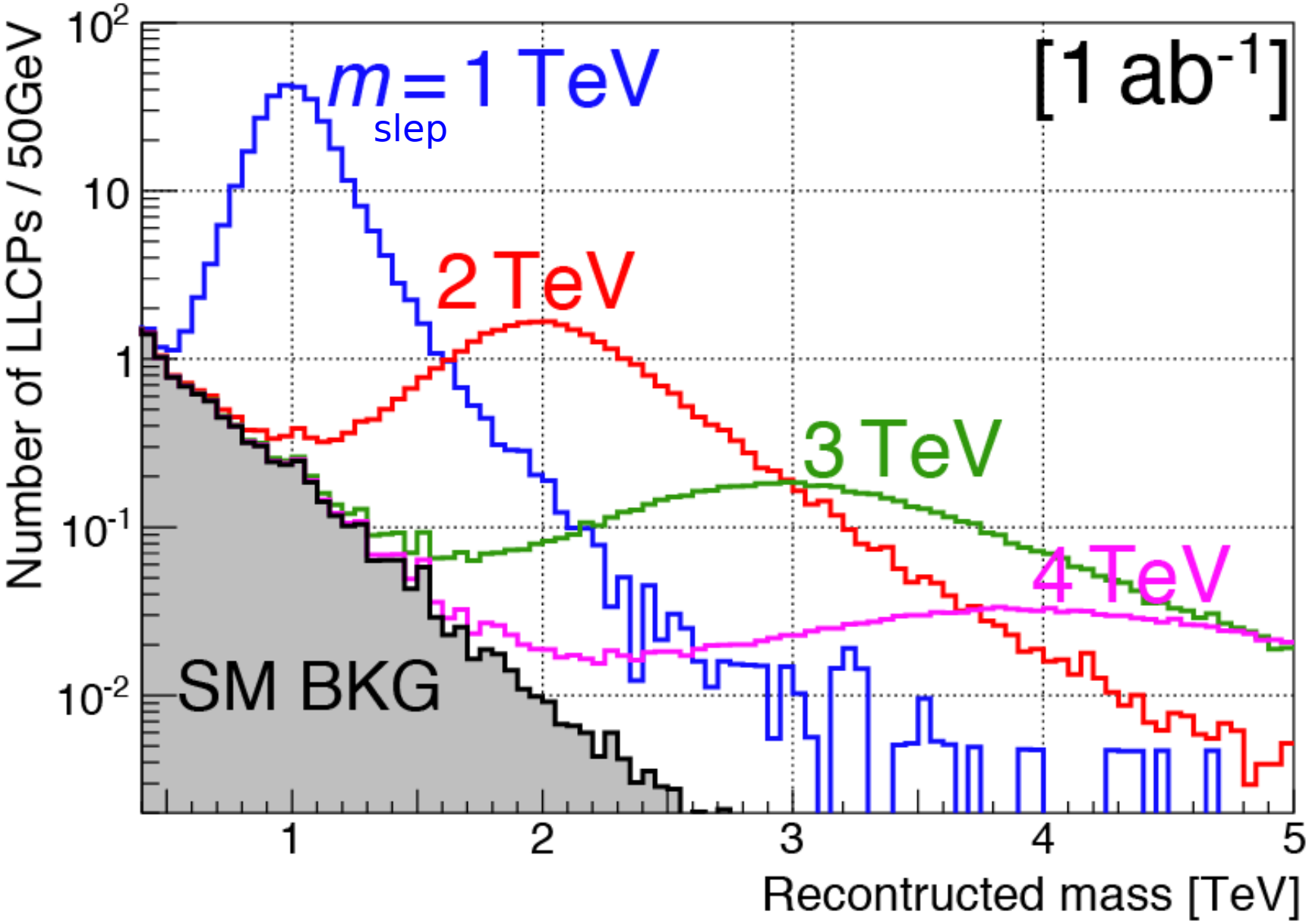
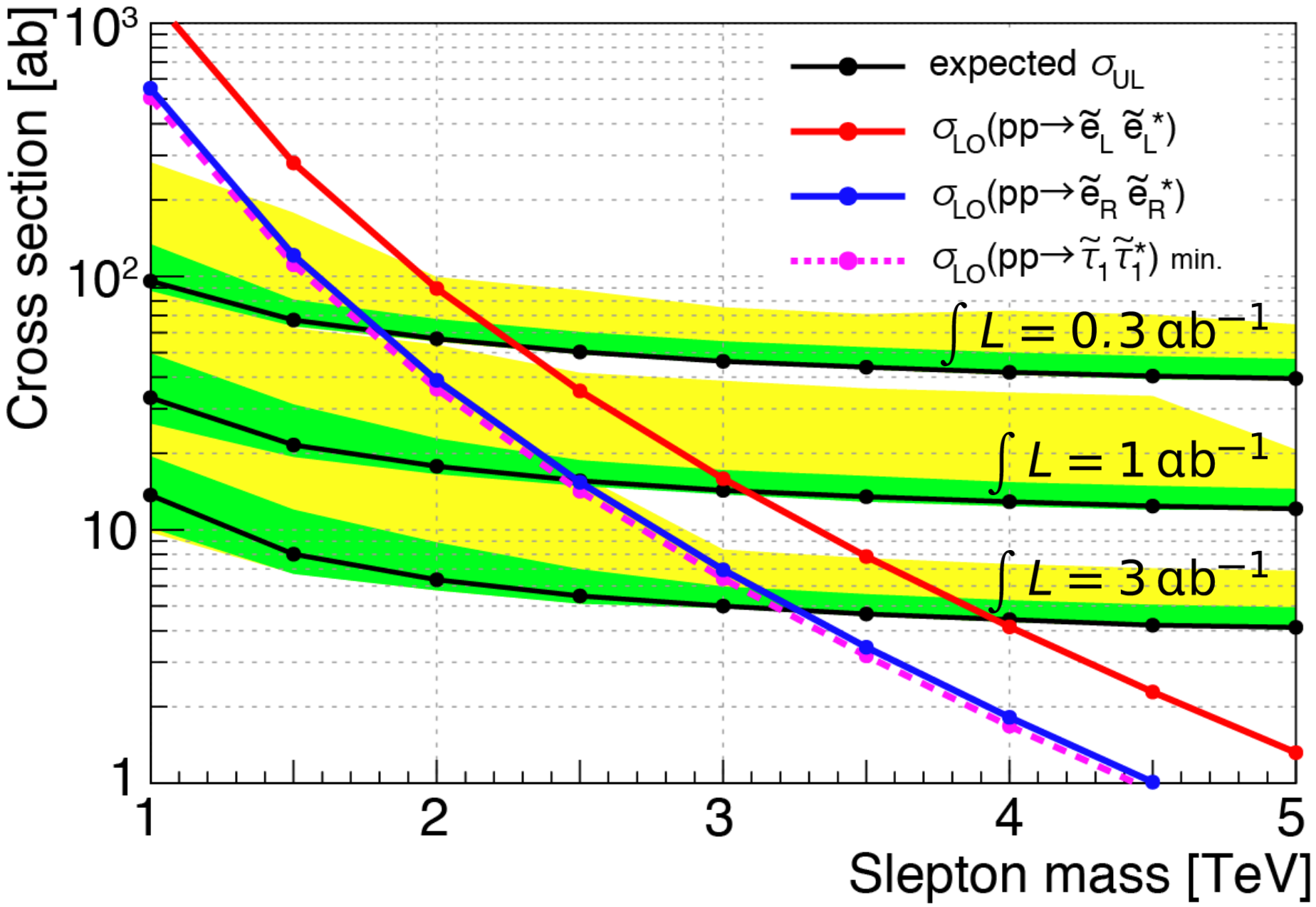
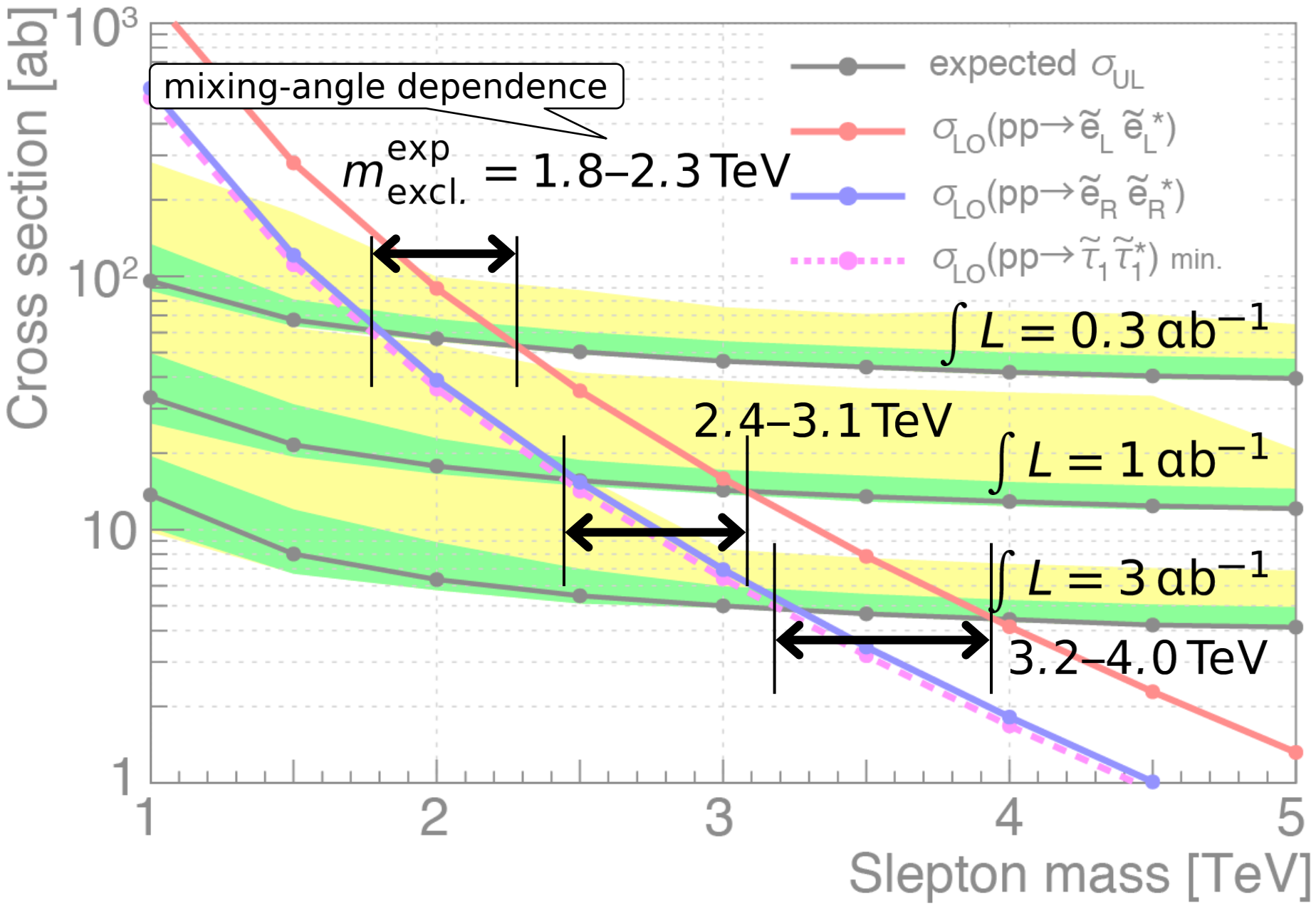

