הטכניון מכון טכנולוגי לישראל
TECHNION Israel Institute of Technology

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

Sho IWAMOTO（岩本　祥）

18 Jan. 2017
1st FCC Physics Workshop @ CERN

Based on

ATLAS
Jonathan. L. Feng, S.I., Yael Shadmi, Shlomit Tarem [1505.02996]
UC Irvine Technion

(collected in FCC report [1606.00947])

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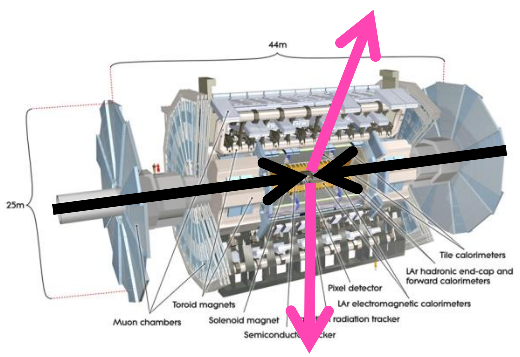
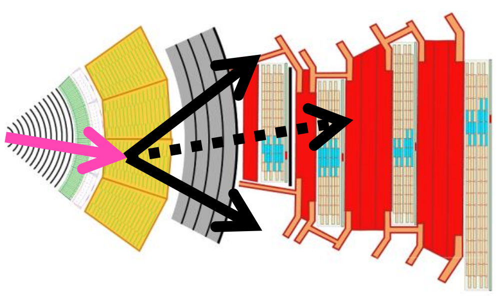
LLCP at FCC-hh ($\sqrt{s}$ = 100 TeV)

Long-lived charged particle

- **“stable”**
- in-flight decay





→ talk by José Francisco Zurita (Friday)

Why should we search for LLCP?

experimental **…Why not?**

phenomenology

long lifetime → an actor in early Universe	FCC-hh will cover most of the standard thermal-WIMP scenario

non-standard DM scenarios with LLCP

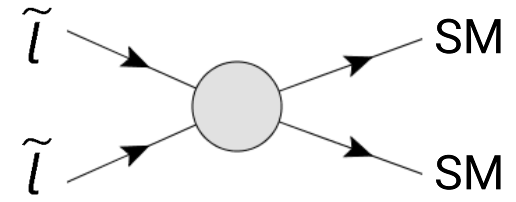
- super-WIMP:
  → next slides
- co-annihilation:
  $(\tilde{B}\text{-}\tilde{\tau}) \lesssim 700\,\mathrm{GeV}$
  $(\widetilde{W}\text{-}\tilde{g}) \lesssim 6\text{–}7\,\mathrm{TeV}$
  $(\tilde{B}\text{-}\tilde{g})$ or $(\tilde{B}\text{-}\tilde{t}) \lesssim 8\,\mathrm{TeV}$

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

theoretical **… SUSY?**

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

Feng, Rajaraman, Takayama [ph/0306024]



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

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

frozen-out

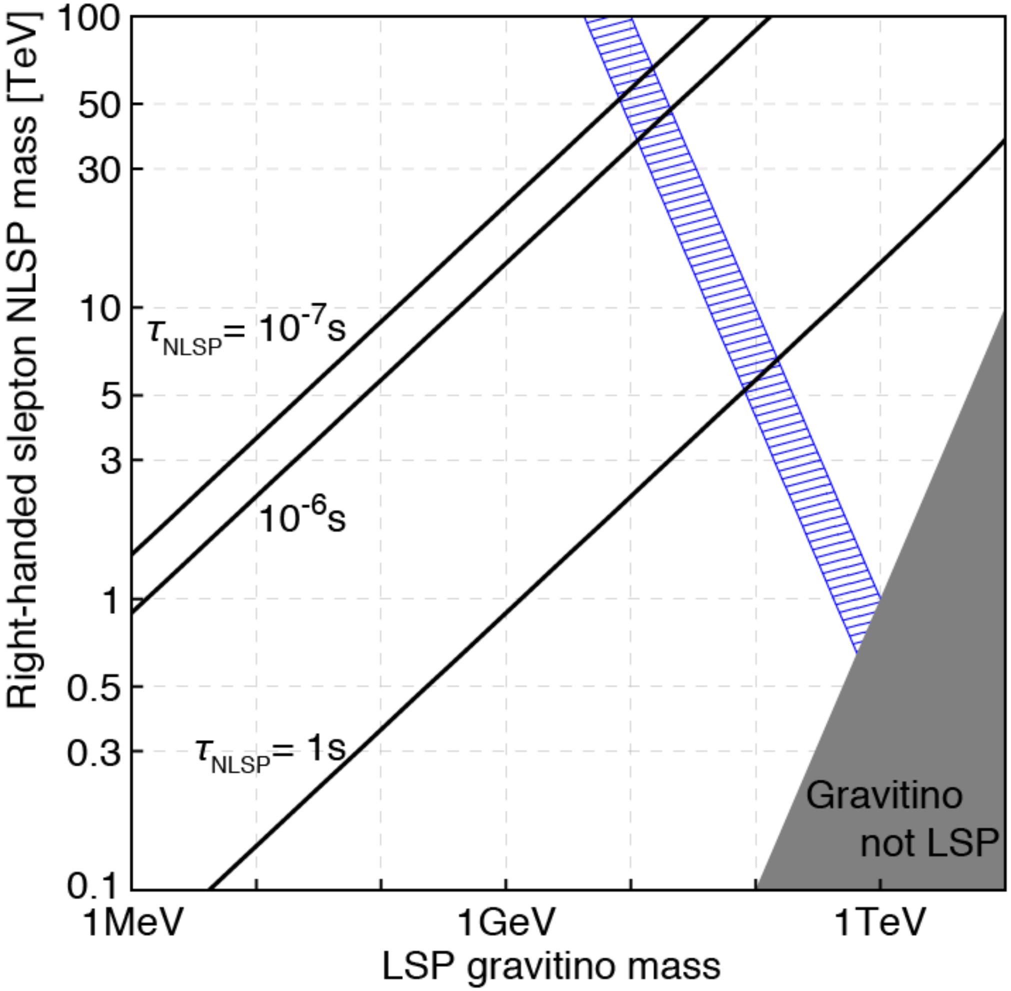
→ thermal relic with $(\Omega h^2)_{\tilde{l}} \gg 0.12$

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?

experimental **...Why not?**

phenomenology

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:

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

- co-annihilation:

  $(\tilde{B}$ - $\tilde{\tau})$ $\lesssim$ 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.

theoretical **... SUSY?**

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

Why should we search for LLCP?

experimental   Why not?

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:

($\tilde{B}$ - $\tilde{\tau}$) $\lesssim$ 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 ($\tilde{l}$)
- 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

...nnihilation:

... t > O(1) TeV

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

($\tilde{W}$ - $\tilde{g}$) $\lesssim$ 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 ($\tilde{l}$)
- split-SUSY: extremely heavy squarks → long-lived gluino ($\tilde{g}$)

1. **Motivations: Why LLCP?**

2. **Searches at (HL-)LHC**

3. **Searches at FCC-hh**
   - Muon radiative energy loss
   - Muon momentum resolution

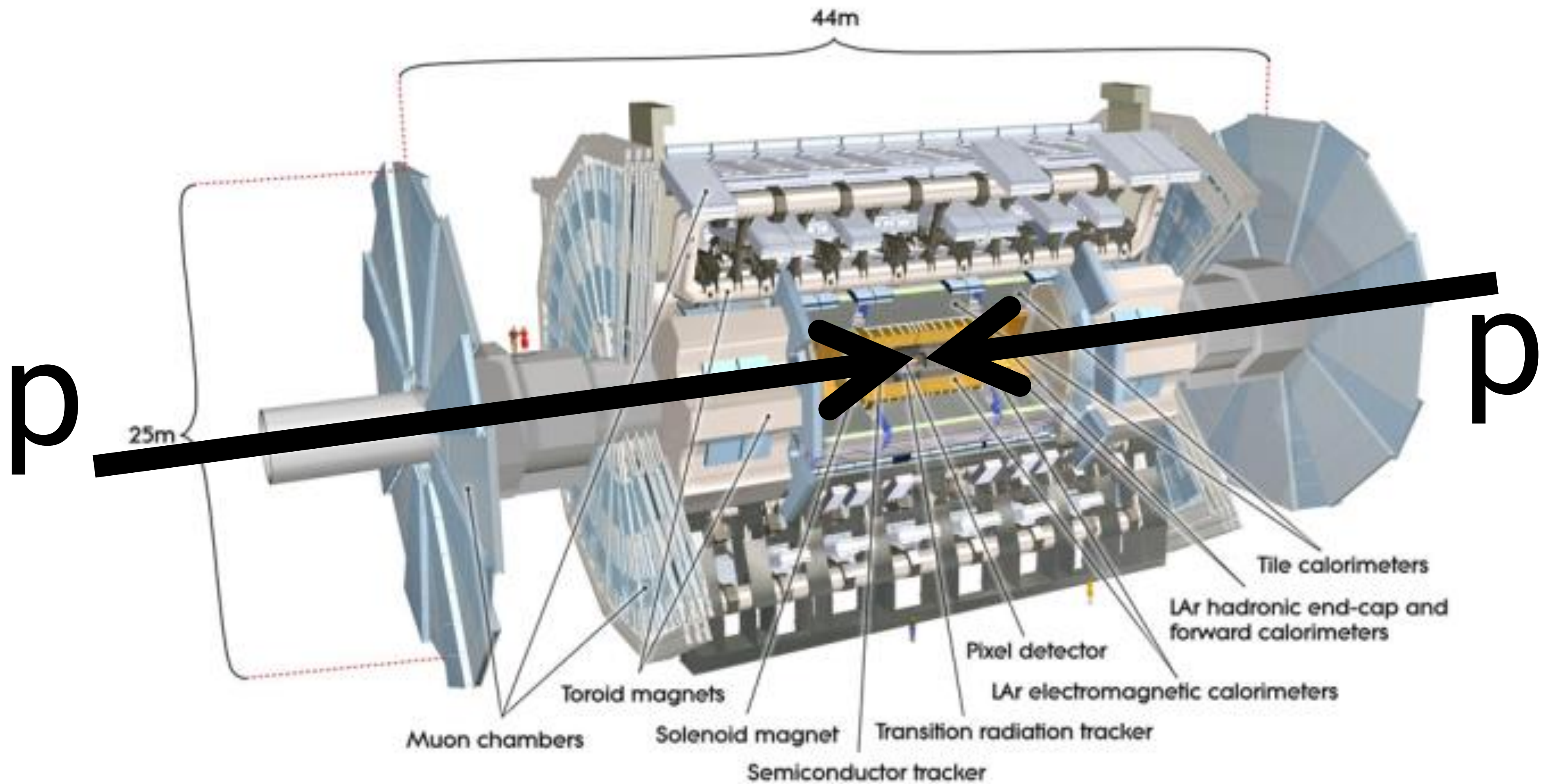
4. **Summary**

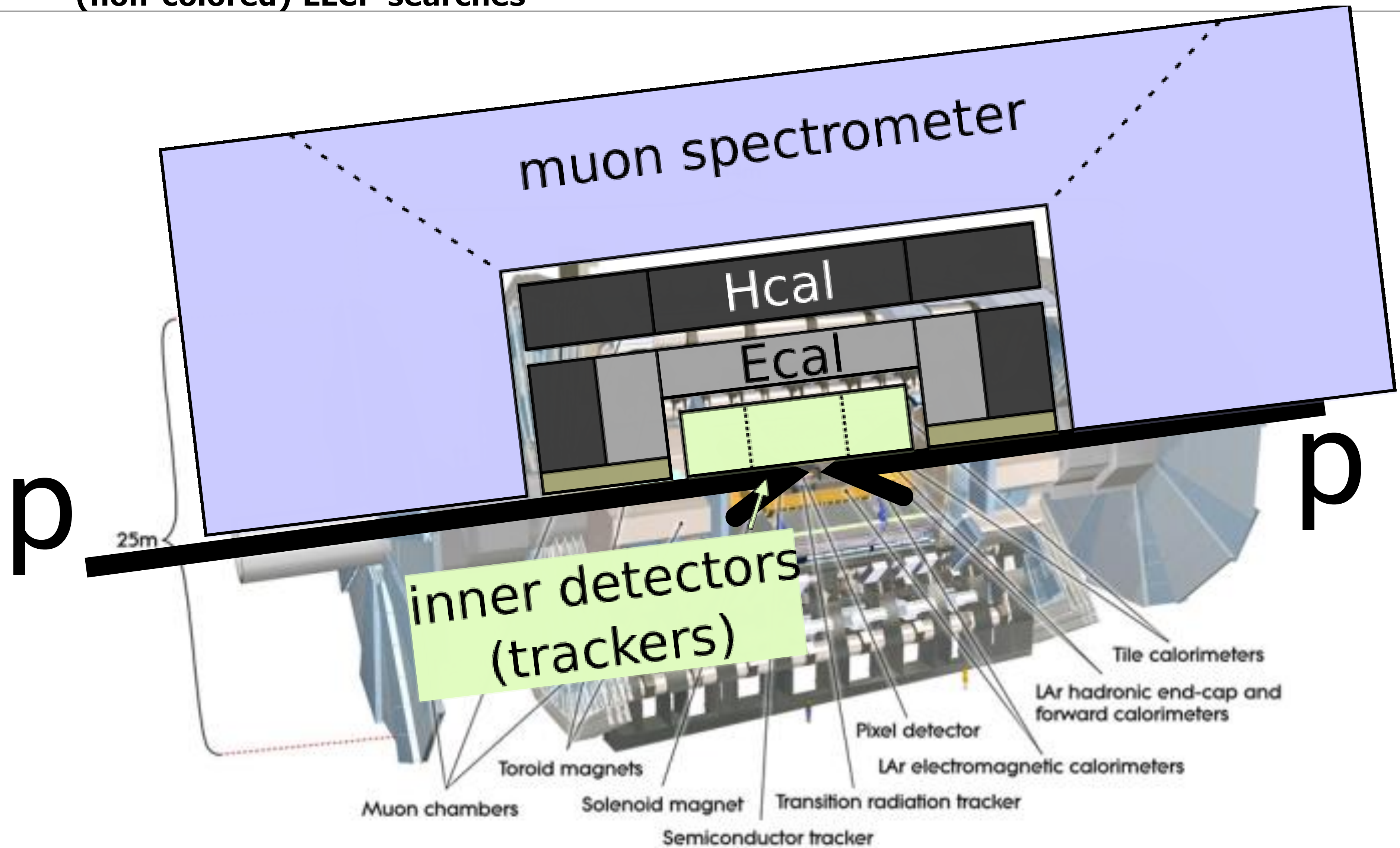
1. Motivations: Why LLCP?

