Long-lived charged particles at future *hh* and *he* colliders

Sho IWAMOTO（岩本　祥）

18 Sep. 2017
Seminar @ National Taiwan University

Based on

hh: Jonathan L. Feng, SI, Yael Shadmi, Shlomit Tarem [1505.02996]
(collected in FCC-hh report [1606.00947])

he: Kechen Wang, SI, Monica D'Onofrio, Georges Azuelos [17??.?????]
(subgroup in BSM@ep collaboration)

1. LLCPs

- Introduction & Motivations
- How to search? & Current bounds

2. Future colliders (FCC-hh and FCC-he)

3. LLCP searches at FCC-hh

4. LLCP searches at FCC-he

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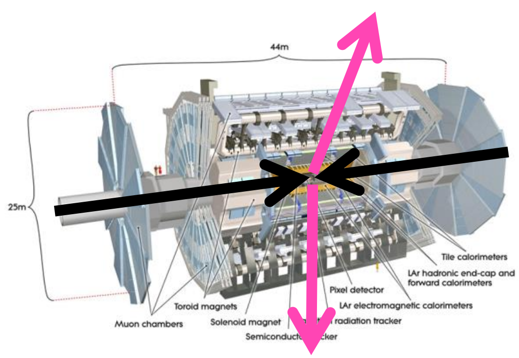
- Particle property

$m > O(100)\mathrm{GeV}$

  - Heavy colored → hadronize → { R-hadron / stopping particles
  - **Heavy non-colored**
  - Light non-colored, milli-charged → dedicated searches

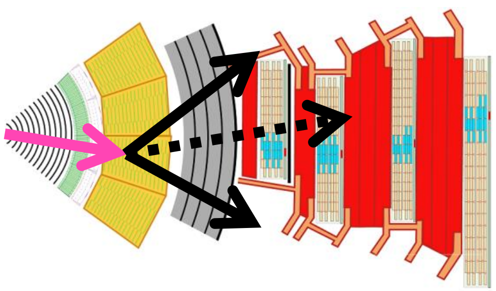
×

- Lifetime
  - "stable"



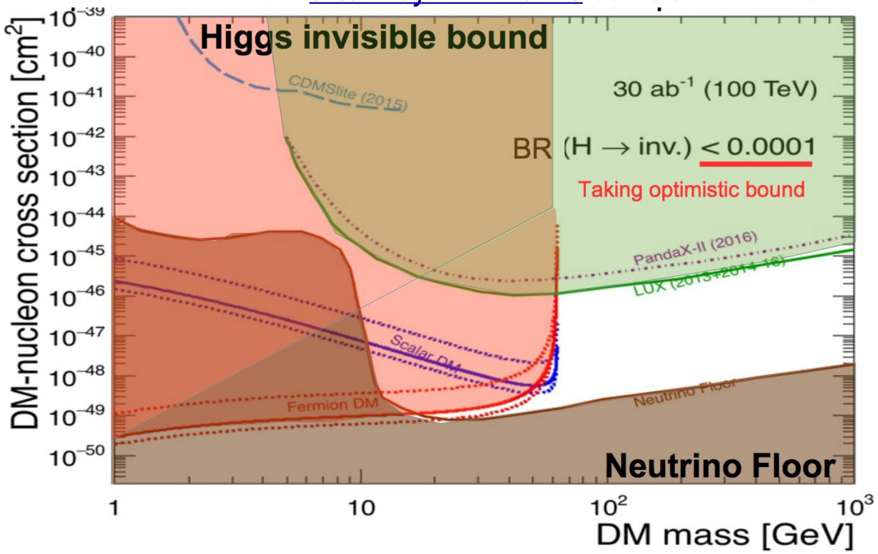
$c\tau \gtrsim 1\,\mathrm{m}$

  - "in-flight decay"