$m = 1$ TeV
slep
[1 ab^{-1}]
2 TeV
3 TeV
4 TeV
SM BKG
Number of LLCPs / 50GeV
10^2
10
1
10^{-1}
10^{-2}
1
2
3
4
5
Recontructed mass [TeV]

Feng, SI, 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.
$\int L = 0.3\,\text{ab}^{-1}$
$\int L = 1\,\text{ab}^{-1}$
$\int L = 3\,\text{ab}^{-1}$

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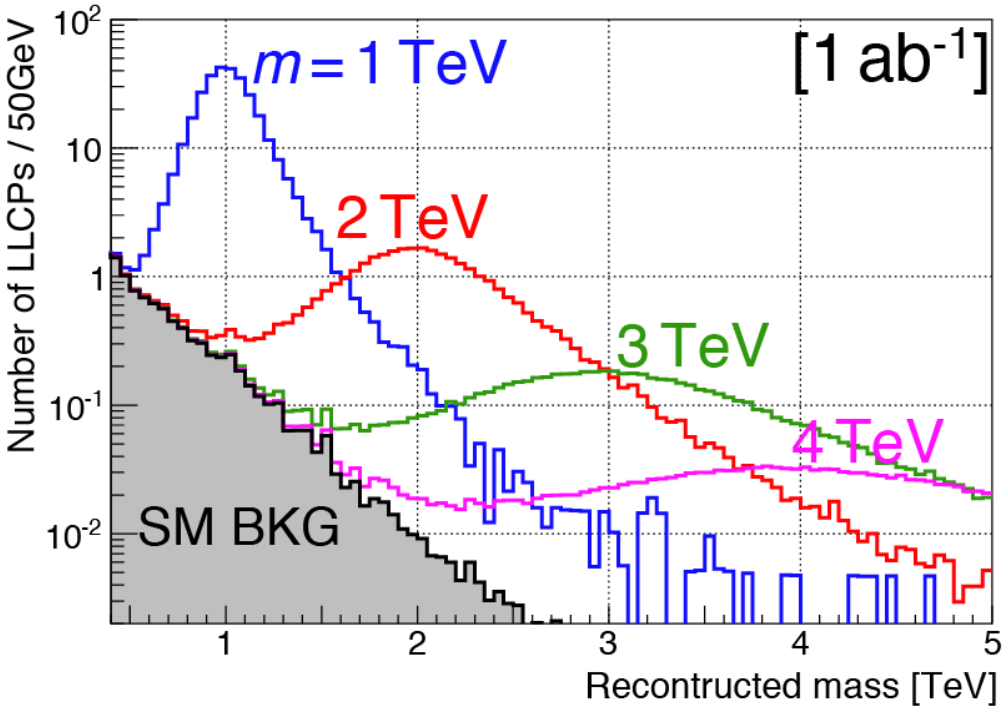
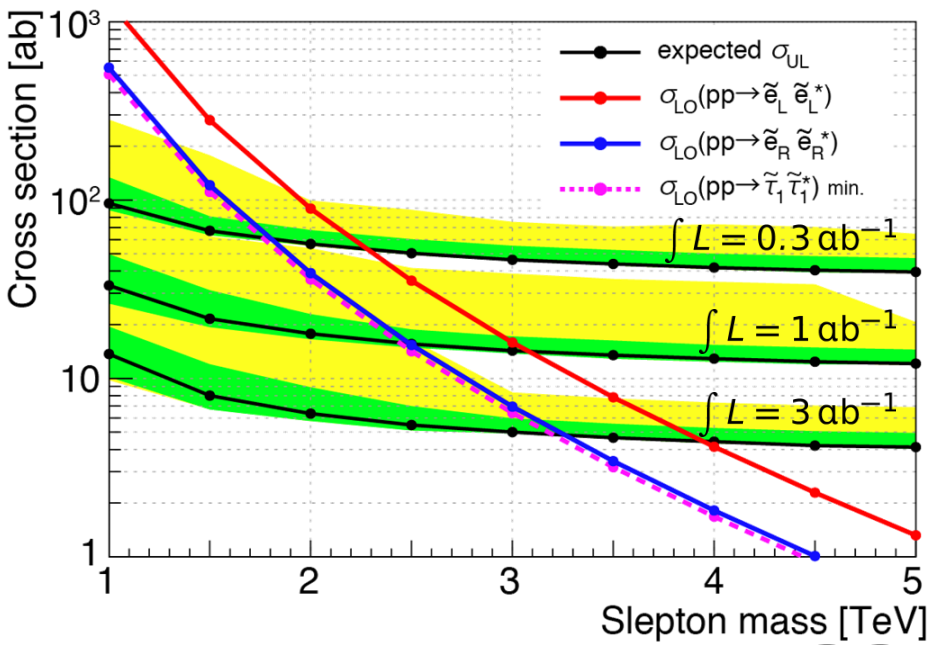
SR