2. Searches at (HL-)LHC

3. Searches at FCC-hh
   - Muon radiative energy loss
   - Muon momentum resolution

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
inner detectors (trackers)
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
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Toroid magnets
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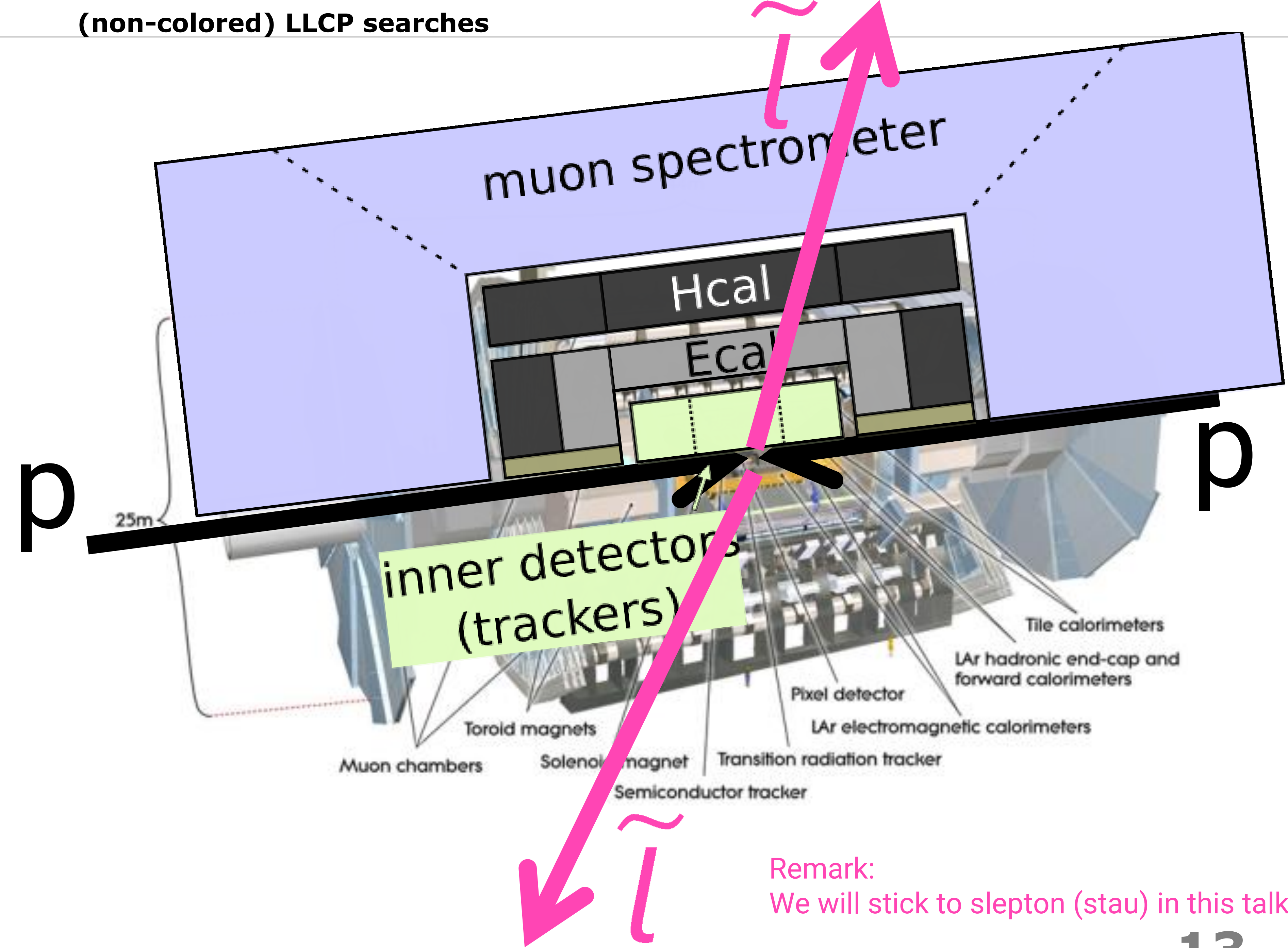
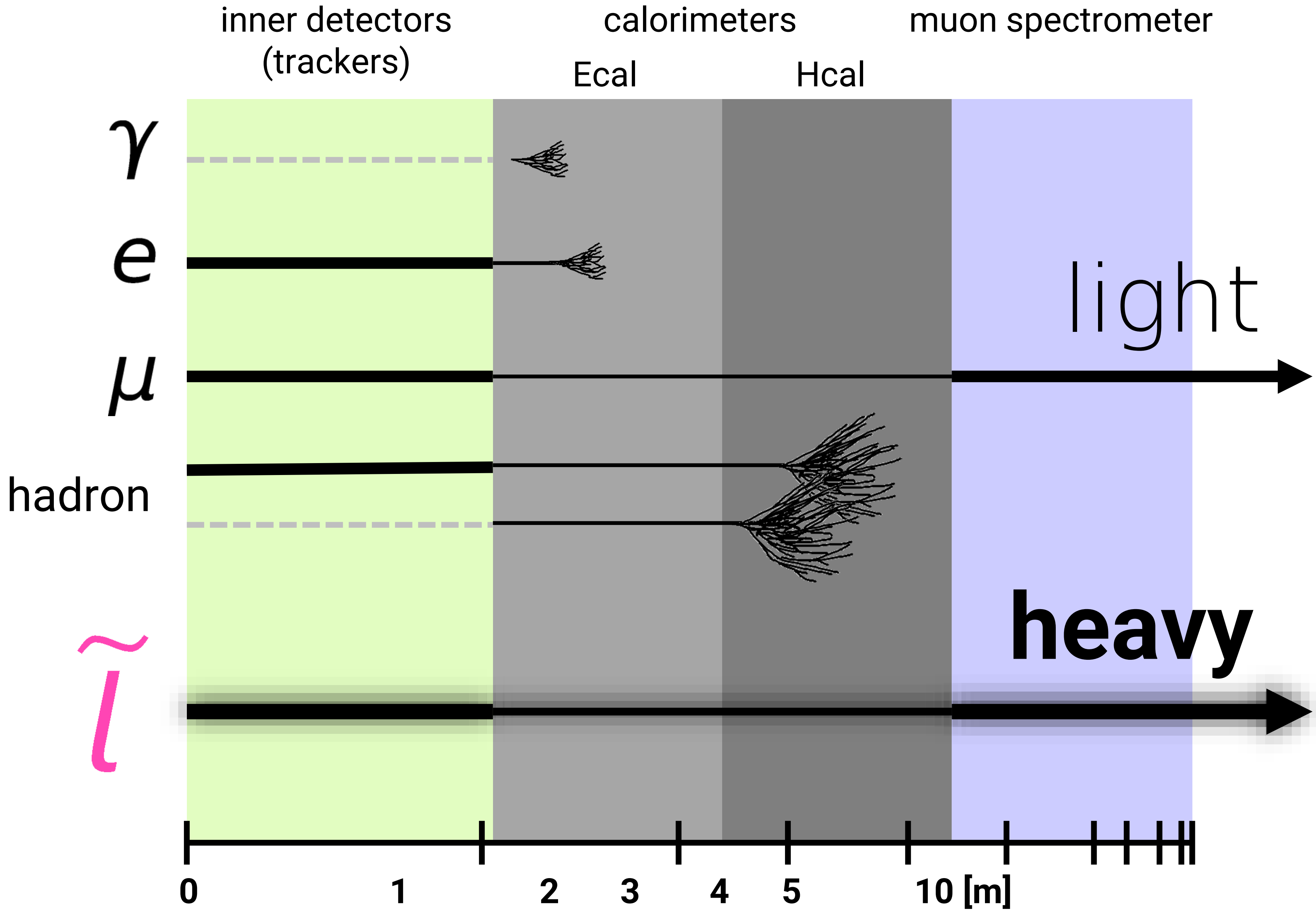
Transition radiation tracker
Semiconductor tracker



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


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

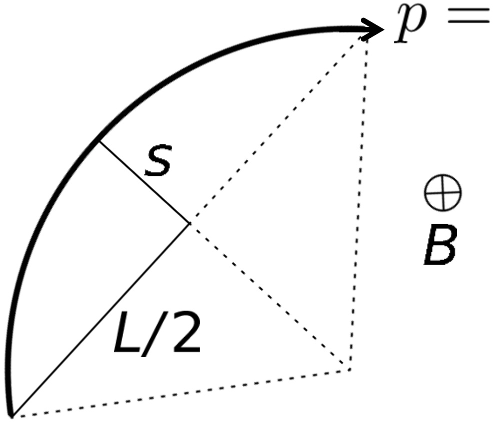
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

momentum & velocity

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

  - momentum

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



  - velocity
    - TOF [time-of-flight]

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

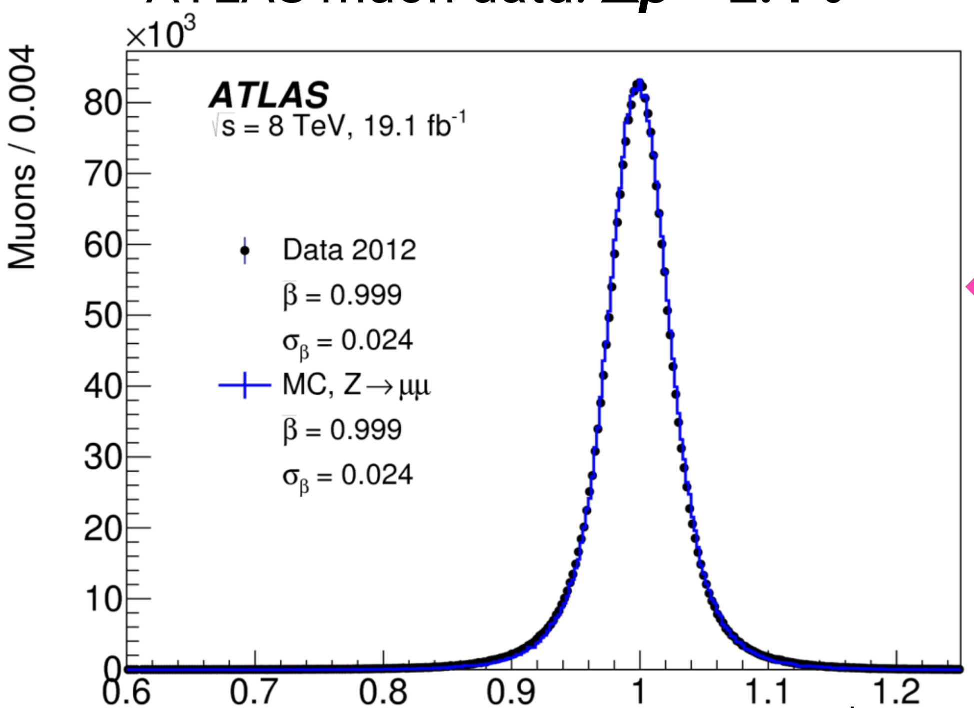
    - dE/dx [ionization energy loss]