$c\tau \sim 1\,\mathrm{mm}\text{–}1\,\mathrm{m}$

From a talk by Phil Harris at FCC WEEK 2017



- experimental
  - …why not?
  - relevant for detector design
- phenomenology

long lifetime
→ an actor in early Universe

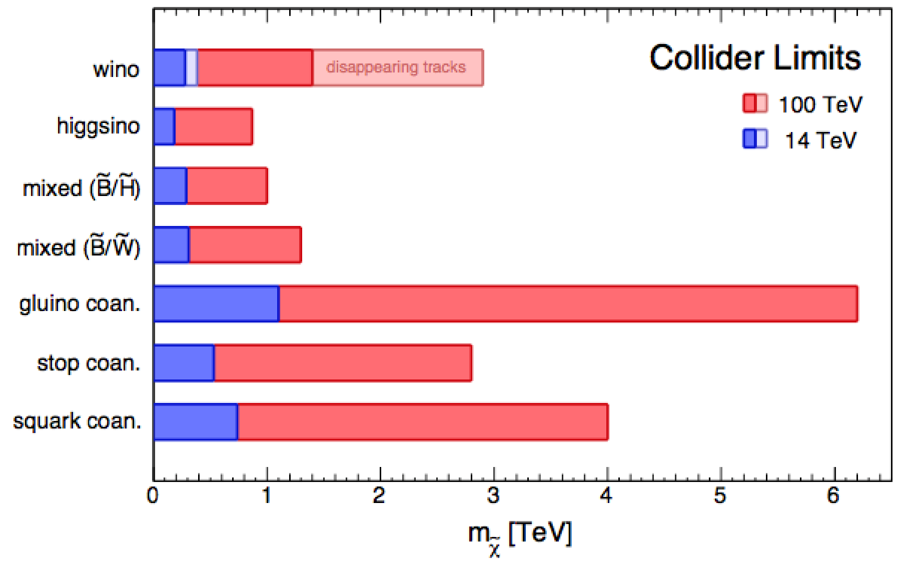
FCC-hh will(?) cover most of the standard thermal-WIMP scenario

non-standard DM/cosmology with LLCP
→ next slides

- theoretical … **SUSY?** biased
  - GMSB scenario: light gravitino → long-lived sleptons
  - split-SUSY: extremely heavy squarks → long-lived gluino

- **Dark Matter** (especially to ameliorate DM over-abundance)
  - co-annihilation
    - $(\tilde{B} - \tilde{\tau}) \lesssim 700\,\mathrm{GeV}$
    - $(\tilde{W} - \tilde{g}) \lesssim 6\text{–}7\,\mathrm{TeV}$
    - $(\tilde{B} - \tilde{g})$ or $(\tilde{B} - \tilde{t}) \lesssim 8\,\mathrm{TeV}$

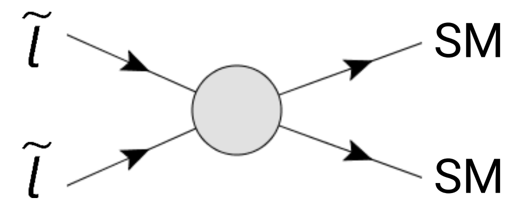
    Harigaya, Kaneta, Matsumoto [1403.0715], Ellis, Olive, Zheng [1404.5571], etc.
  - super-WIMP scenario
    → $\tilde{l} > O(1)\,\mathrm{TeV}$



"Physics at the FCC-hh" Report [1606.00947]

- **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]