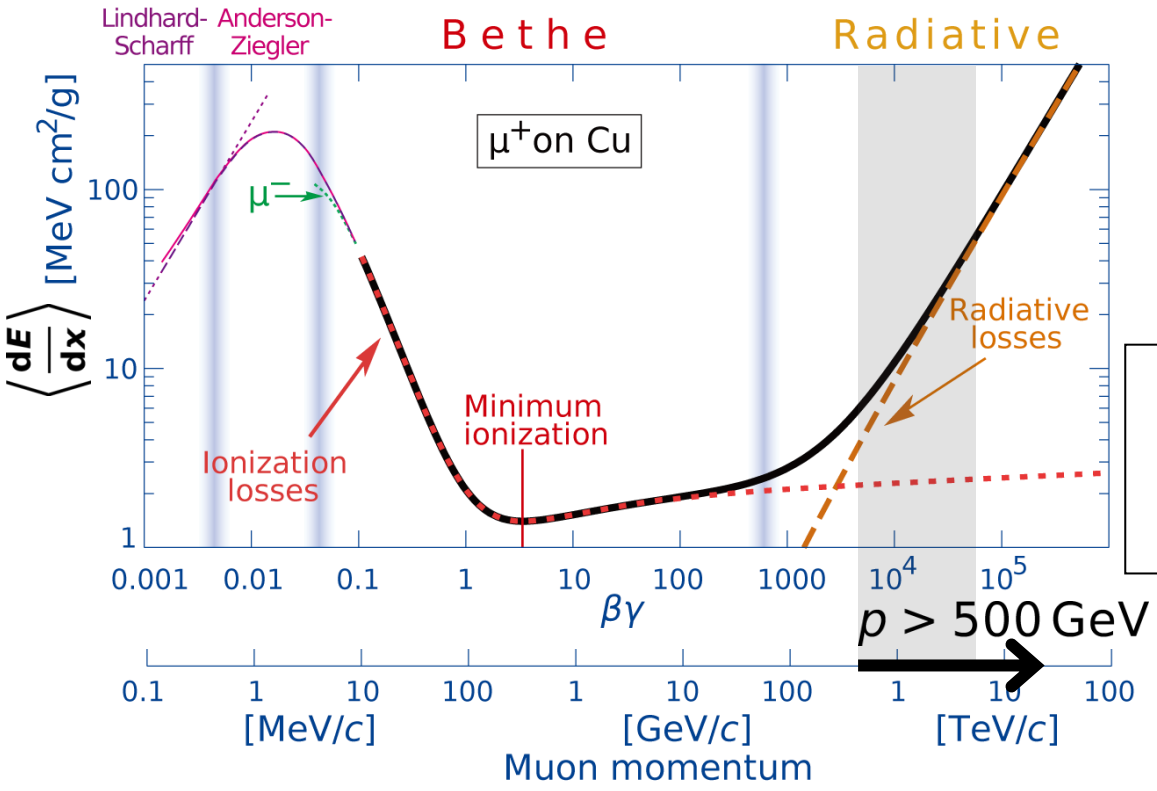


Take-home SUSI

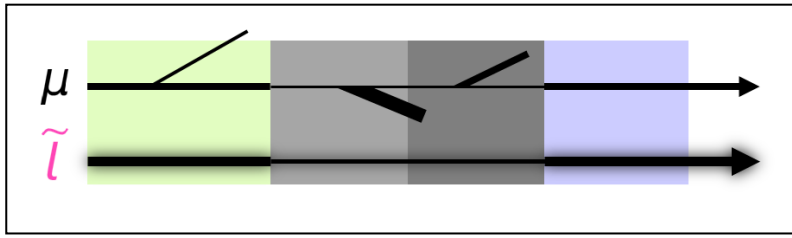
- Expected exclusion reach @100 TeV

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

- **"Muon radiative energy loss"**



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



→ **34%** of BKG reduction

Sushi picture (c) Paylessimages, inc.

1. How searched at the LHC?

2. at 100 TeV collider?

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3. Our simulation

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A. Note on momentum resolution

B. 14 TeV LHC

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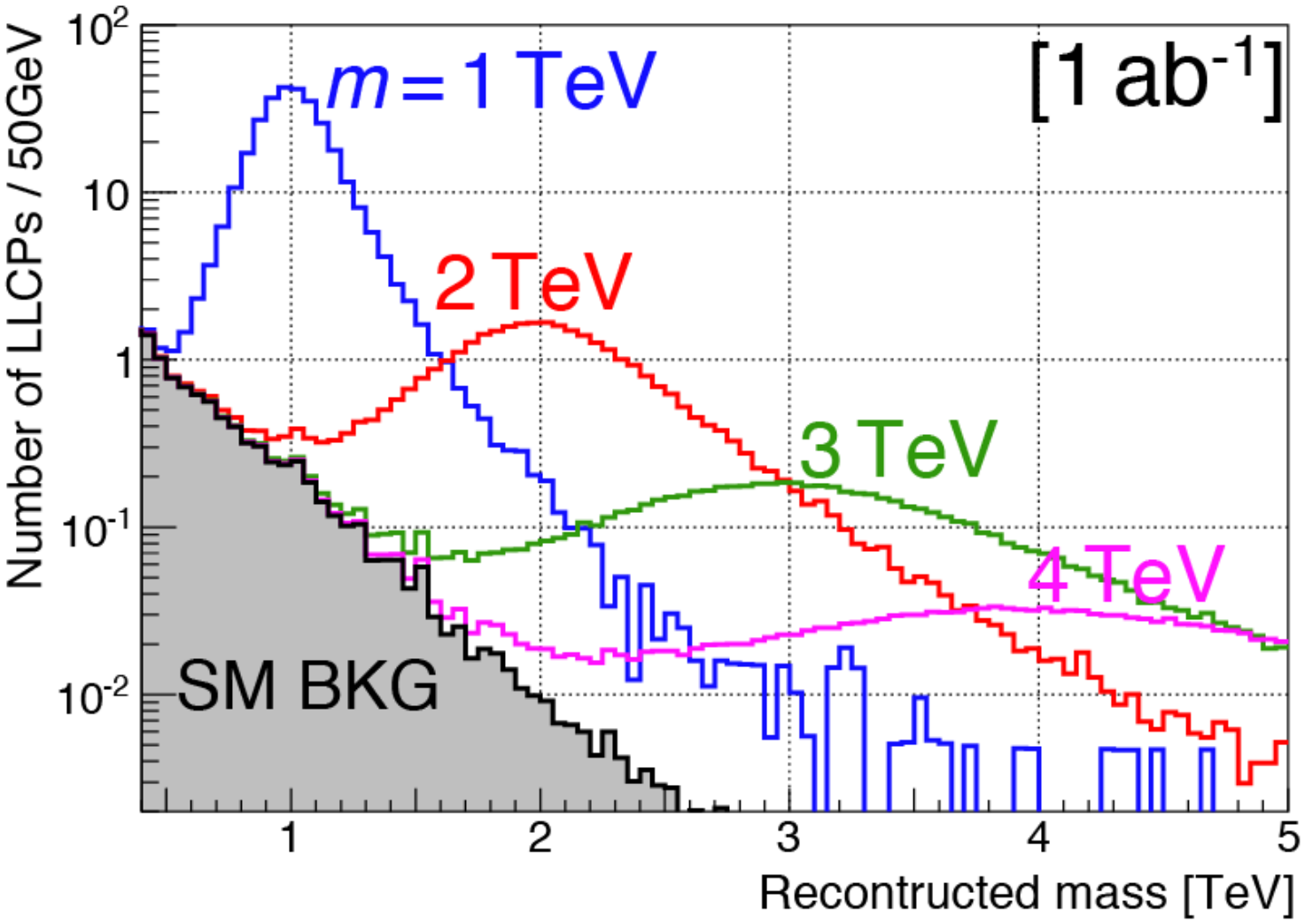
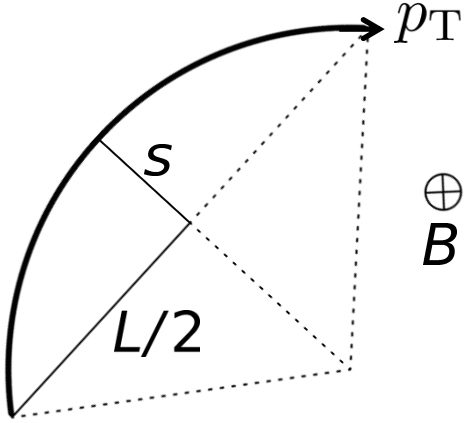


$$\left(= \frac{p}{\beta\gamma} = \frac{p_{\mathrm{T}} \cosh \eta}{\beta\gamma}\right)$$

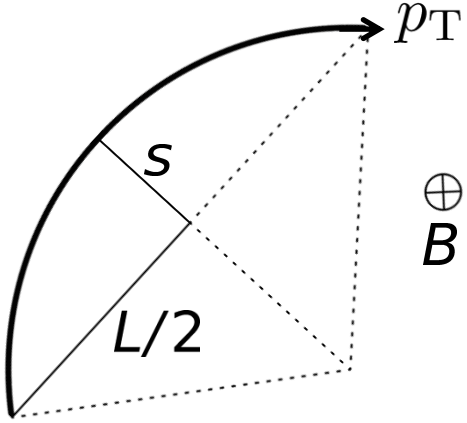


$$p_{\mathrm{T}} = \frac{L^2}{8s}|q|B \Rightarrow \Delta p_{\mathrm{T}} = \frac{L^2|q|B}{8}\frac{\Delta s}{s^2}$$

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

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

ATLAS [1404.4562]; see also [1201.4704]