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

momentum & velocity

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

ATLAS muon data: **Δβ = 2.4%**



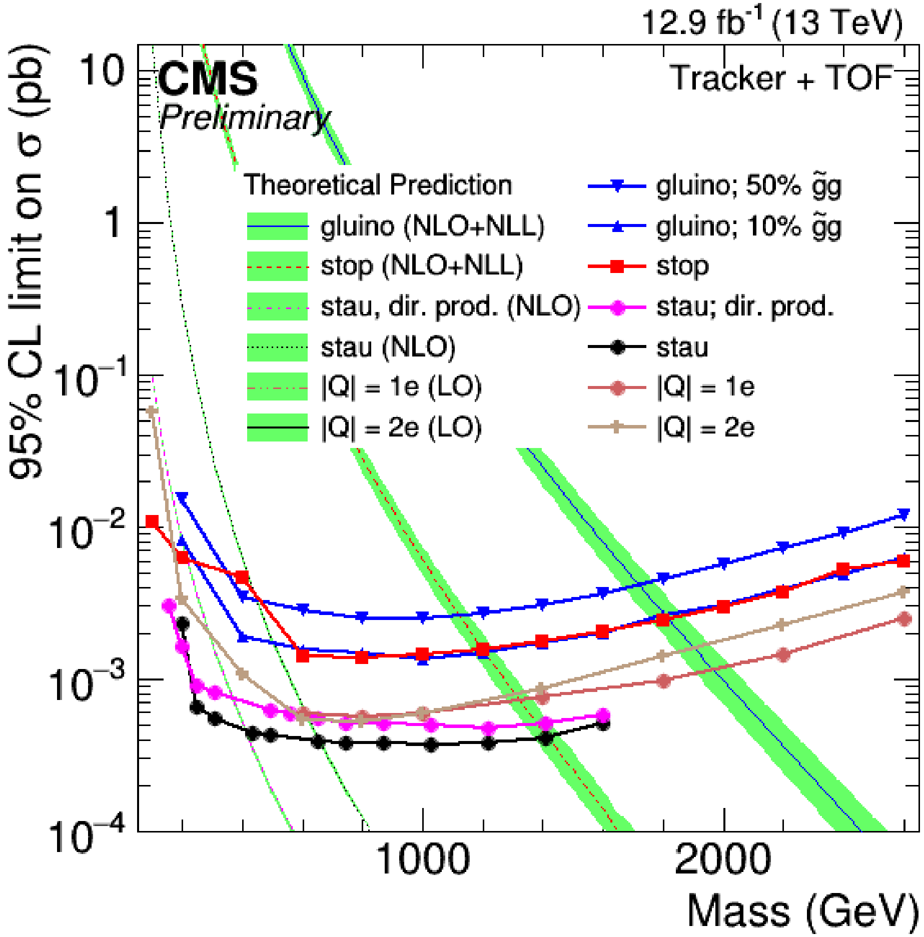
$\beta^{\text{obs}} =: \hat{\beta}$

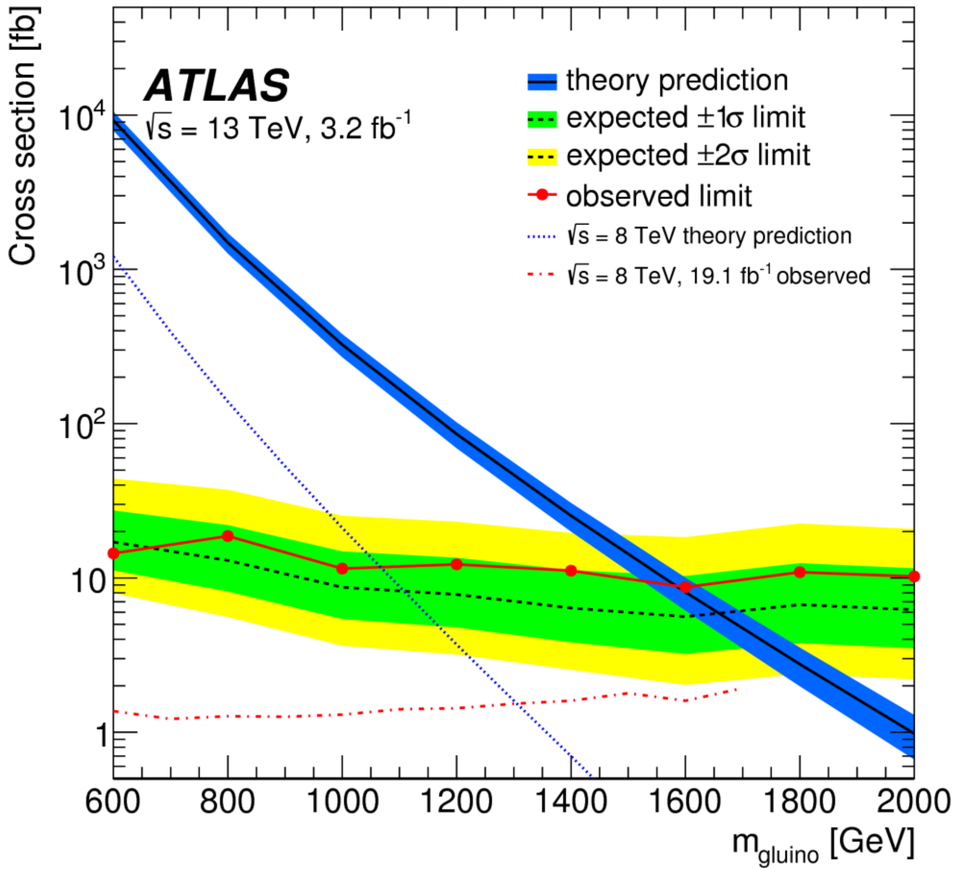
➢ velocity

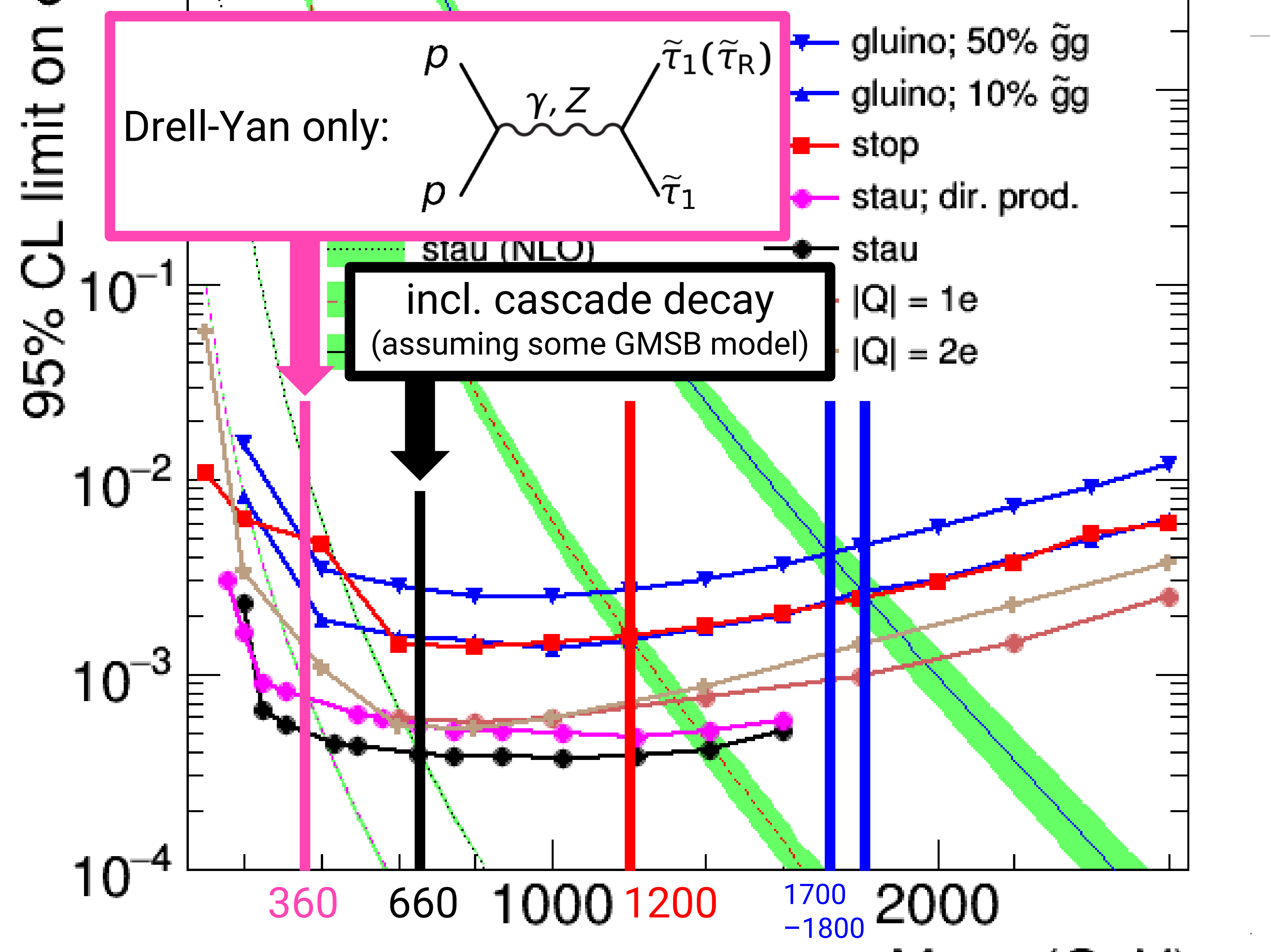
- TOF [time-of-flight]

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

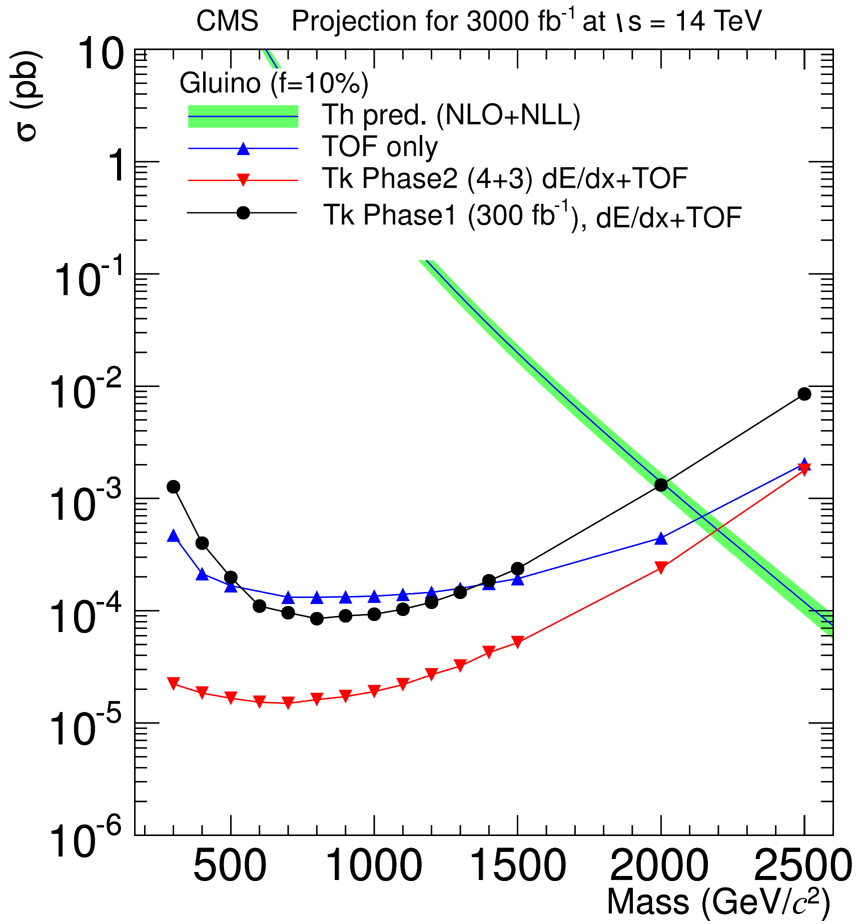
- d*E*/d*x* [ionization energy loss]

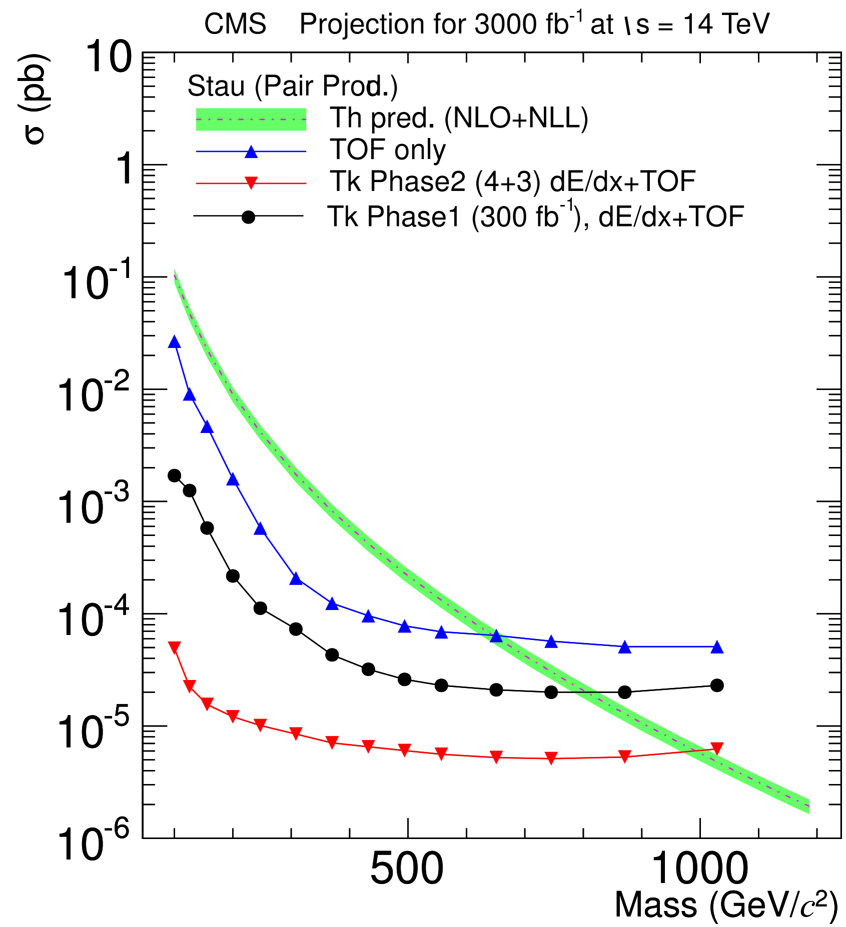

12.9 fb-1 (13 TeV)
CMS
Preliminary
Tracker + TOF
Theoretical Prediction
gluino (NLO+NLL)
stop (NLO+NLL)
stau, dir. prod. (NLO)
stau (NLO)
|Q| = 1e (LO)
|Q| = 2e (LO)
gluino; 50% g̃g
gluino; 10% g̃g
stop
stau; dir. prod.
stau
|Q| = 1e
|Q| = 2e
95% CL limit on σ (pb)
Mass (GeV)


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





	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

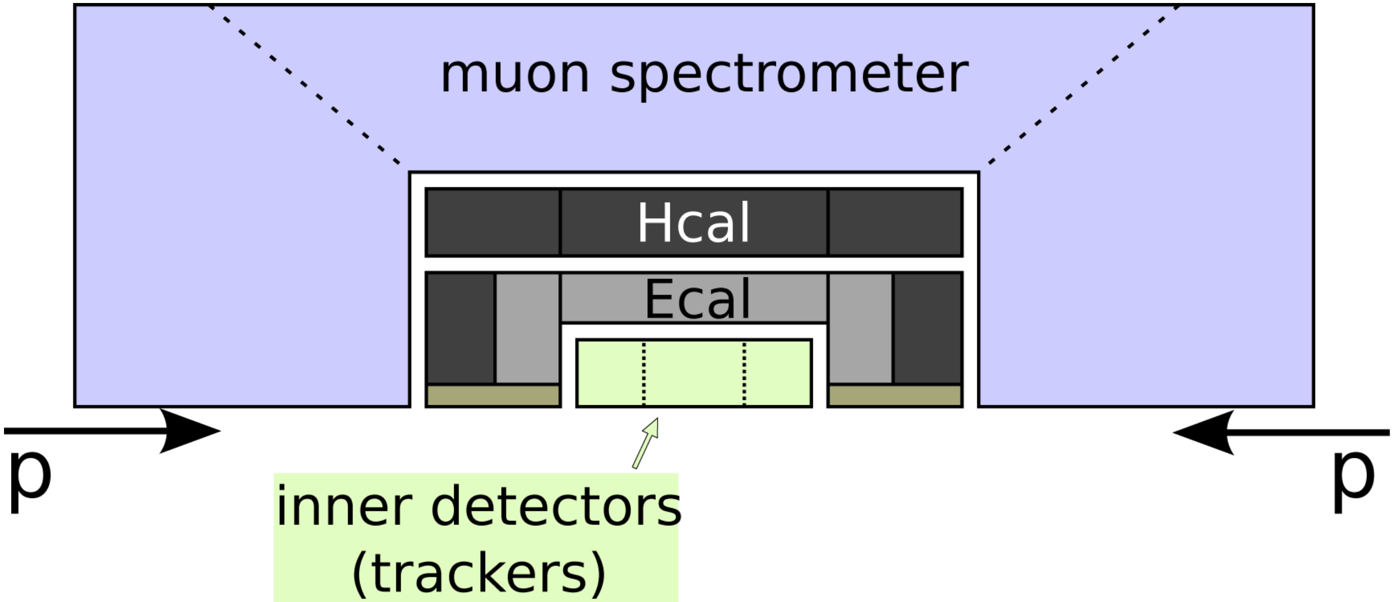
our selection flow

$\tilde{l}$ = 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]