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

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

frozen-out

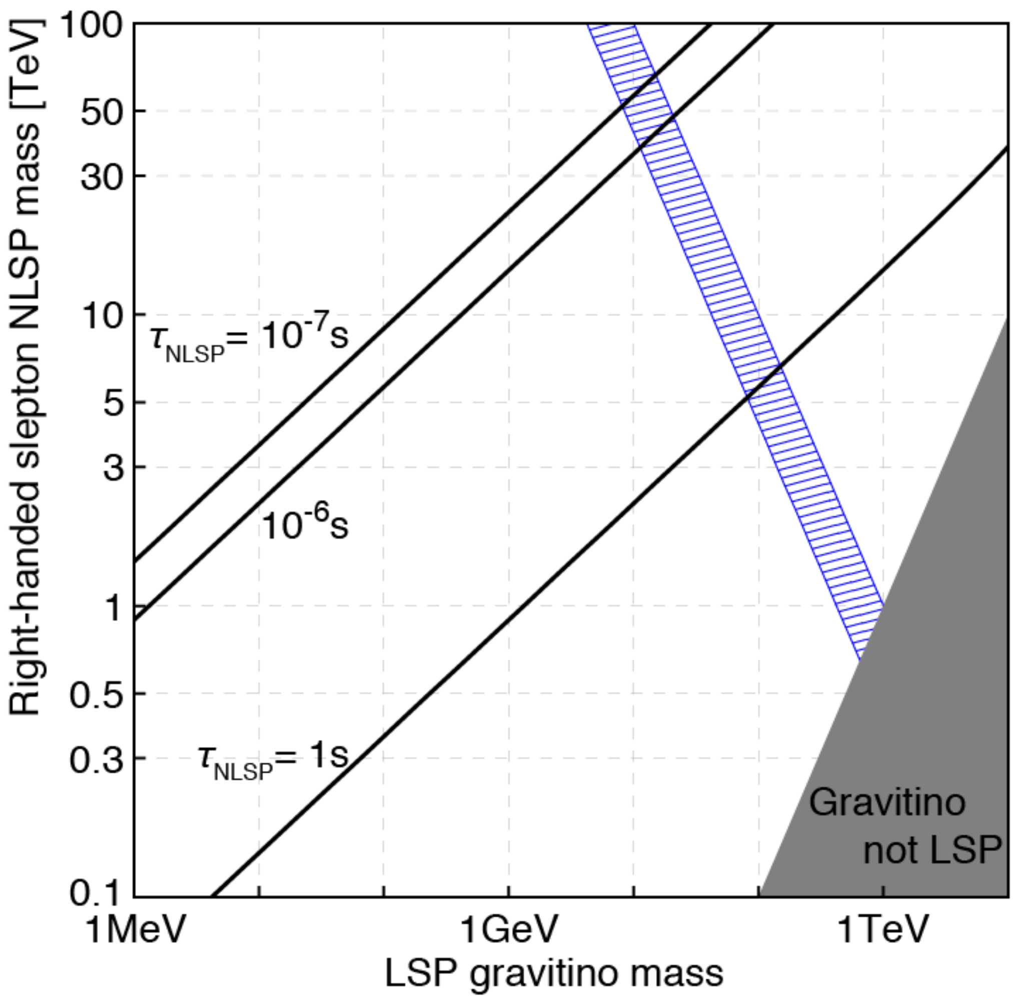
→ thermal relic with $(\Omega h^2)_{\tilde{l}} \gg 0.12$

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.)

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

Dark Matter (especially to ameliorate DM over-abundance)

- co-annihilation
  - $(\tilde{B}\text{-}\tilde{\tau}) \lesssim 700\,\text{GeV}$
  - $(\tilde{W}\text{-}\tilde{g}) \lesssim 6\text{–}7\,\text{TeV}$
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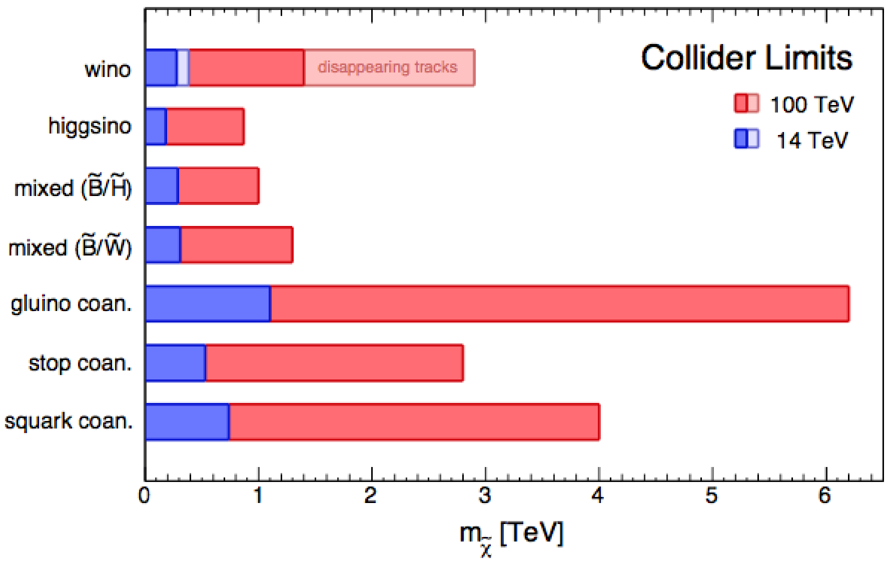