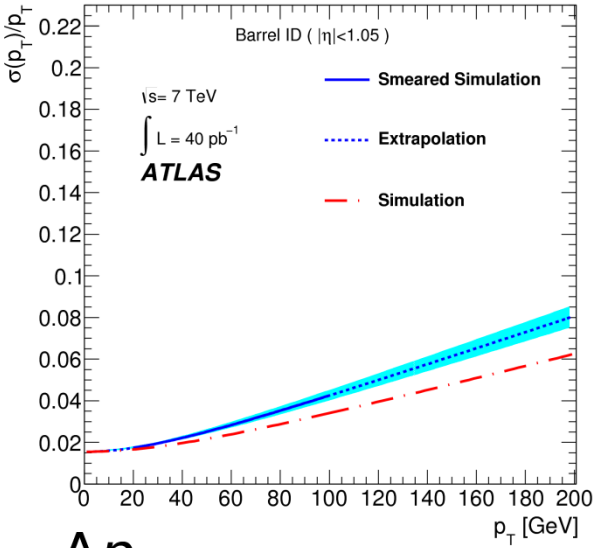


$$p_{\mathrm{T}} = \frac{L^2}{8s}|q|B \Rightarrow \Delta p_{\mathrm{T}} = \frac{L^2|q|B}{8}\frac{\Delta s}{s^2} = \frac{8\Delta s}{L^2|q|B}\cdot p_{\mathrm{T}}^2$$

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

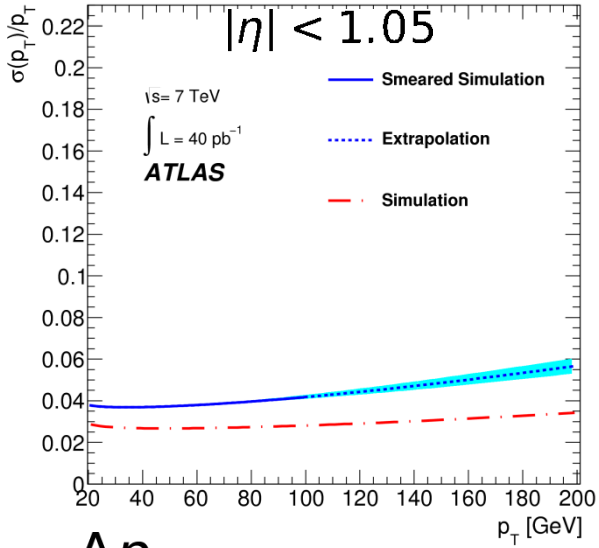
ATLAS 7 TeV results on muon momentum resolution

Inner Detector, $|\eta| < 1.05$

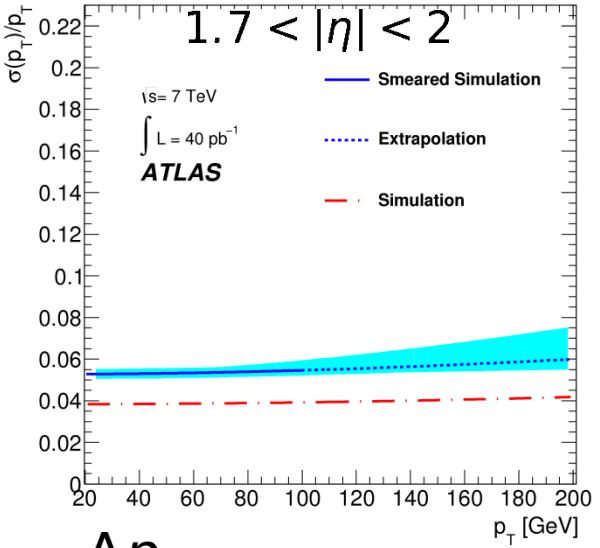


$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.38 p_{\mathrm{T}}/\mathrm{TeV}$$