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



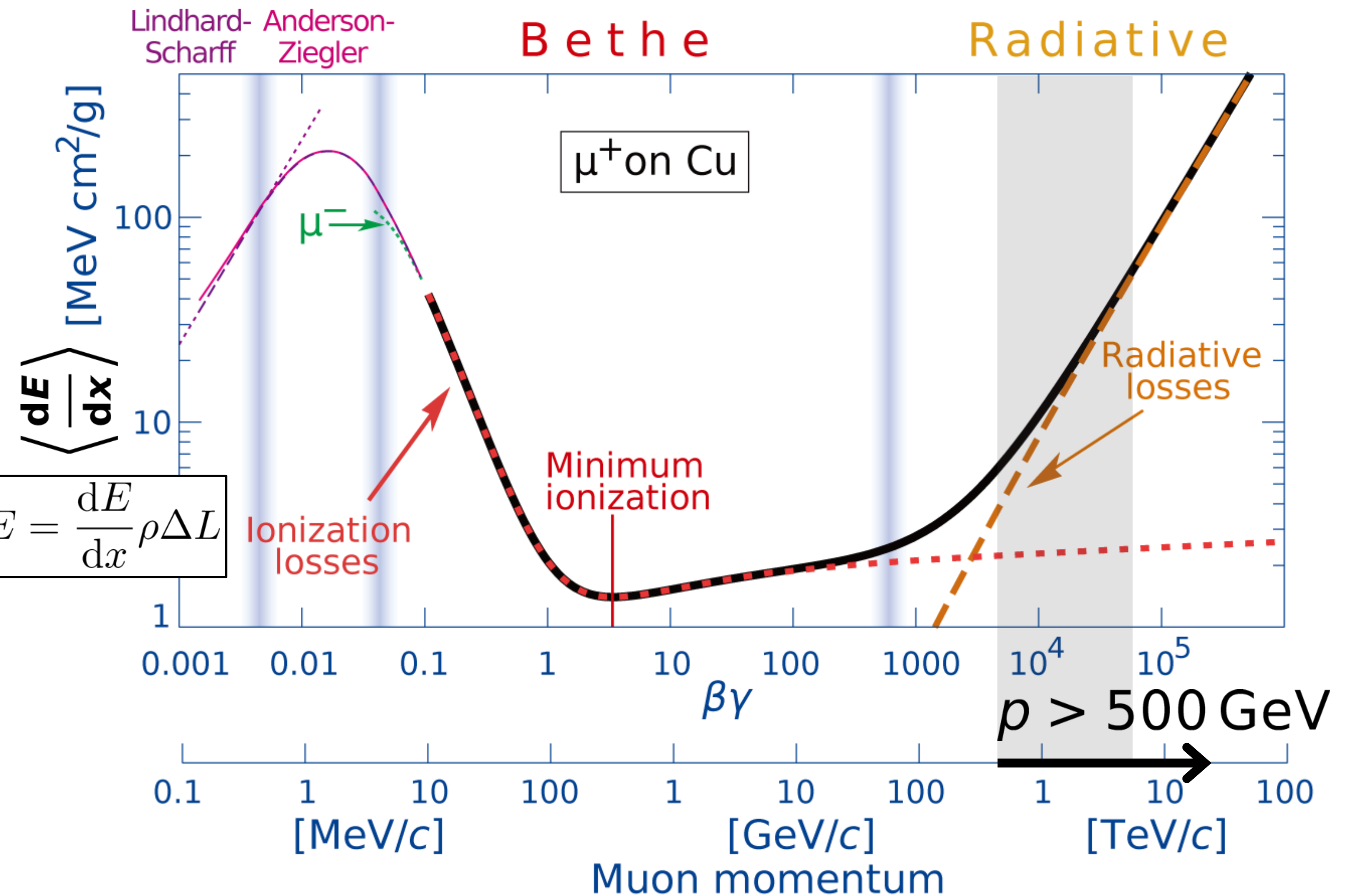
1. Motivations: Why LLCP?

2. Searches at (HL-)LHC

3. Searches at FCC-hh

   - **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

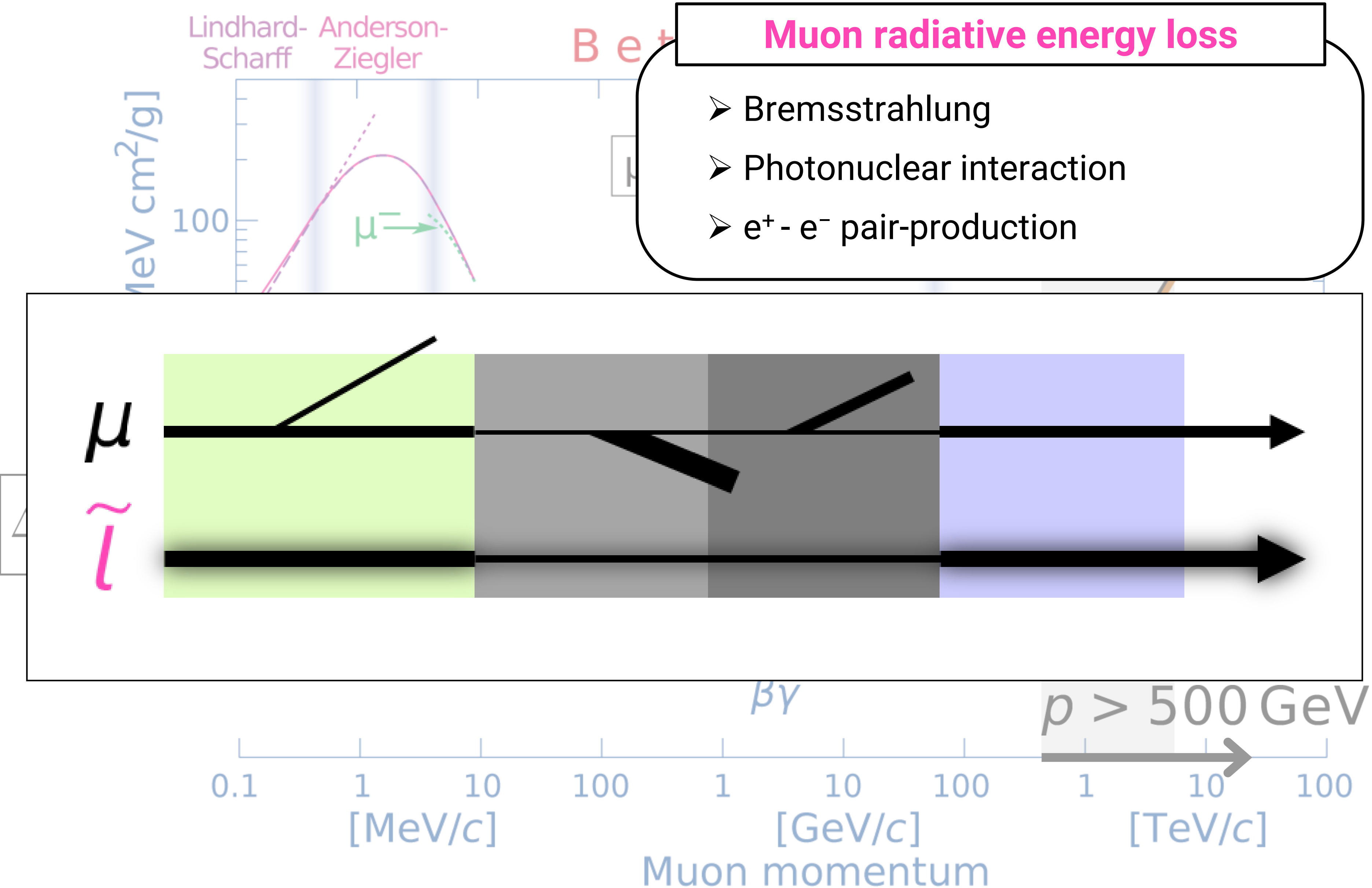
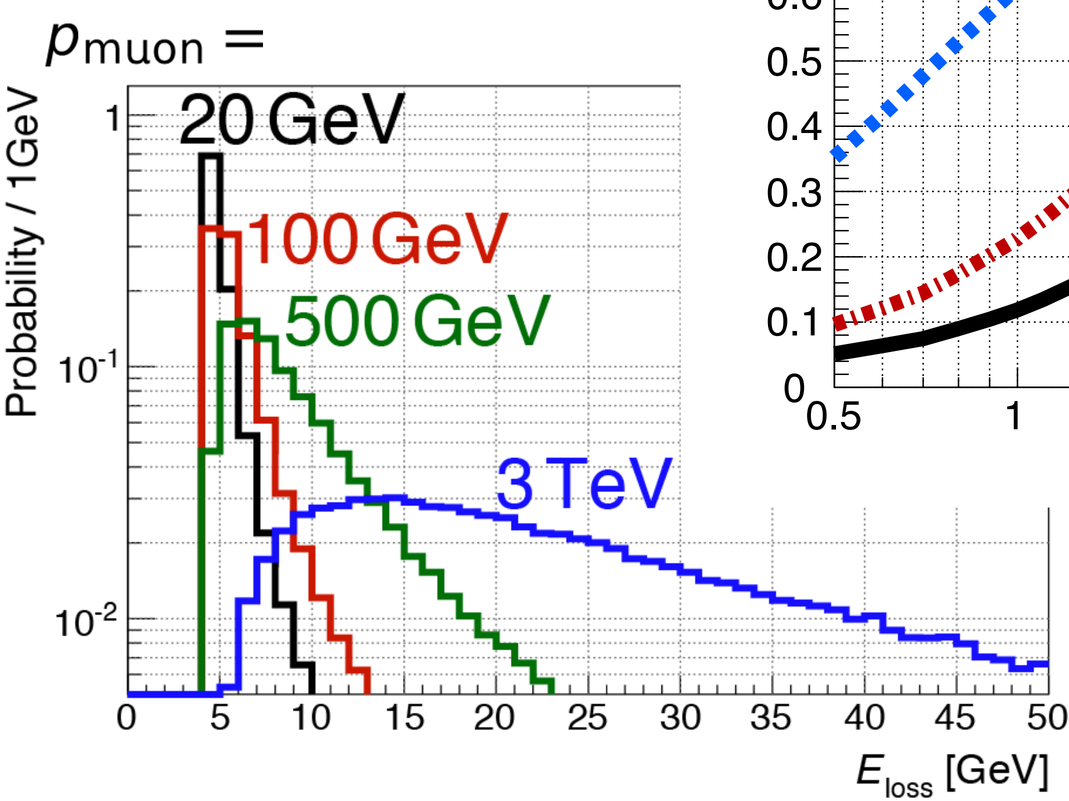
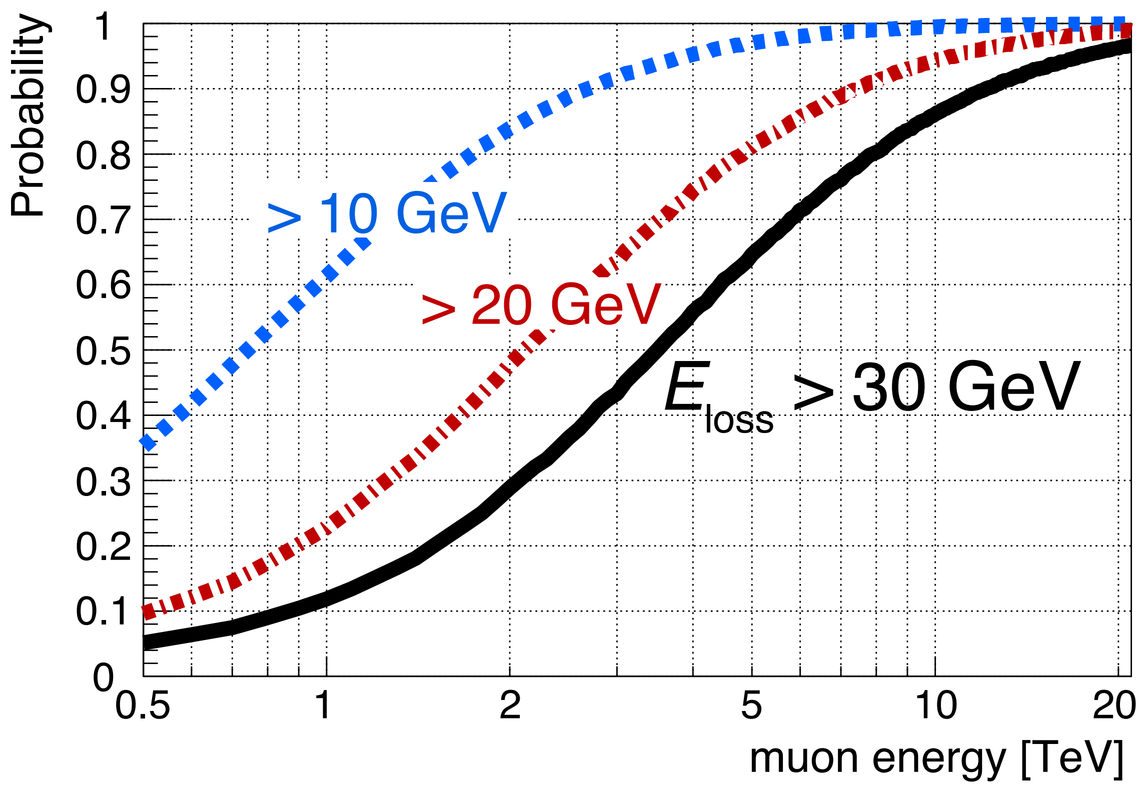


Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

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

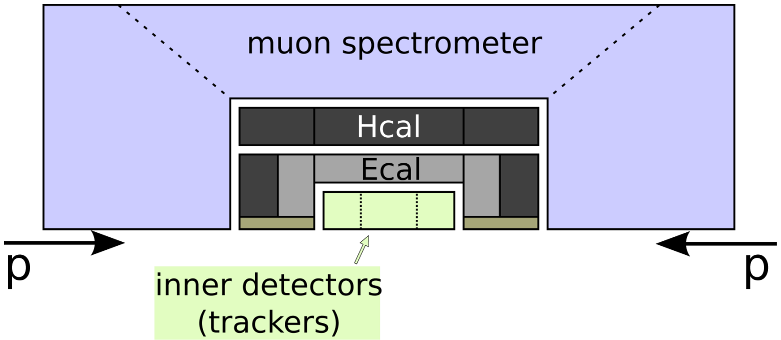
→ some of μ (P_T > 500 GeV): > 30 GeV energy deposit.