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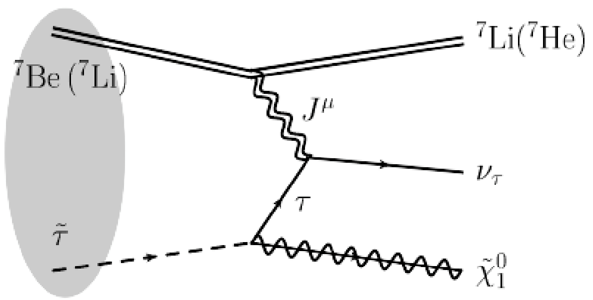
- super-WIMP scenario
  → $\tilde{l} > O(1)\,\text{TeV}$

Li problem

- MSSM $\tilde{\tau}$ with

  $m_{\tilde{\tau}} \sim 400\,\text{GeV}$

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



Sato, Shimomura, Yamanaka [1604.04769]

- **Dark Matter** (especially to am

non-colored LLCP

… covered in this talk

(slepton $\tilde{l}$ / stau $\tilde{\tau}$ as benchmarks)

  - co-annihilation
    - $(\tilde{B}\text{-}\tilde{\tau}) \lesssim 700$ GeV
    - $(\widetilde{W}\text{-}\tilde{g}) \lesssim 6\text{–}7$ TeV
    - $(\tilde{B}\text{-}\tilde{g})$ or $(\tilde{B}\text{-}\tilde{t}) \lesssim 8$ TeV

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

[1606.00947]

colored LLCP

(→ hadronize: "R-hadron")

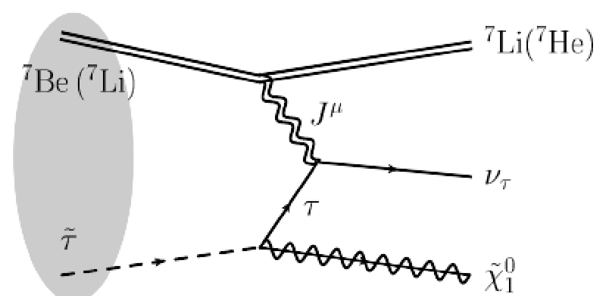
  - super-WIMP scenario
    → $\tilde{l} >$ O(1) TeV

(as we see soon.)

- **Li problem**
  - MSSM $\tilde{\tau}$ with

$m_{\tilde{\tau}} \sim 400$ GeV

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



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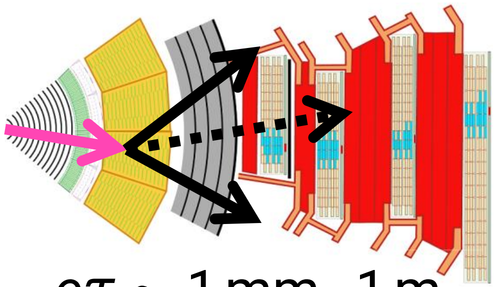
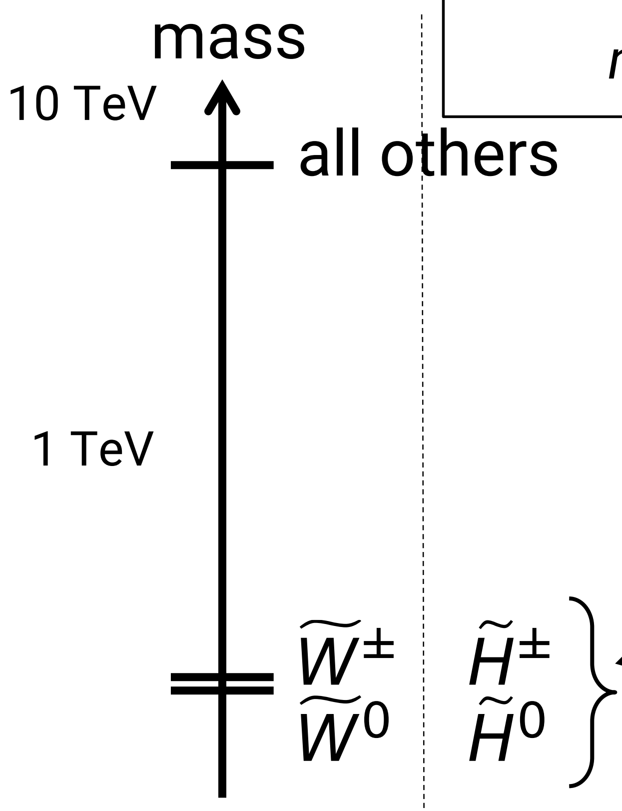