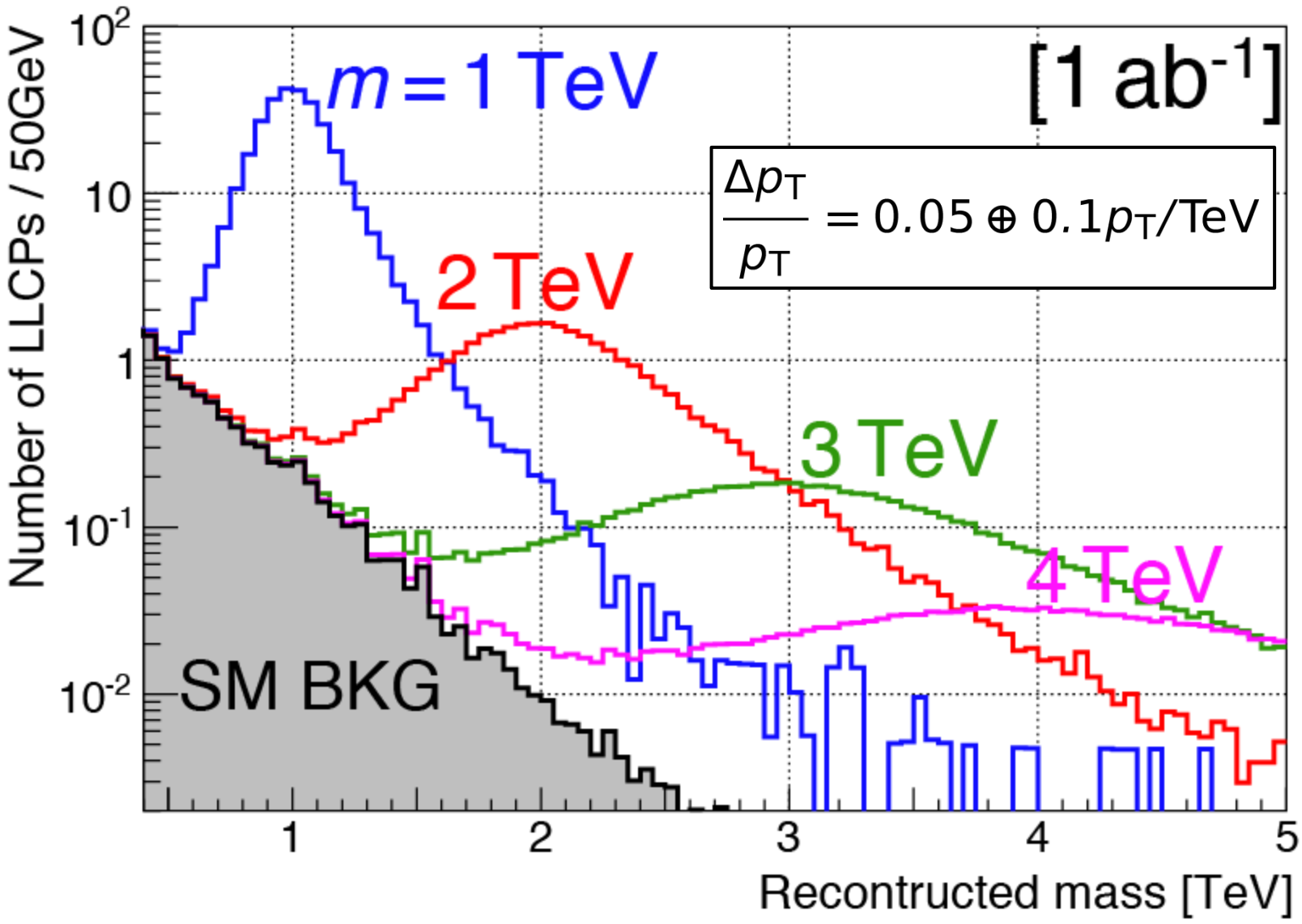
Muon spectrometer

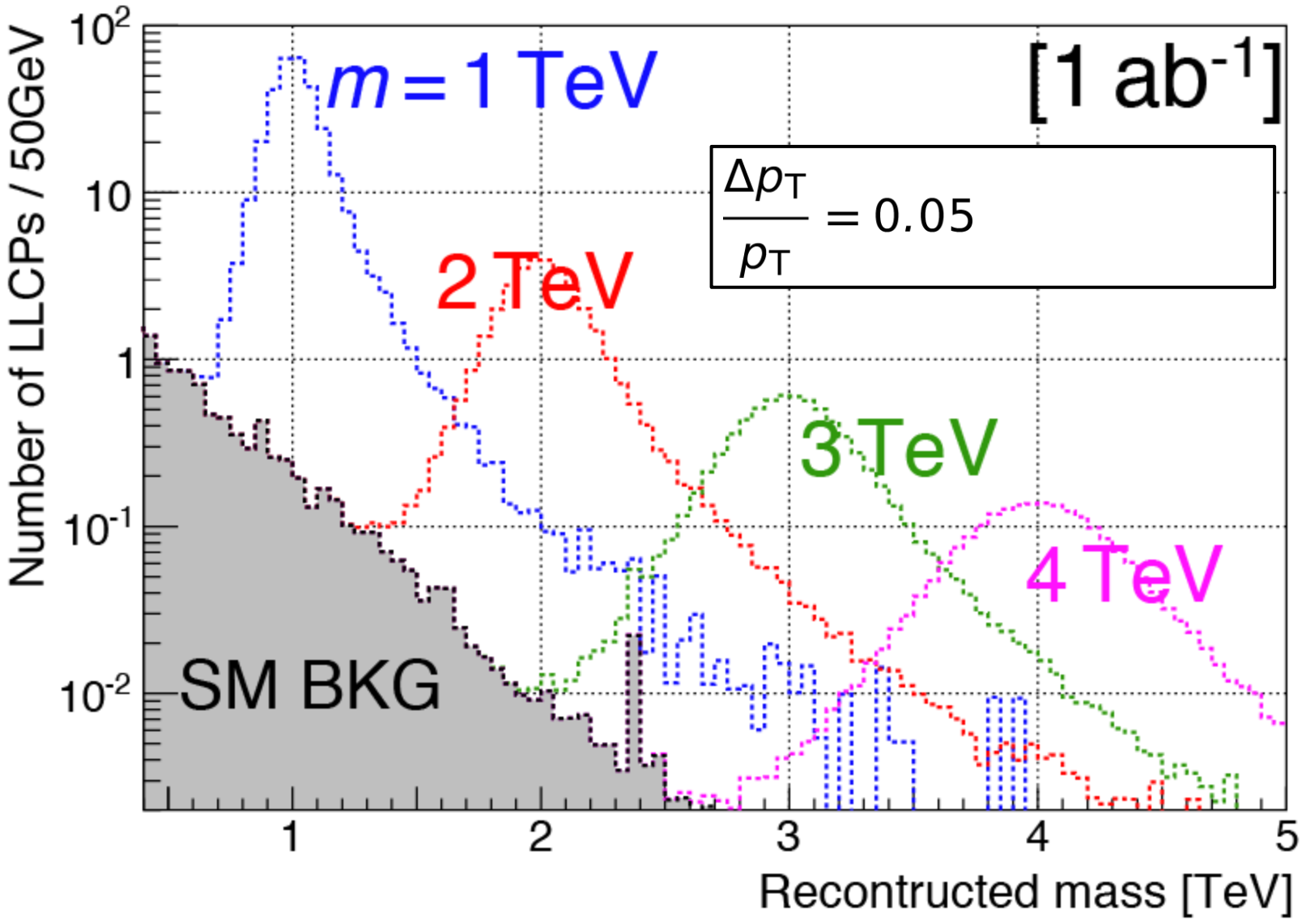


$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.14 p_{\mathrm{T}}/\mathrm{TeV}$$



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


$m = 1$ 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]