[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

  $\tilde{l}$ = reconstructed "muon" with
  - $P_T > 500\,\text{GeV}$
  - $|\eta| < 2.4$
  - $0.4 < \hat{\beta} < 0.95$ (from ToF)
  - $E_{\text{loss}} < 30\,\text{GeV}$
- 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%	—

$\times 0.82$

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

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

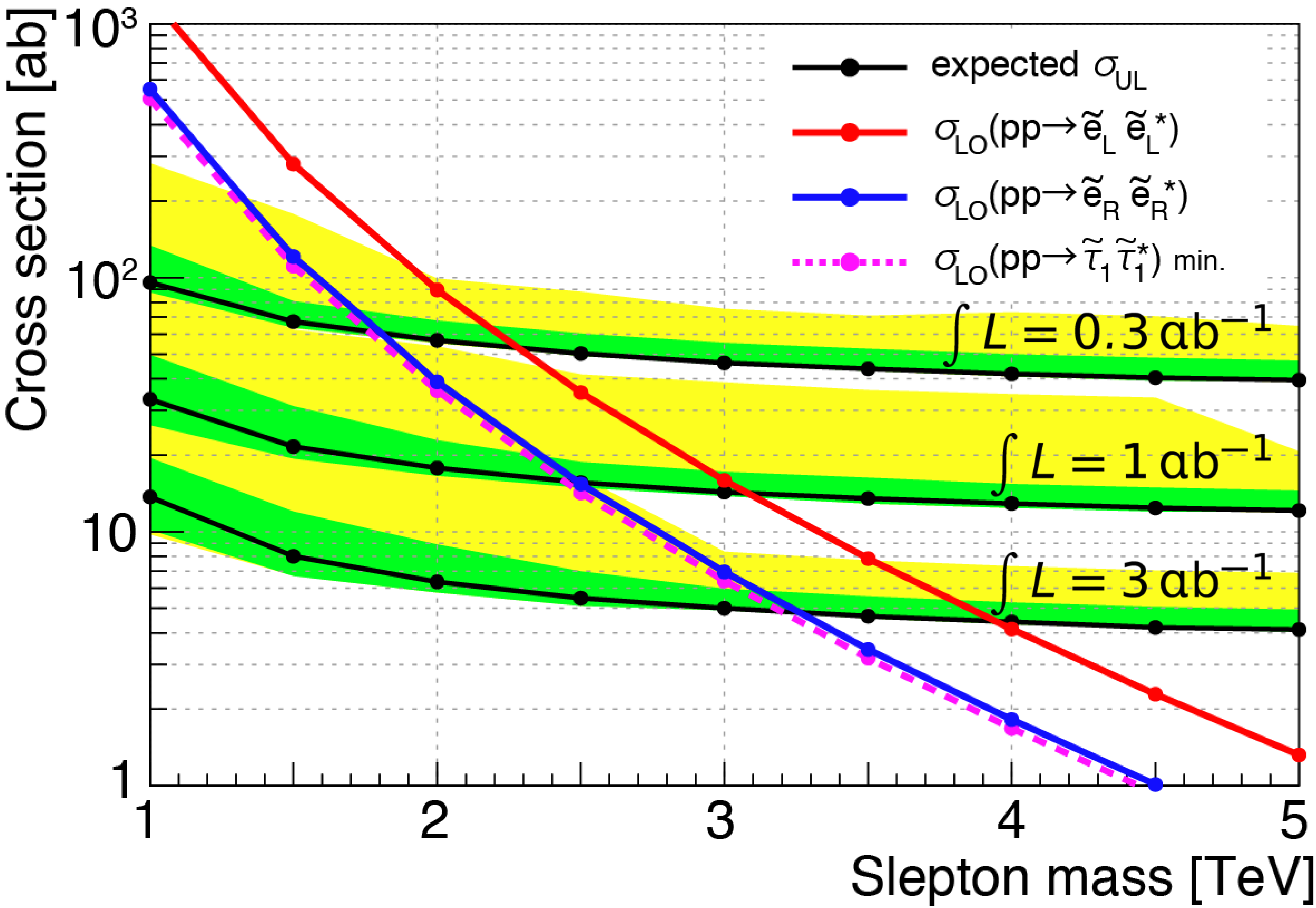
Event categorization ($\int L = 1\,\mathrm{ab}^{-1}$)

	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

Feng, SI, Shadmi, Tarem [1505.02996]



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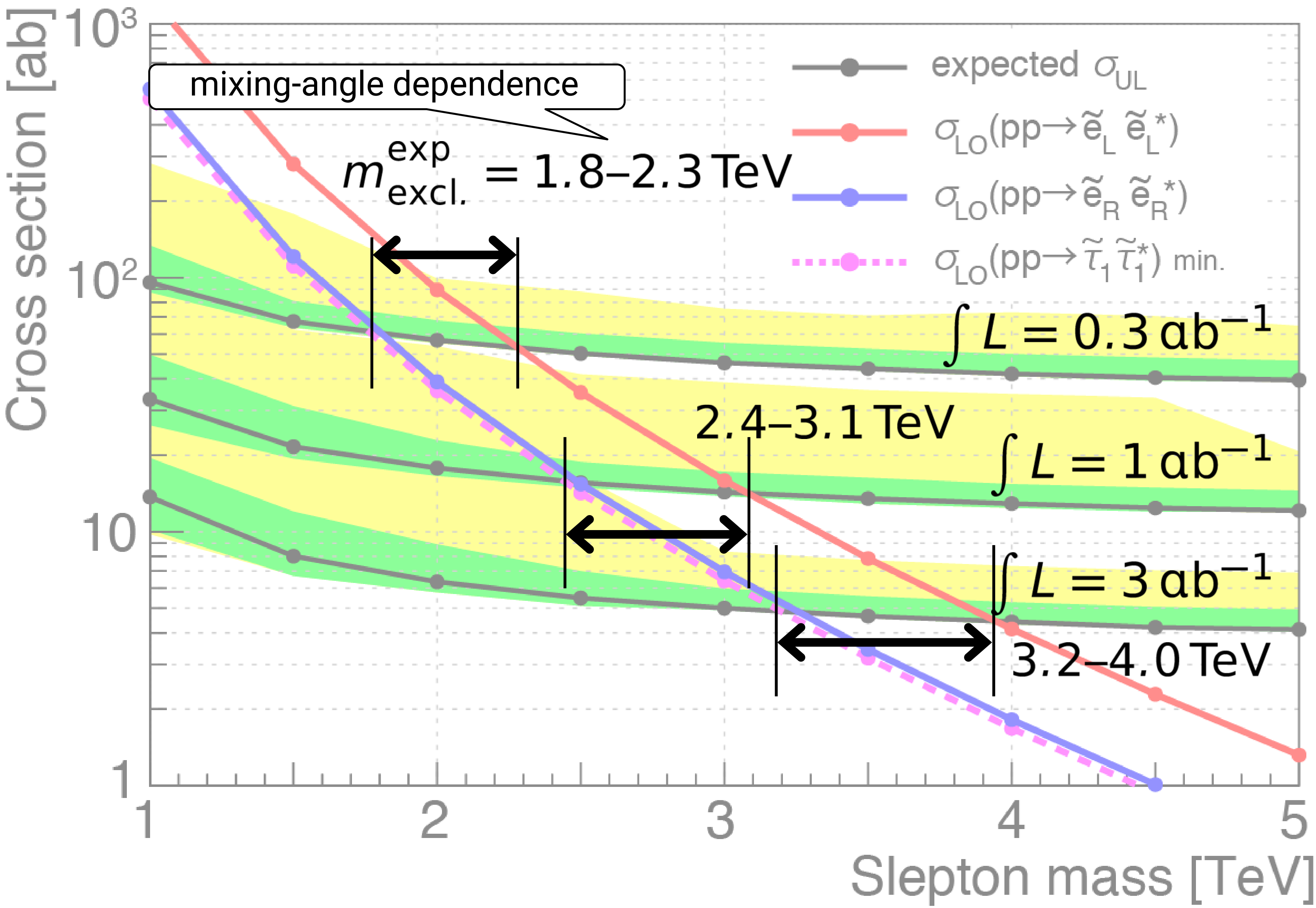

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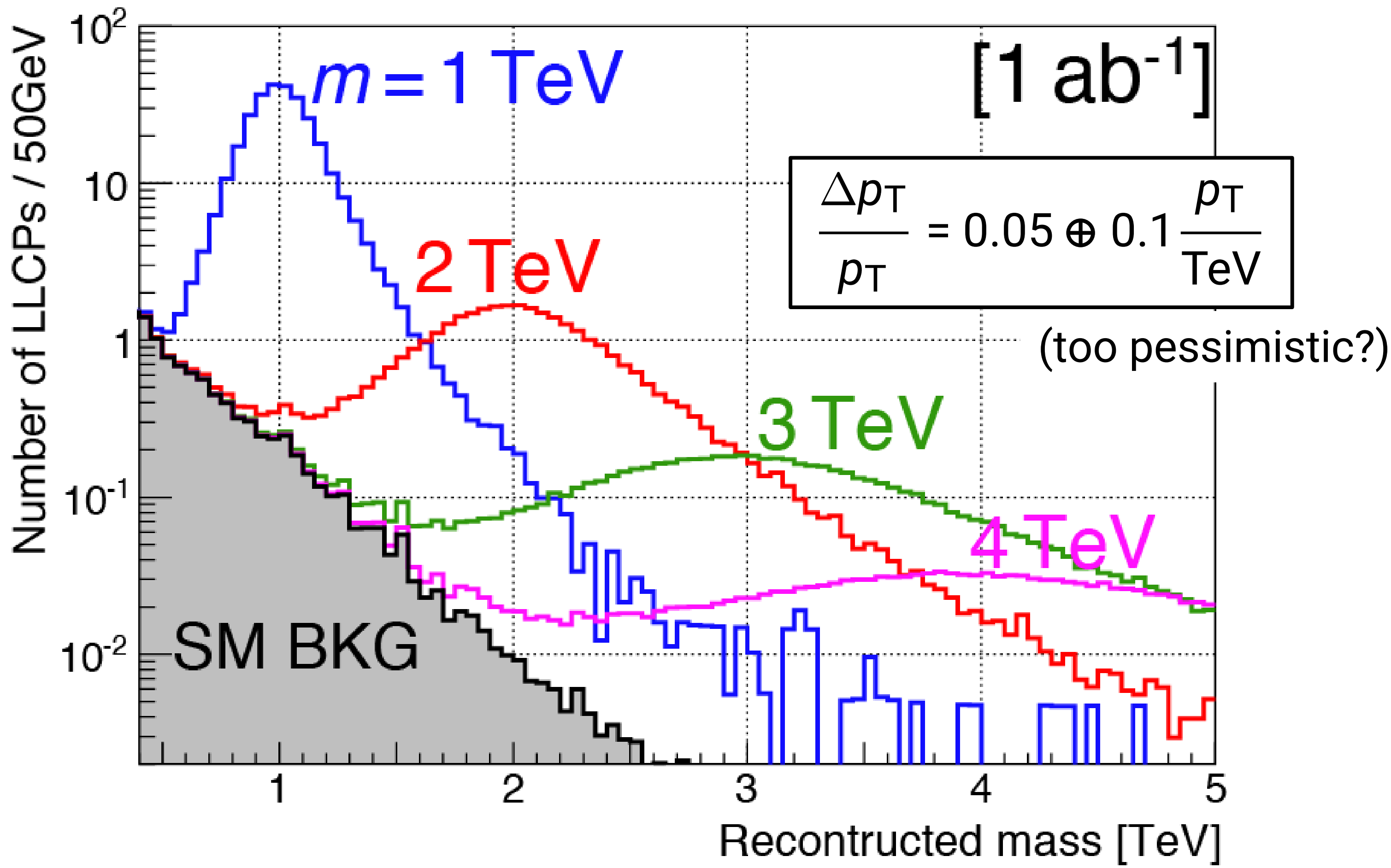
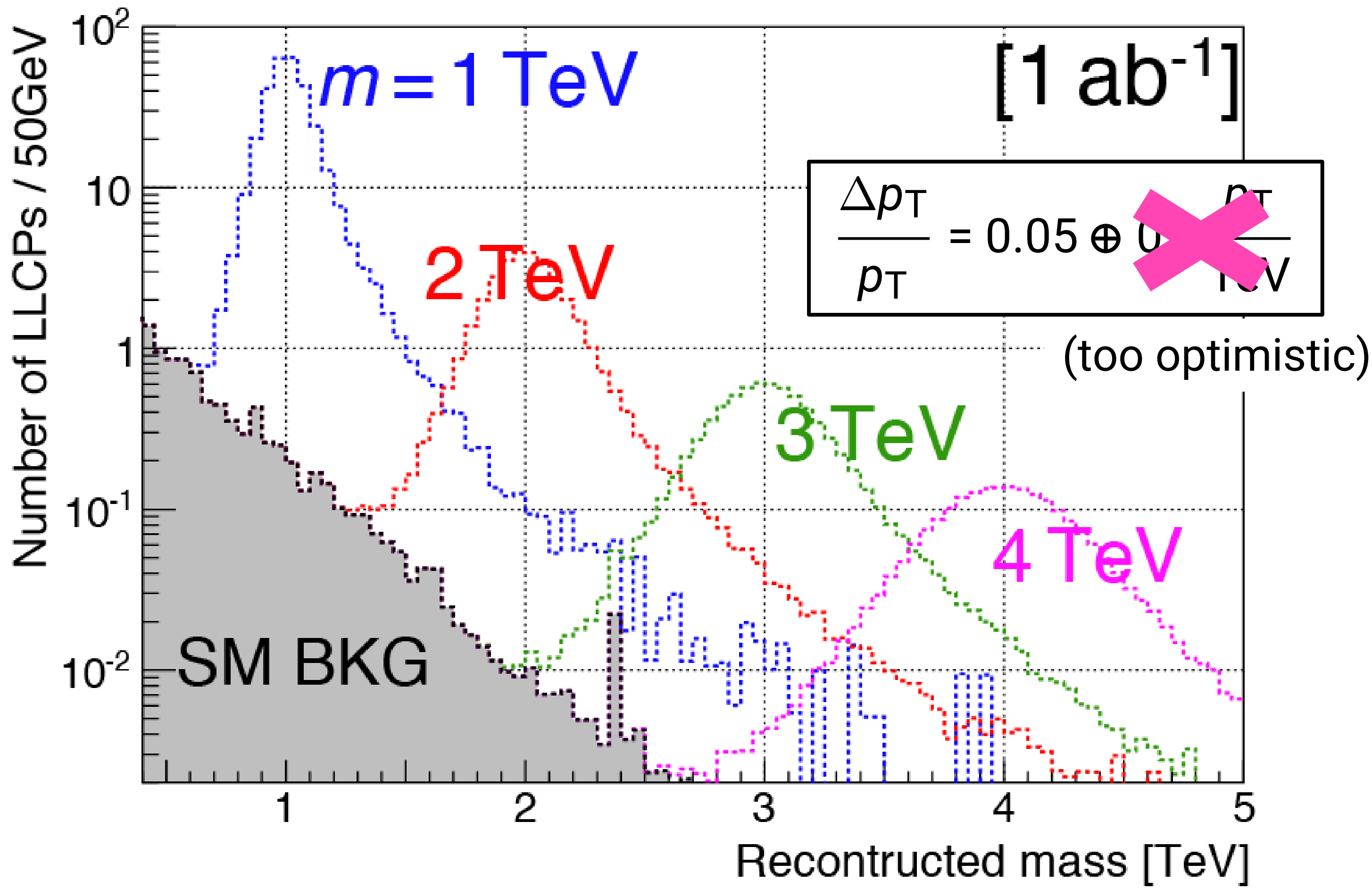