$c\tau \sim 1\,\mathrm{mm}$–$1\,\mathrm{m}$

$$\delta m = m_{\tilde{W}^\pm} - m_{\tilde{W}^0},\quad m_{\tilde{H}^\pm} - m_{\tilde{H}^0}$$



- Simple MSSM models
  - Pure-Wino dark matter
  - Pure-Higgsino dark matter

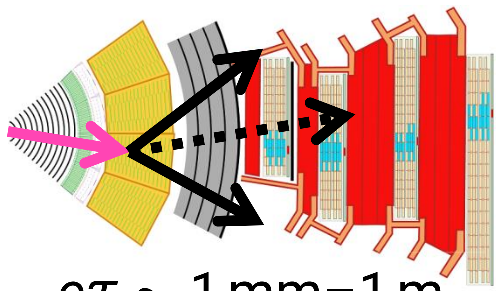
⇓

$\tilde{\chi}^\pm$ long-lived because of small δm ($\delta m > 0$)

- Other MSSM models
  - Gauge-Mediation
  - R-parity violation

Same SU(2) multiplet → mass degenerate

($\delta m = m_{\tilde{W}^\pm} - m_{\tilde{W}^0}$, $m_{\tilde{H}^\pm} - m_{\tilde{H}^0}$ from EW loop corrections)



$c\tau \sim 1\,\text{mm}-1\,\text{m}$

$$\delta m = m_{\tilde{W}^\pm} - m_{\tilde{W}^0},\quad m_{\tilde{H}^\pm} - m_{\tilde{H}^0}$$

- Simple MSSM models
  - Pure-Wino dark matter **60mm**
  - Pure-Higgsino dark matter **7mm**

⇩

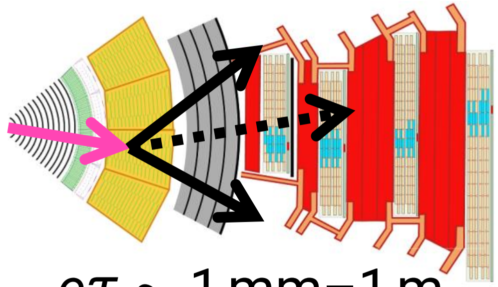
$\tilde{\chi}^\pm$ long-lived because of small δm

($\delta m > 0$)

$m_{\tilde{W}}$ [GeV]	200	250	300	350	400	450	500	550	600	700	800	900
δm [MeV]	159	160	161	162	162	163	163	163	163	164	164	164
$c\tau$ [mm]	71	67	64	63	62	61	60	60	59	59	59	59

- R-parity violation

$m_{\tilde{H}}$ [GeV]	200	250	300	350	400	450	500	550	600	700	800	900
δm [MeV]	297	306	313	319	323	326	329	331	333	336	338	340
$c\tau$ [mm]	11	10	9.4	8.9	8.5	8.2	8.0	7.8	7.7	7.4	7.2	7.1



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(but DM underabundant for "observable" region)