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

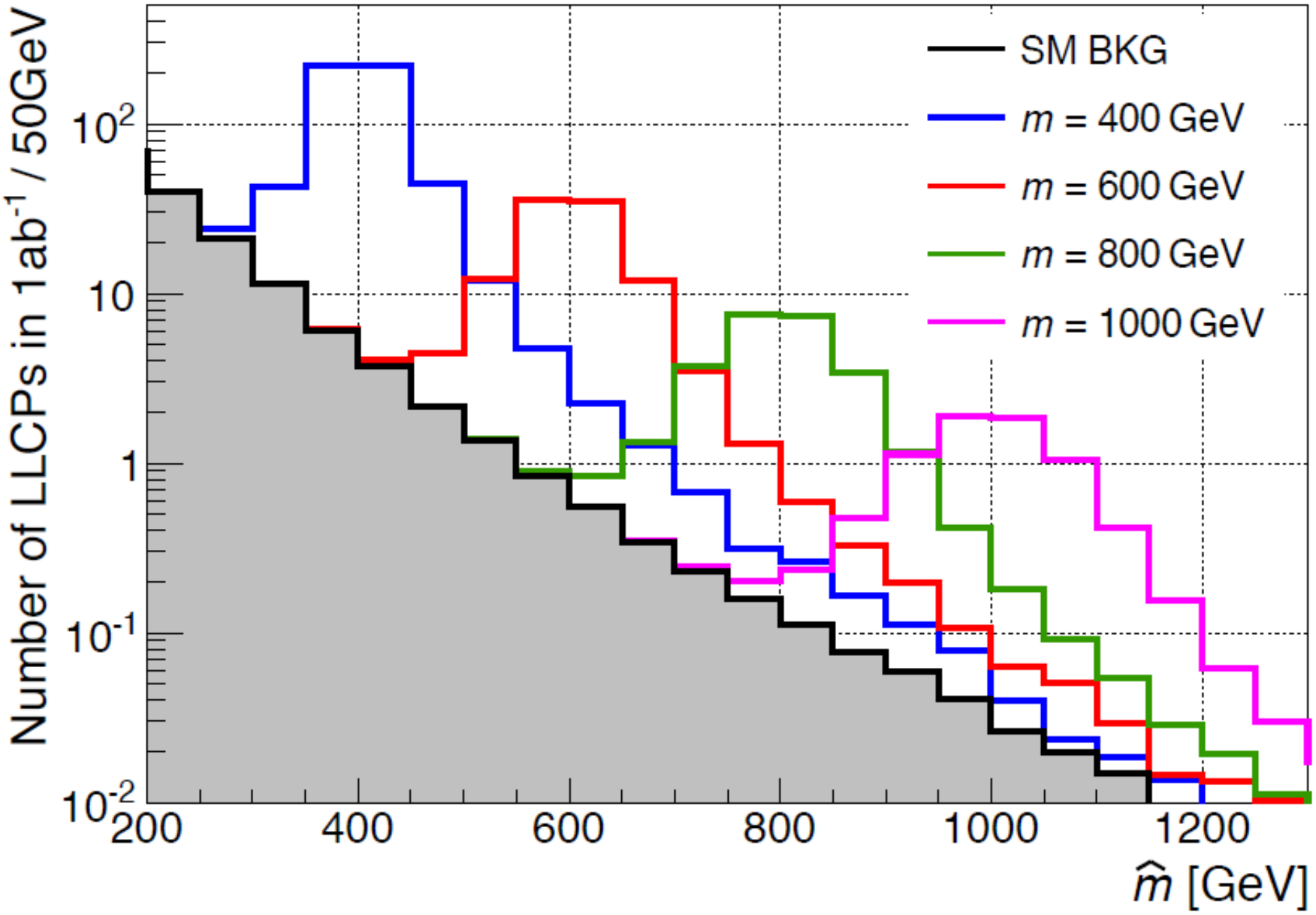
B. 14 TeV LHC

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

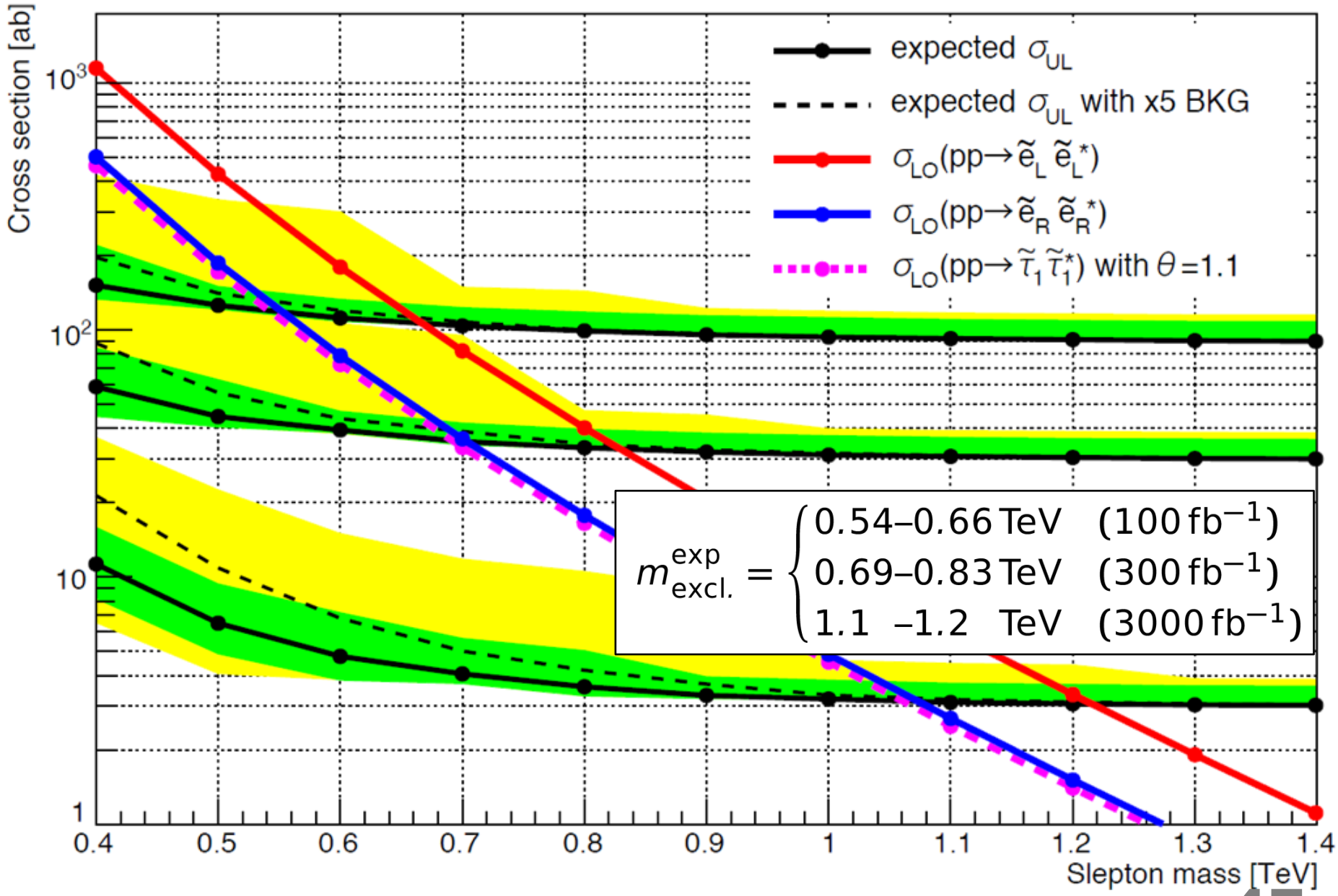
- $\tilde{l}$ -selection flow

  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

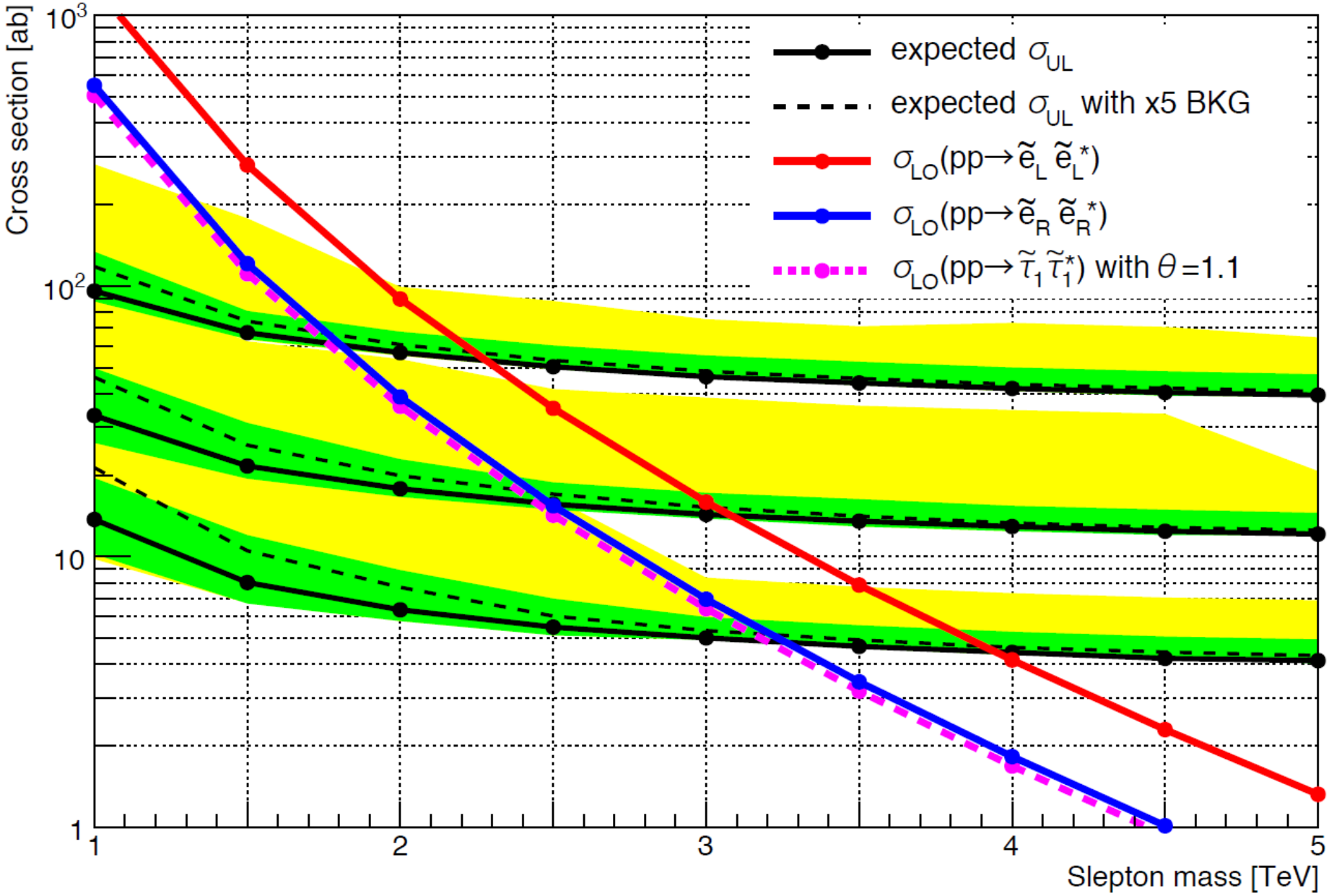

SM BKG
m = 400 GeV
m = 600 GeV
m = 800 GeV
m = 1000 GeV
Number of LLCPs in 1ab-1 / 50GeV
10^2
10
1
10^-1
10^-2
200
400
600
800
1000
1200
m̂ [GeV]