FCC-hh trk. goal: 10–20% @ 10 TeV (Michele Selvaggi's talk) $\left(= \frac{p}{\beta\gamma} = \frac{p_T \cosh\eta}{\beta\gamma} \right)$

cf. ATLAS 7 TeV commissioning:

(ID-barrel, MS-barrel, MS-extbarrel) = (38%, 14%, 6%) @ 1 TeV



$$\left(= \frac{p}{\beta\gamma} = \frac{p_T \cosh\eta}{\beta\gamma}\right)$$

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2. Searches at (HL-)LHC

3. Searches at FCC-hh

   ➢ **Muon radiative energy loss** for BKG rejection

   ➢ Our simulation

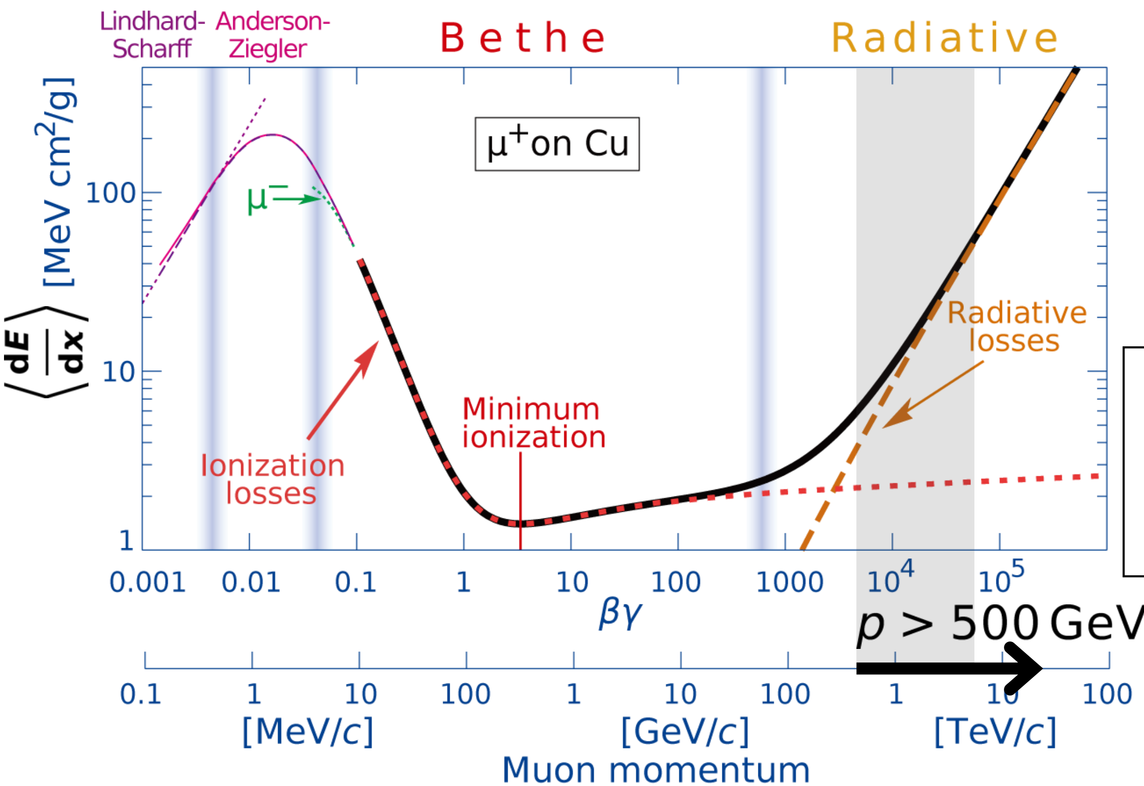
4. **Summary: FCC-hh prospects**

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

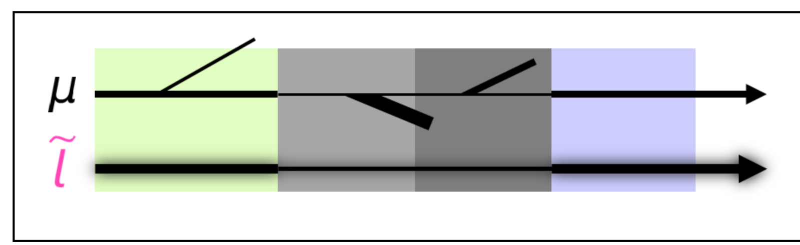
	$0.3ab^{-1}$	$1ab^{-1}$	$3ab^{-1}$
Exclusion	1.8−2.3	2.4−3.1	3.2−4.0
Discovery	1.6−2.2	2.3−3.0	3.1−4.0