- Other MSSM models
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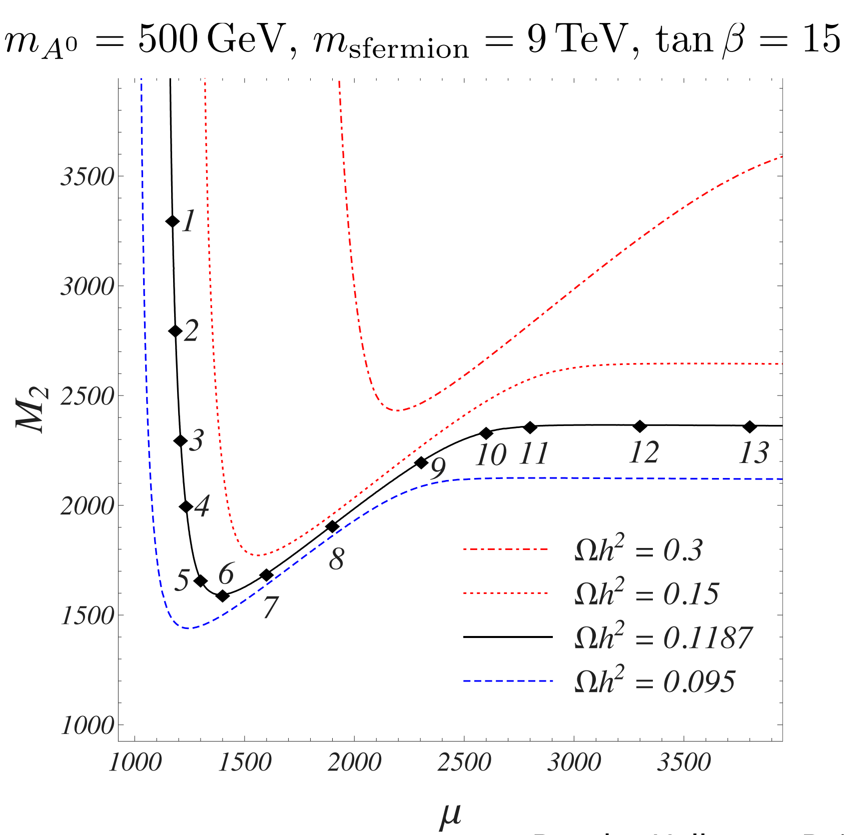
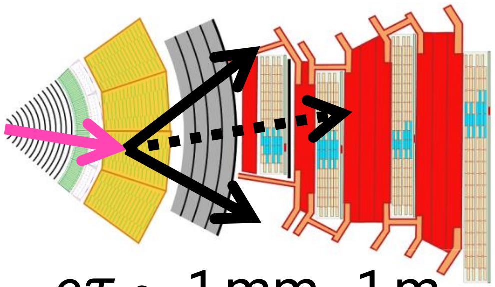


Beneke, Hellmann, Ruiz-Femenia [1411.6930]



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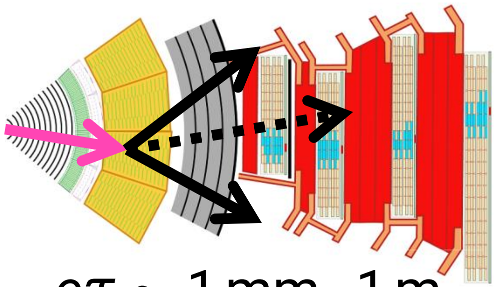
- Other MSSM models
  - Gauge-Mediation (keV $\tilde{G}$)
  - R-parity violation

with $\tilde{l}$ -LSP

⇨ $\tilde{l}$ long-lived because of tiny couplings.



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$$c\tau \sim 1.8 \times 10^{-5}\,\mathrm{m}\left(\frac{m_{\tilde{l}}}{100\,\mathrm{GeV}}\right)^{-5}\left(\frac{m_{\tilde{G}}}{1\,\mathrm{eV}}\right)^{2}$$

for Gauge-Mediation: "gravity is weak",

$$0.50\,\mathrm{m}\left(\frac{m_{\tilde{l}}}{100\,\mathrm{GeV}}\right)^{-1}\left(\frac{\lambda_{ijk}}{10^{-8}}\right)^{-2}.$$

for R-parity violation: "if RpV is tiny".