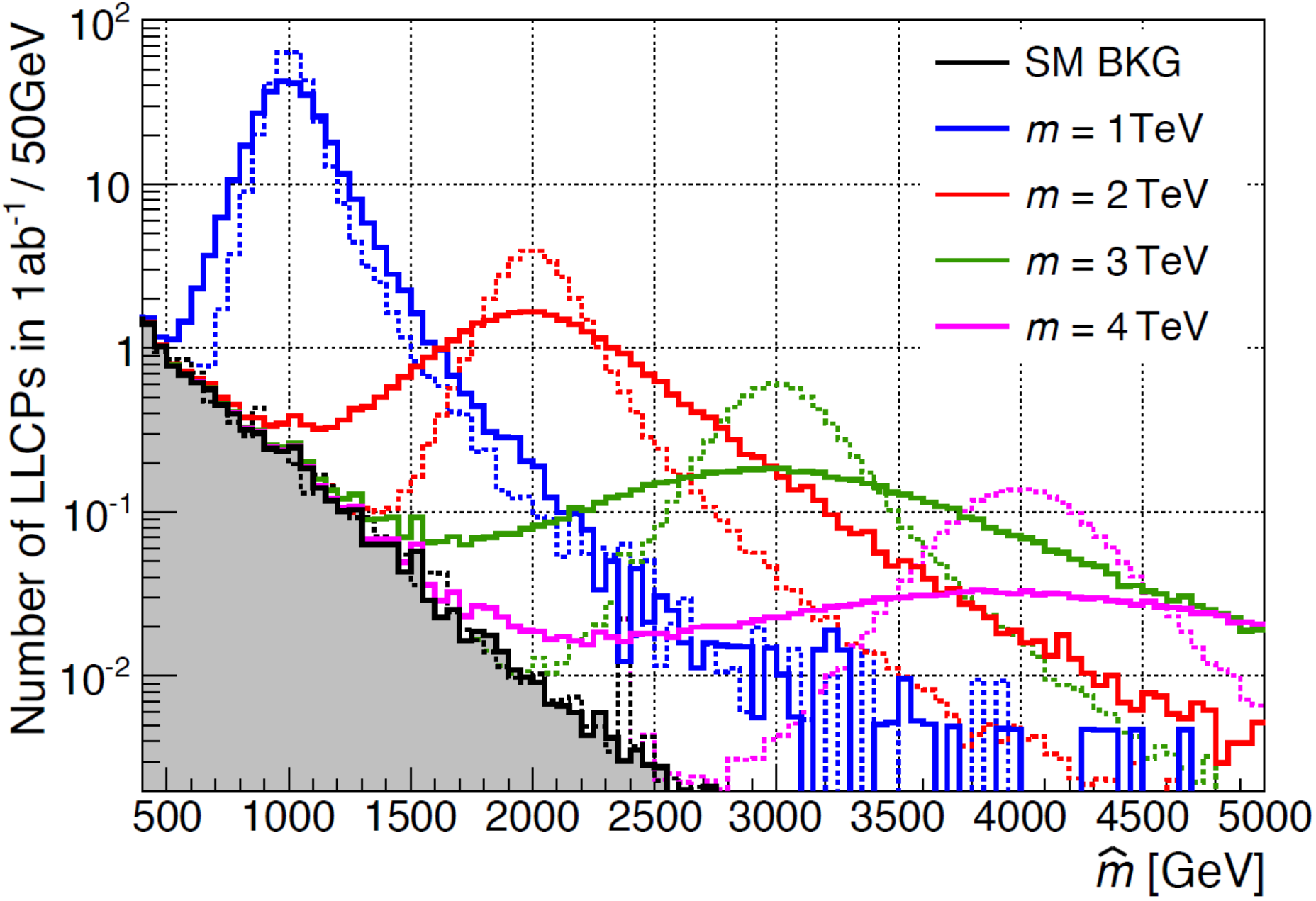
14 TeV LHC expectation

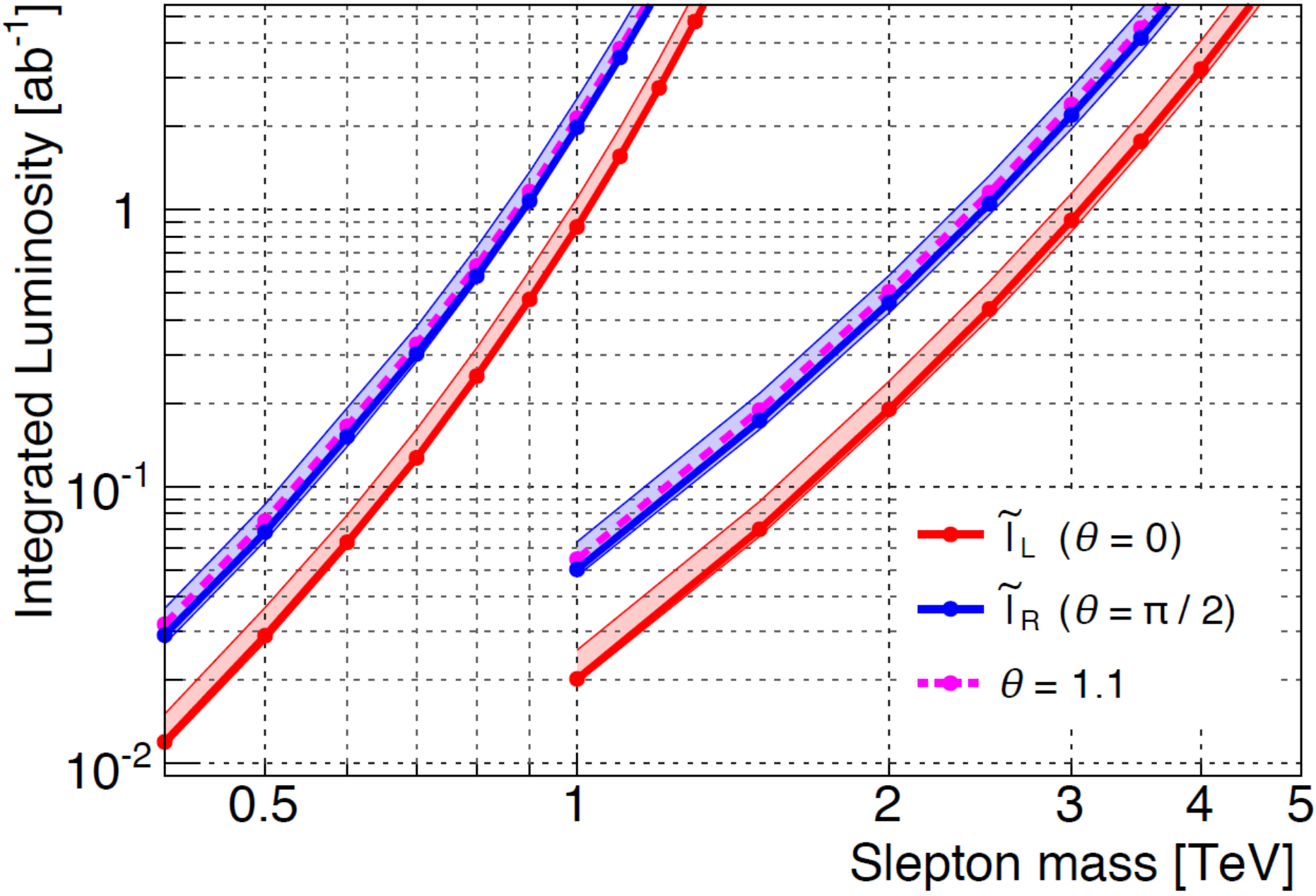
14 TeV LHC prospects are also studied in [1106.0764] & [1203.1581] by J. Heisig and J. Kersten.



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
$\hat{m}$ [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 β>0.4? (slepton dE/dx)

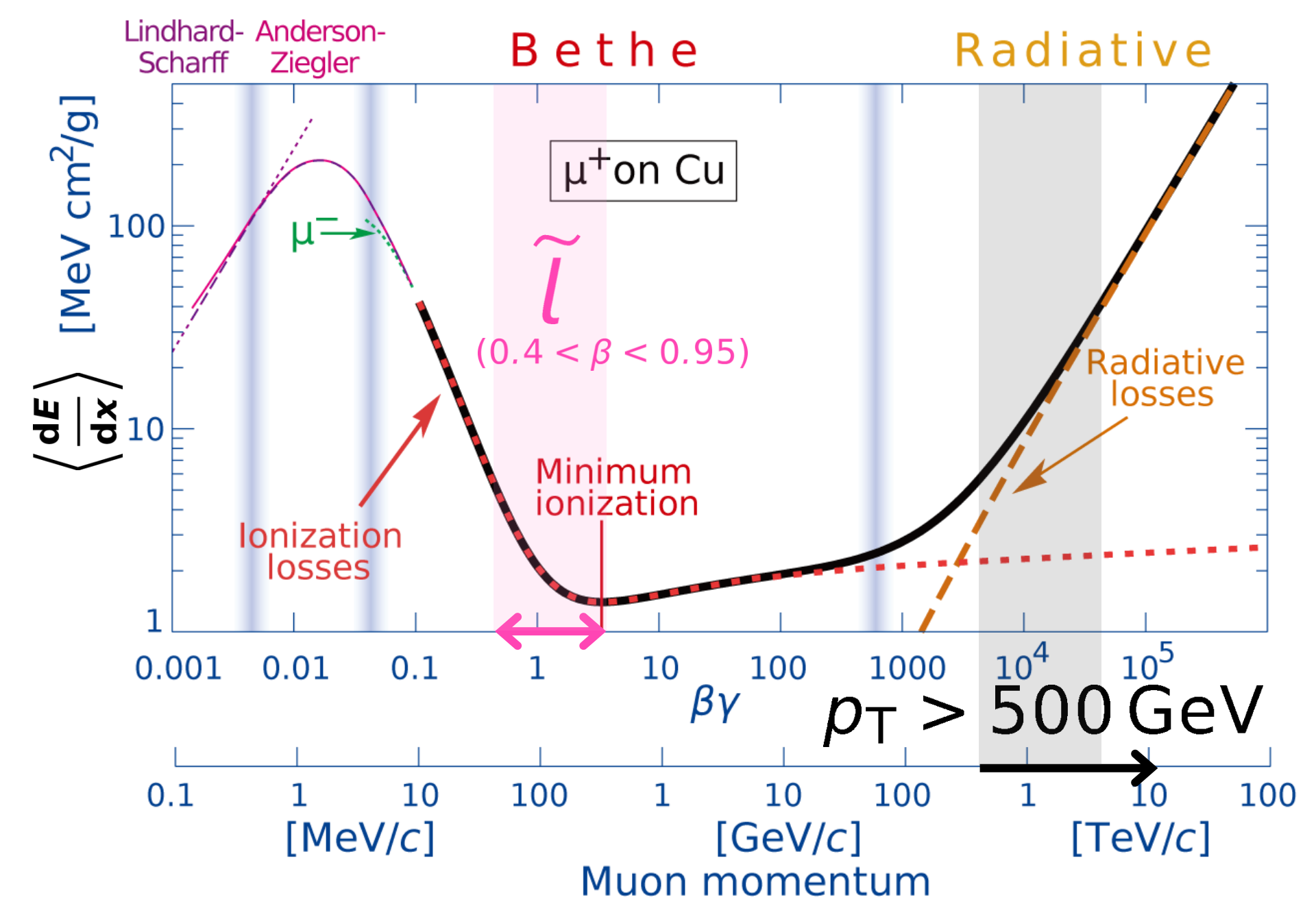
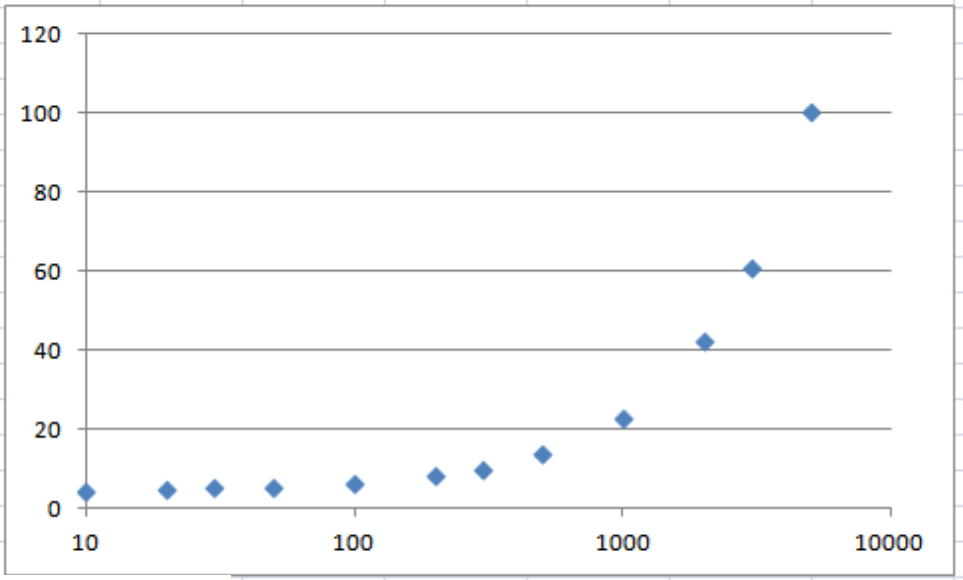