in TeV

- **“Muon radiative energy loss”**



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

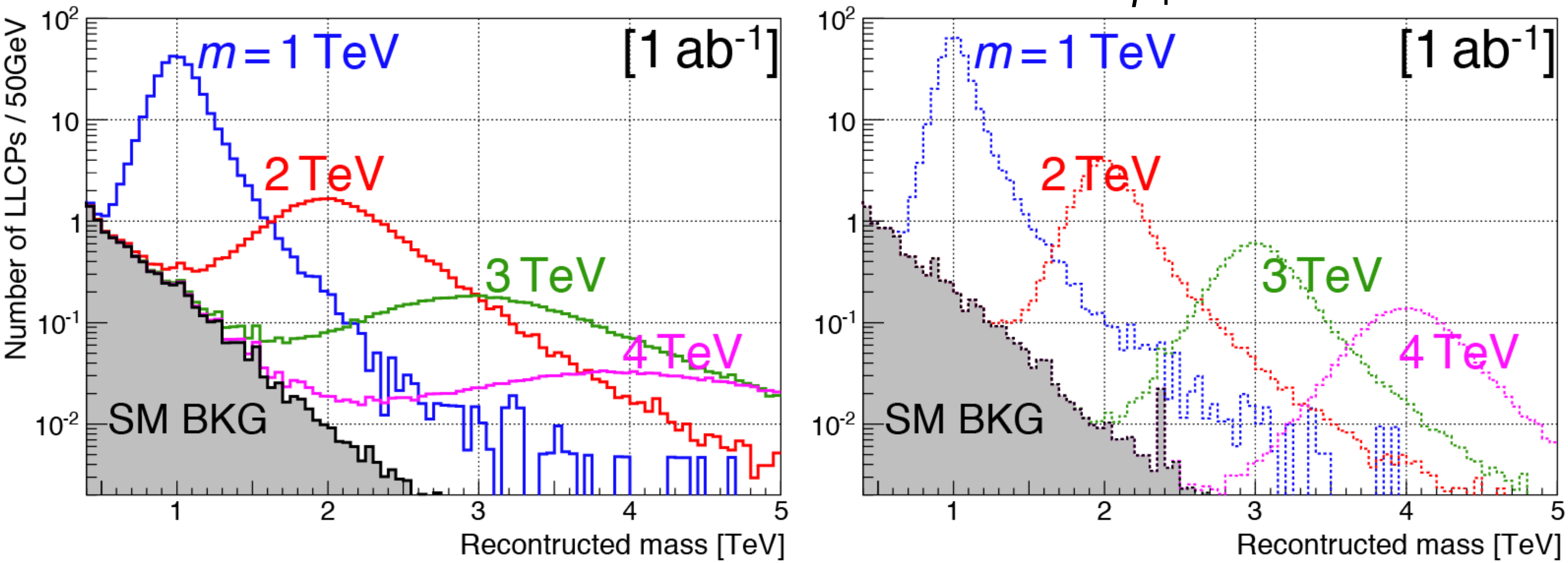


→ 34% of BKG reduction

100 TeV FCC-hh muon momentum resolution

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

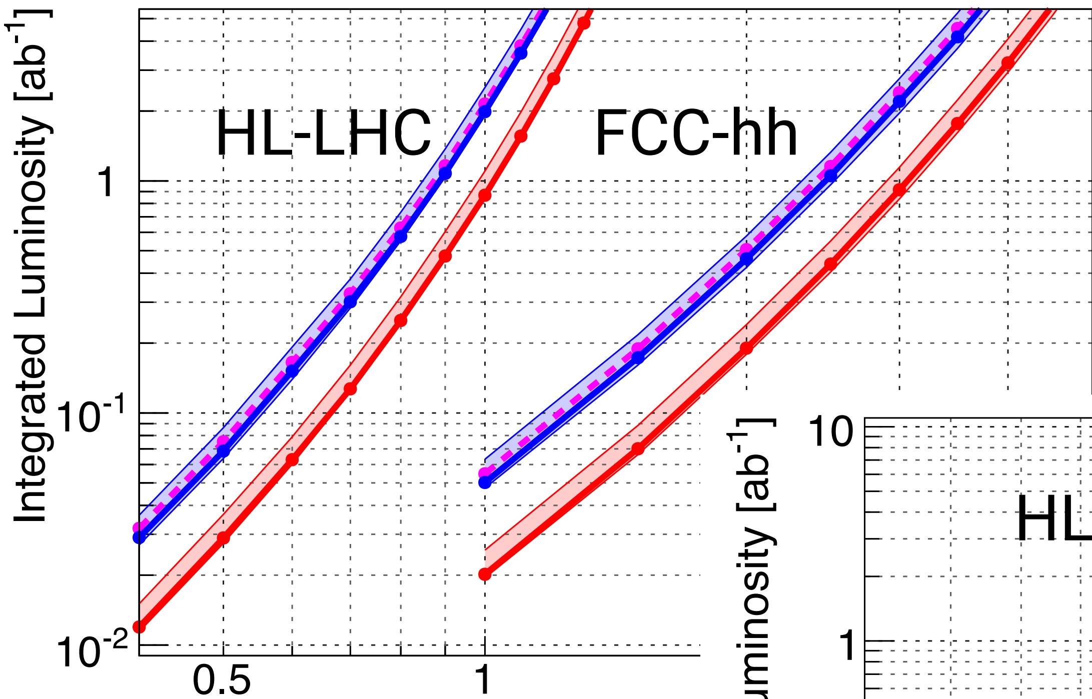
$$\frac{\Delta p_T}{p_T} = 0.05$$



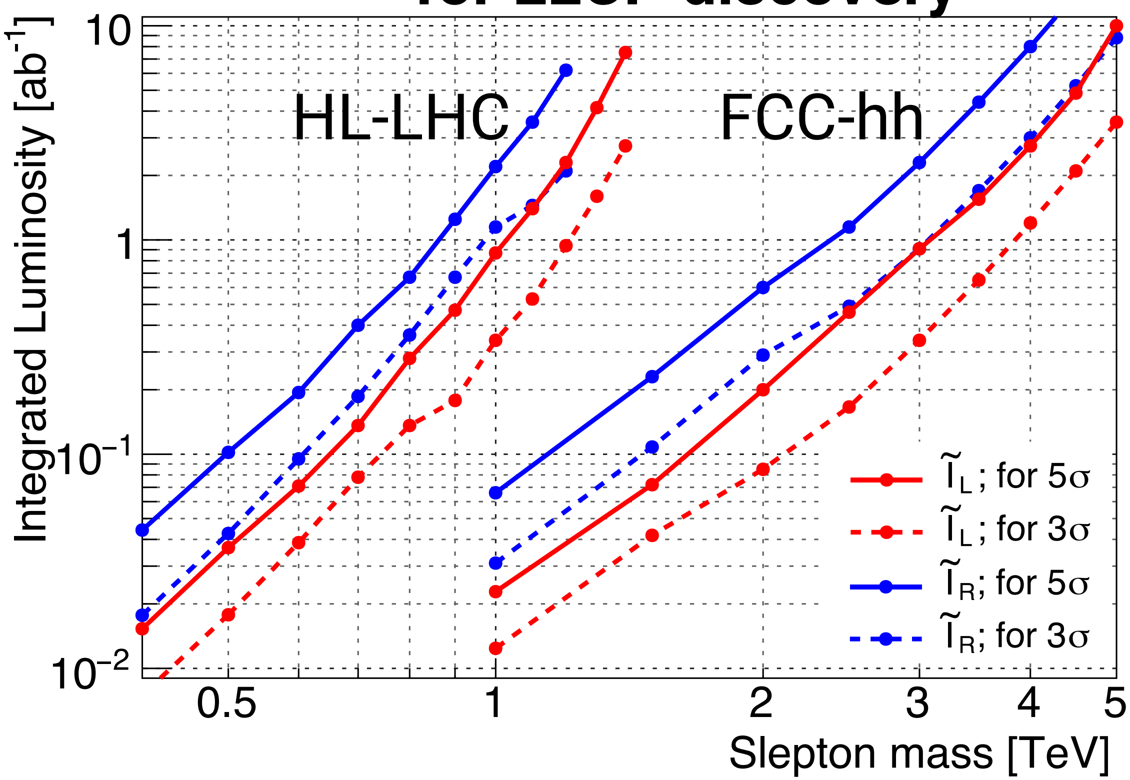
(FCC-hh trk. goal: $\frac{\Delta p_T}{p_T} = (\text{const}) \oplus \frac{(0.01-0.02)p_T}{\text{TeV}}$ **)**

Exclusion & Discovery Reach

for LLCP exclusion



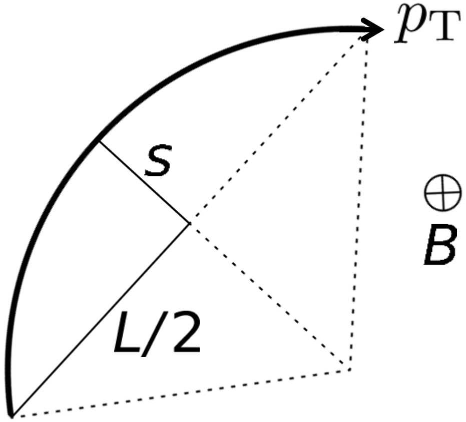
for LLCP discovery



Momentum resolution

Momentum resolution for very-large pT

ATLAS [1404.4562]; see also [1201.4704]



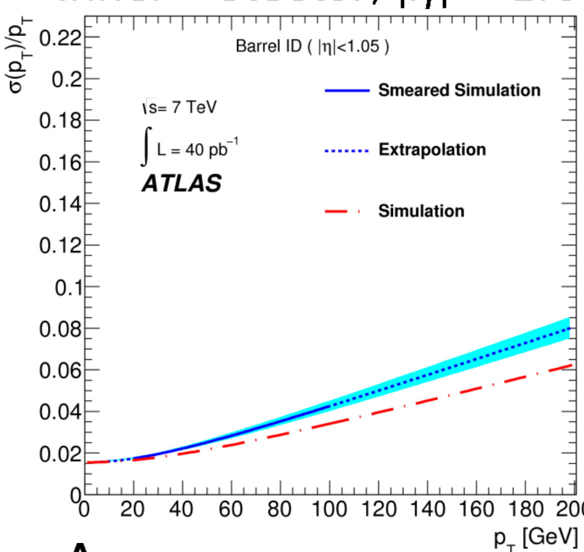
$$p_\mathrm{T} = \frac{L^2}{8s}|q|B \;\Rightarrow\; \Delta p_\mathrm{T} = \frac{L^2|q|B}{8}\frac{\Delta s}{s^2} = \frac{8\Delta s}{L^2|q|B}\cdot p_\mathrm{T}^2$$

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

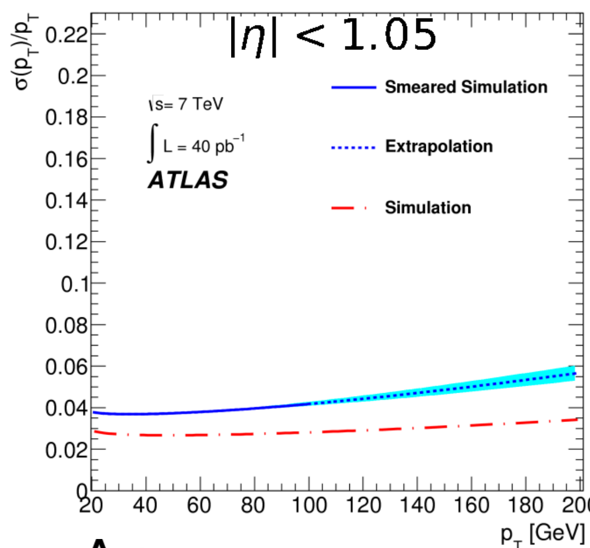
ATLAS 7 TeV results on muon momentum resolution

Inner Detector, $|\eta| < 1.05$

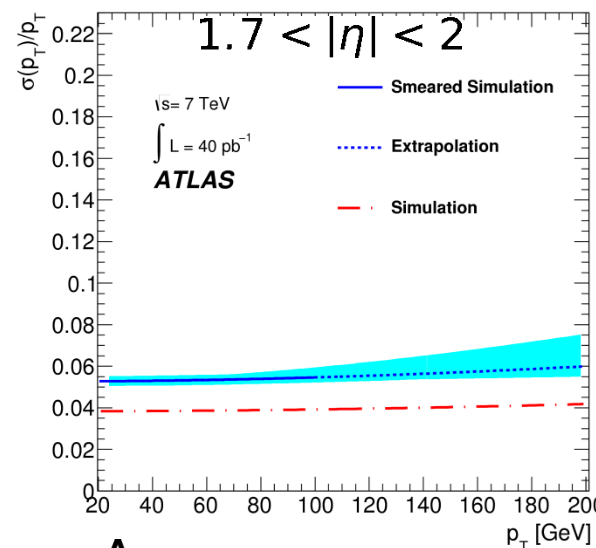
Muon spectrometer



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



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



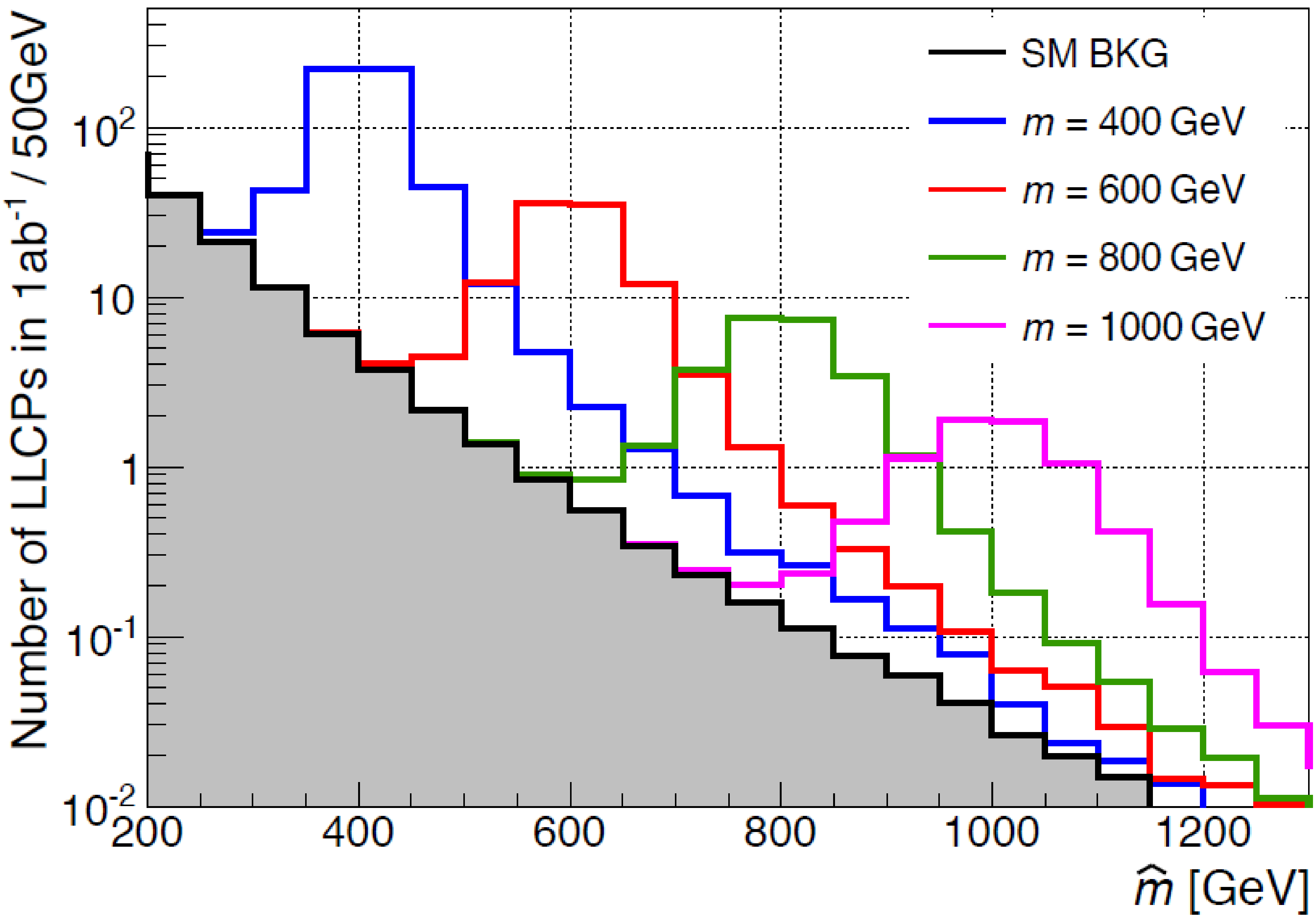
$$\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}} \sim 0.06 p_\mathrm{T}/\mathrm{TeV}$$

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

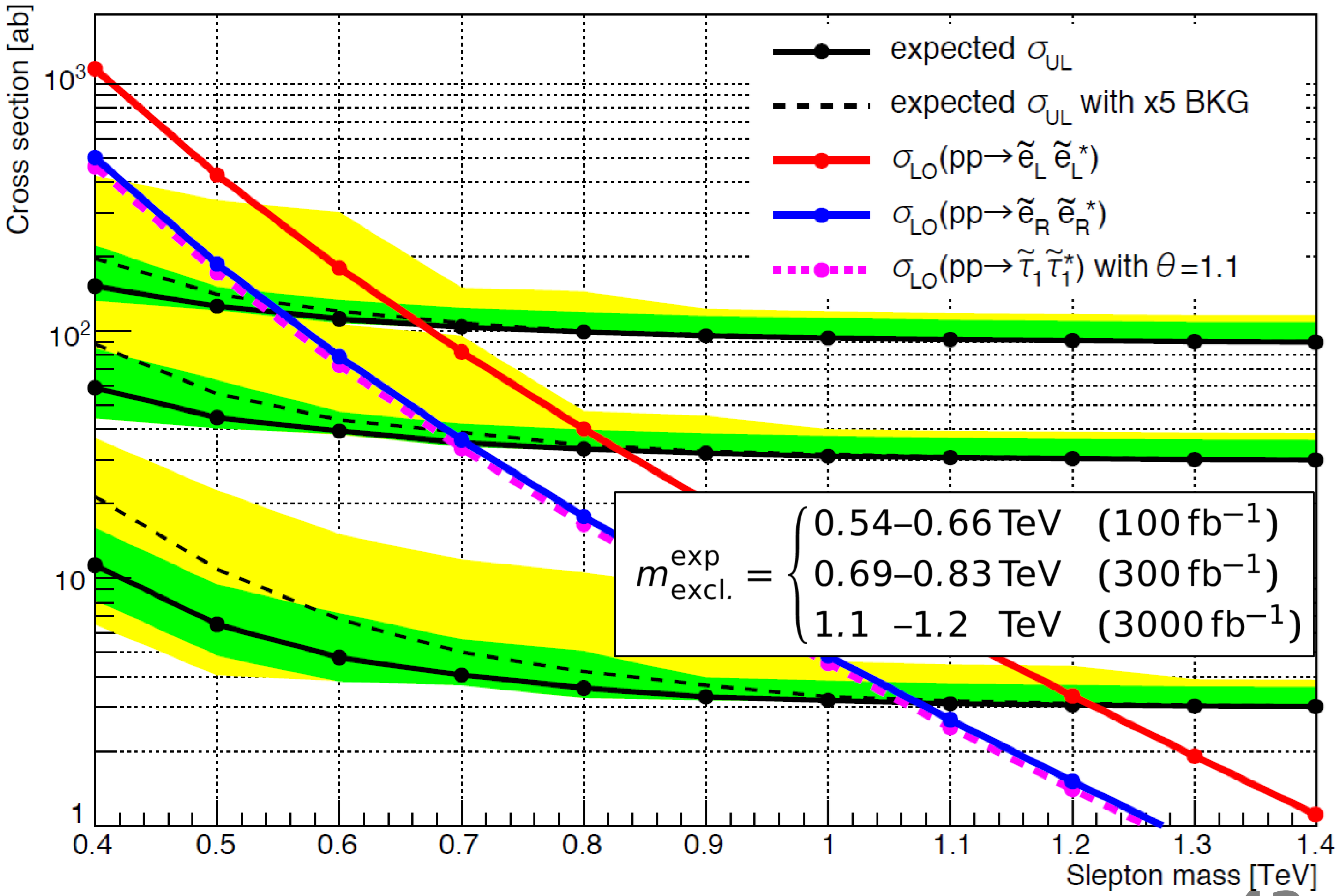
- $\tilde{l}$-selection flow

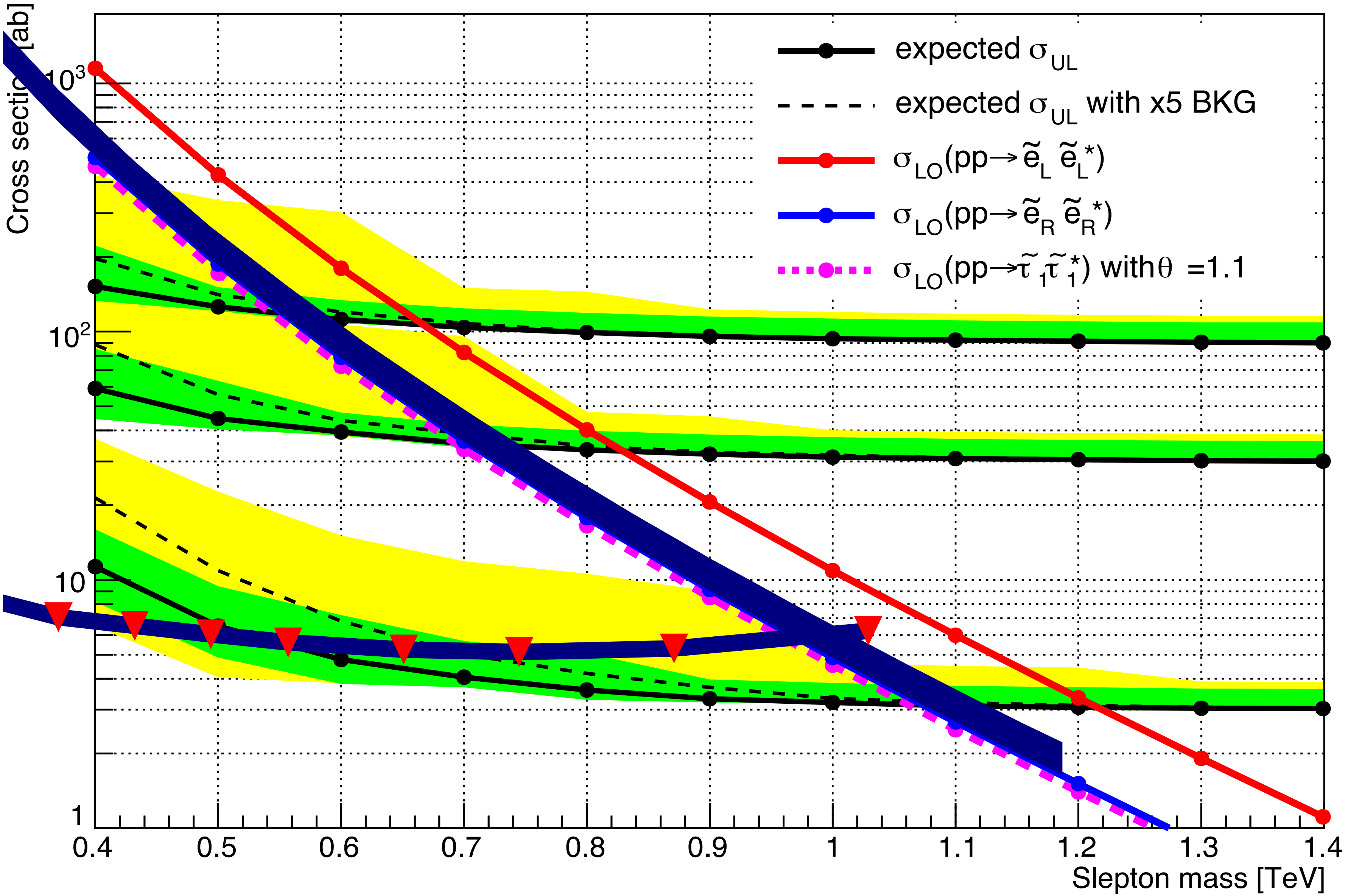
  reconstructed "muon" w.
  - $p_T > \mathbf{100}$ GeV
  - $|\eta| < 2.4$
  - $0.3 < \hat{\beta} < 0.95$
  - ~~$E_{\text{loss}} < 30$ GeV~~
- Event selection
  - two $\tilde{l}$-candidates



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
1
10
102
200
400
600
800
1000
1200
m̂ [GeV]

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





Cross section [ab]
expected σ UL
expected σ UL with x5 BKG
σ LO(pp→ẽL ẽL*)
σ LO(pp→ẽR ẽR*)
σ LO(pp→τ̃1τ̃1*) with θ =1.1
Slepton mass [TeV]

Why β>0.4? (slepton dE/dx)

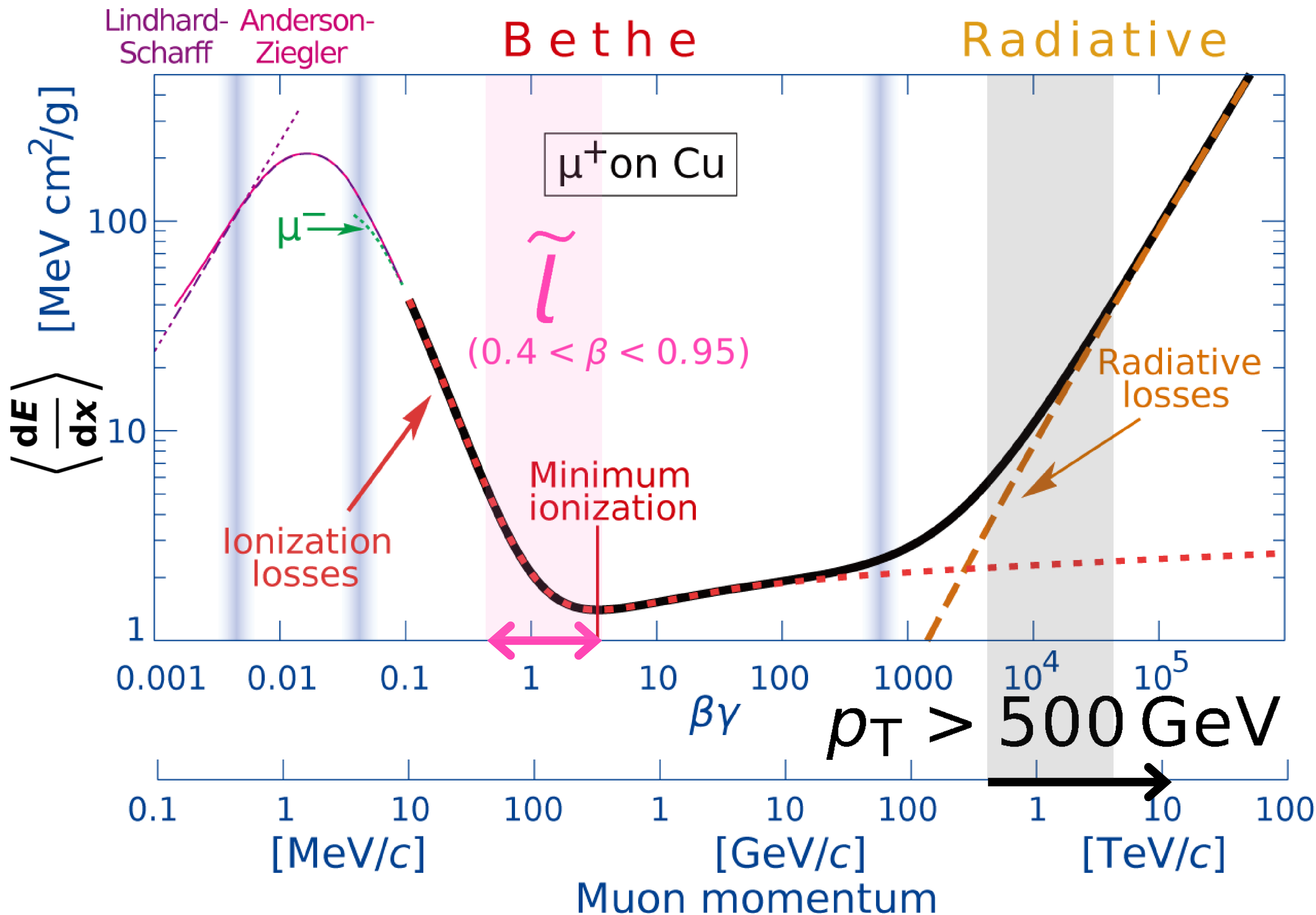


Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

dE/dx to measure β

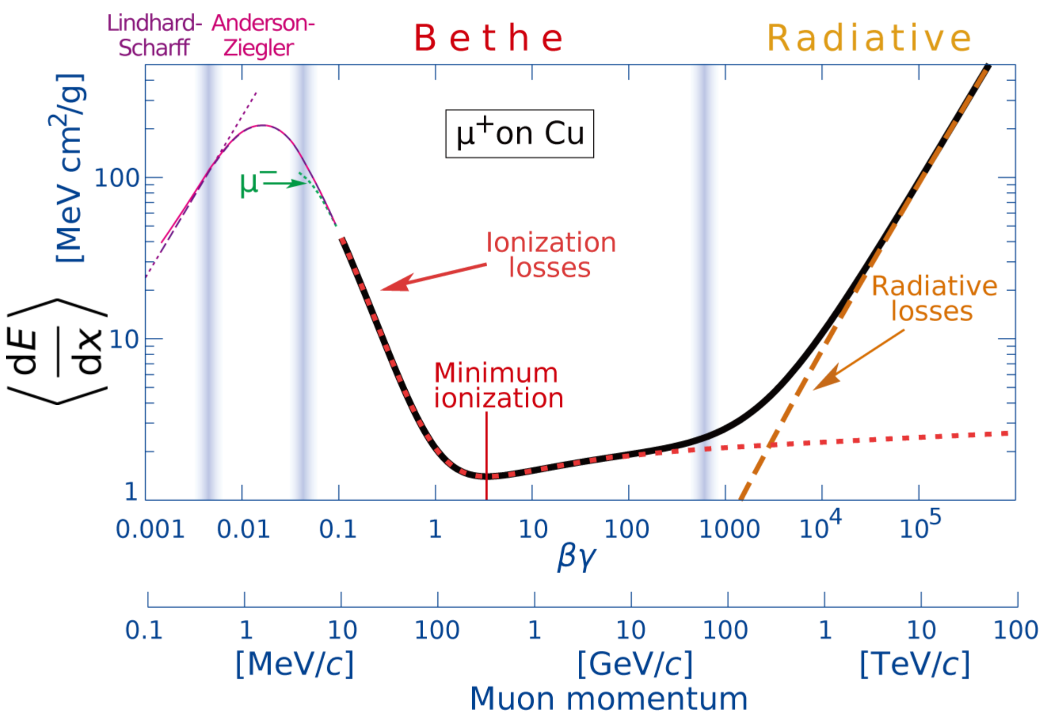
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

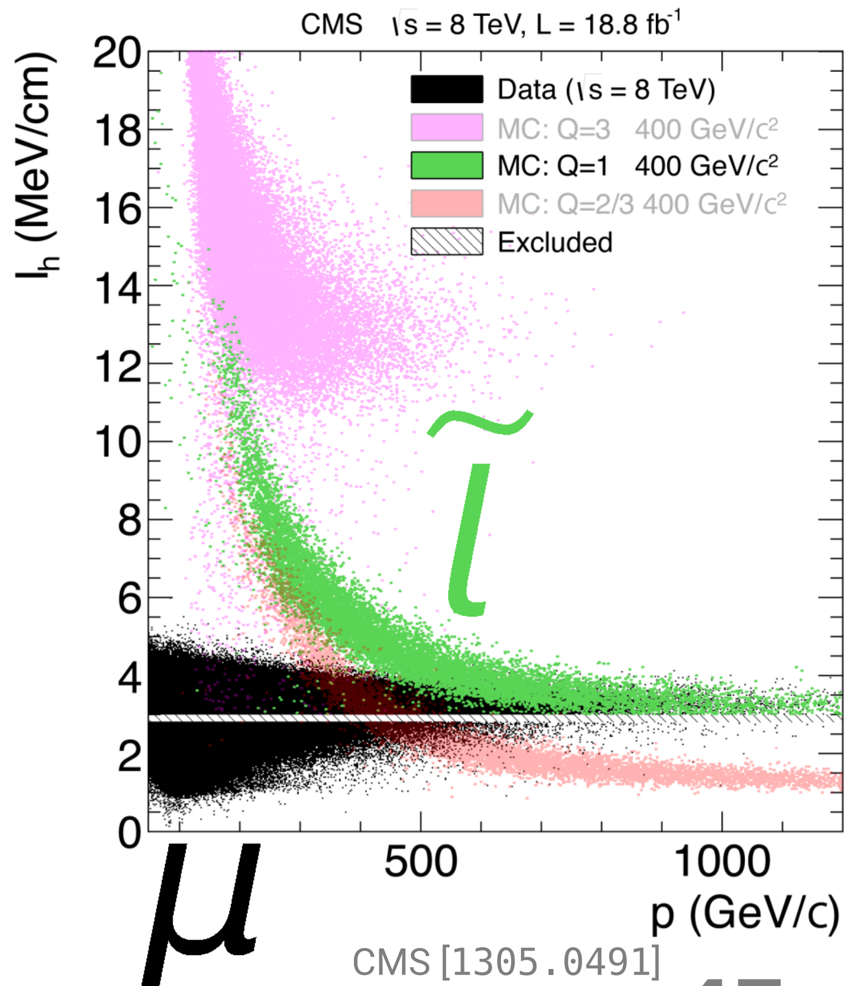
$$I_h = \rho \cdot \frac{\mathrm{d}E}{\mathrm{d}x}\Big|_{\mathrm{estimated}}$$

- TOF : time-of-flight

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

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





CMS [1305.0491]