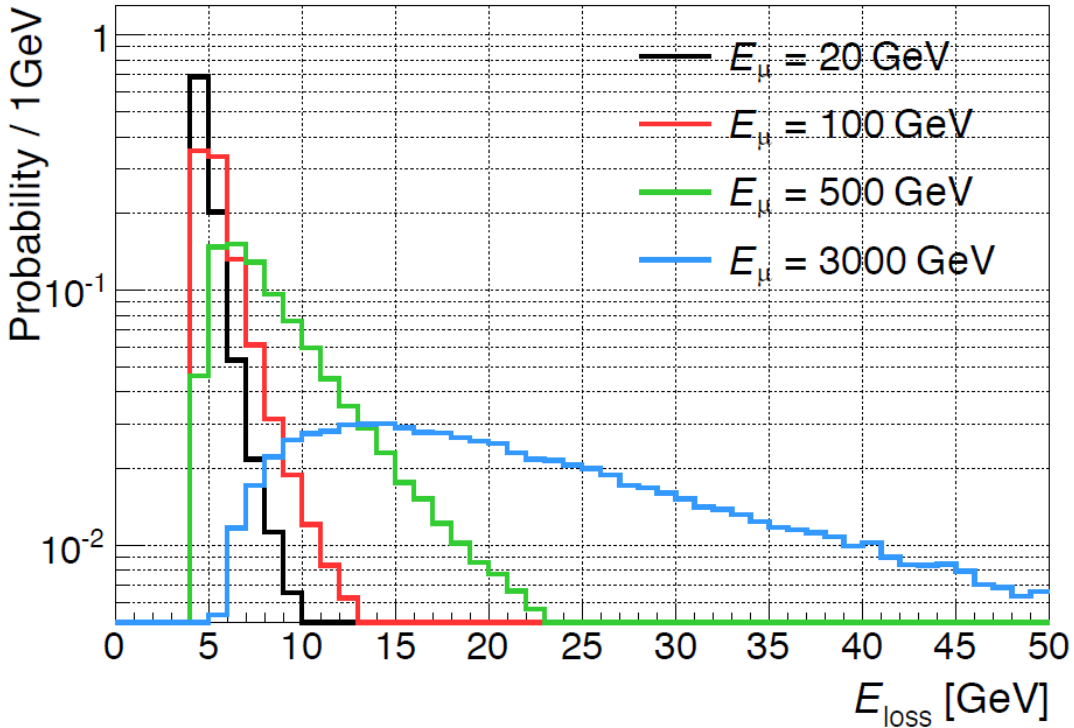
Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

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

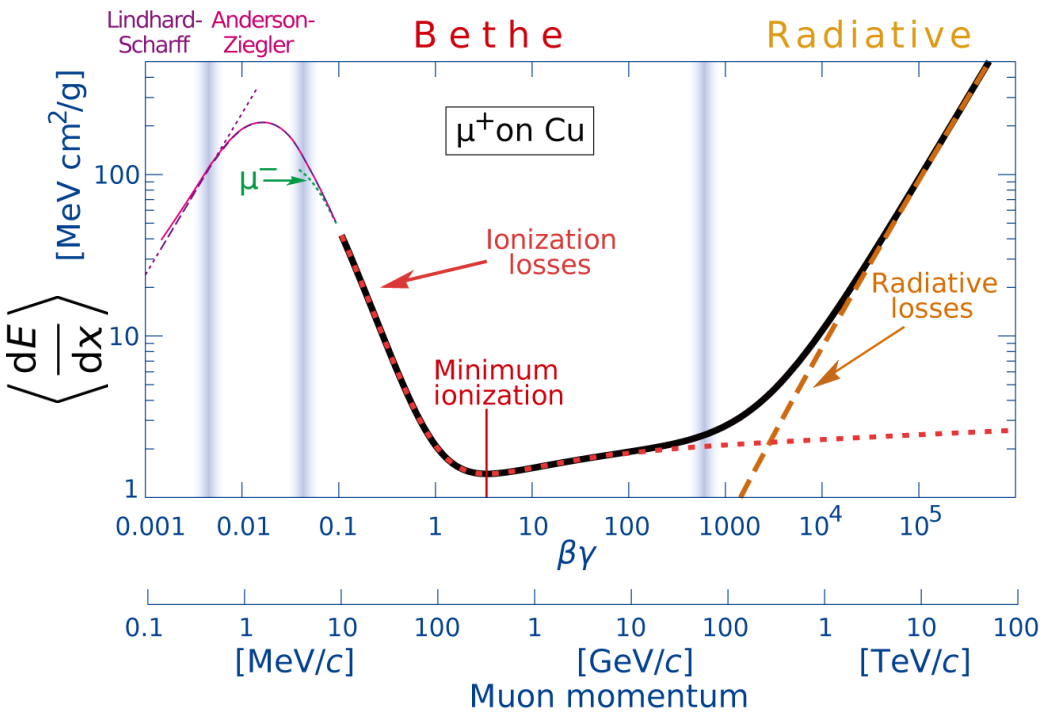
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

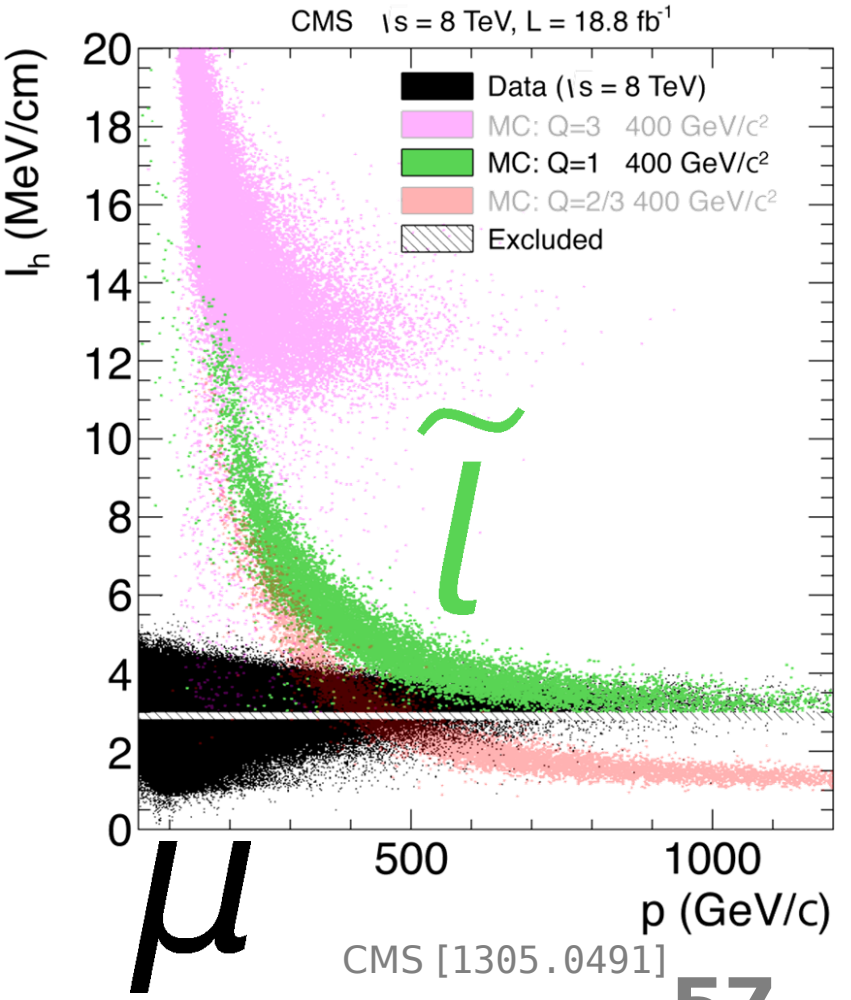
$$I_h = \rho \cdot \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{estimated}}$$

- TOF : time-of-flight

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

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





CMS [1305.0491]