- Other MSSM models
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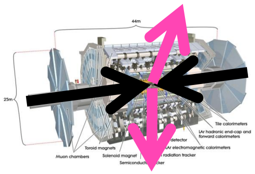
with $\tilde{l}$ -LSP

⇨ $\tilde{l}$ long-lived because of tiny couplings. **any $c\tau$**



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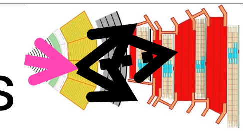

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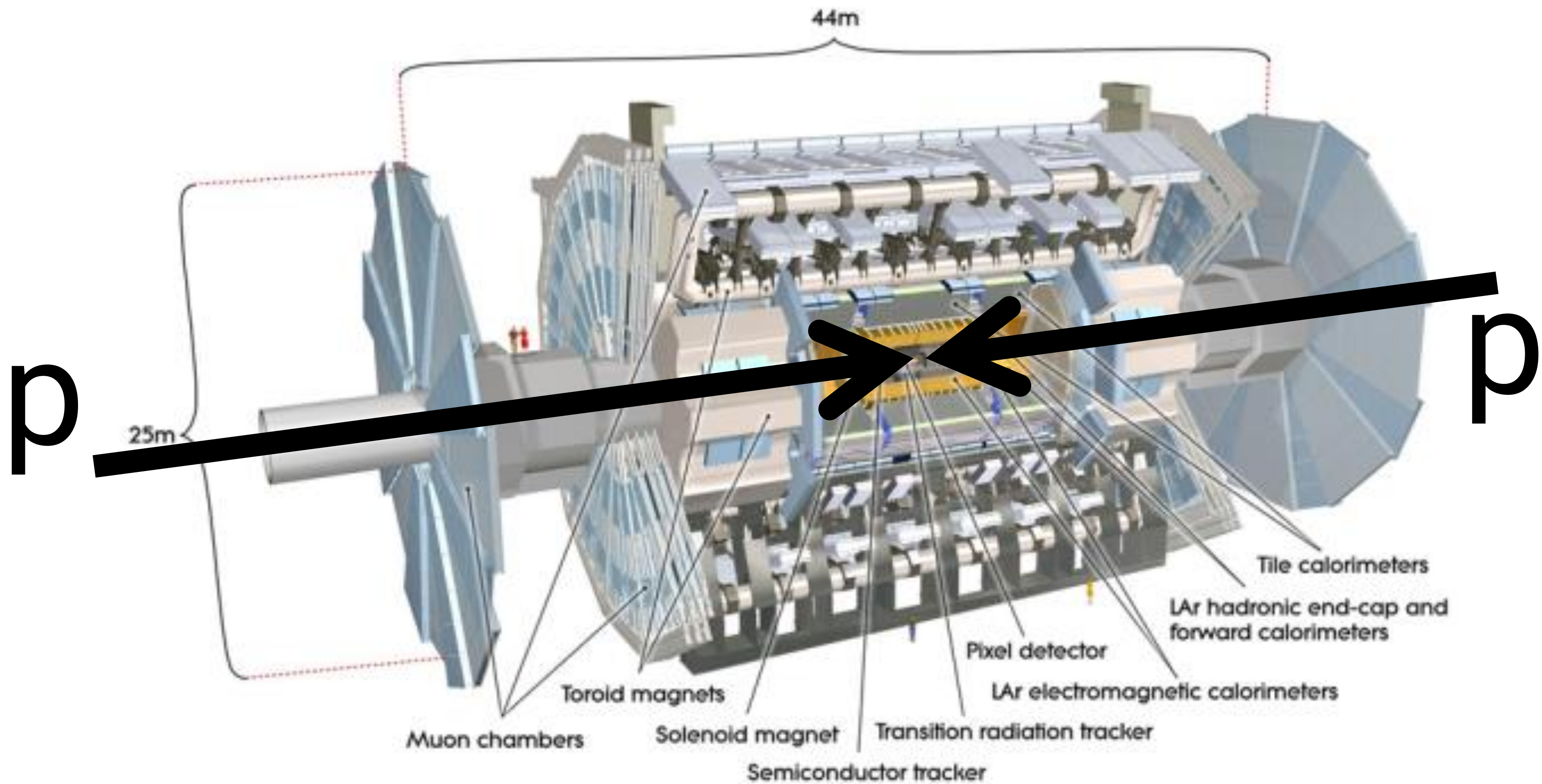
- (1) “stable” non-colored LLCPs



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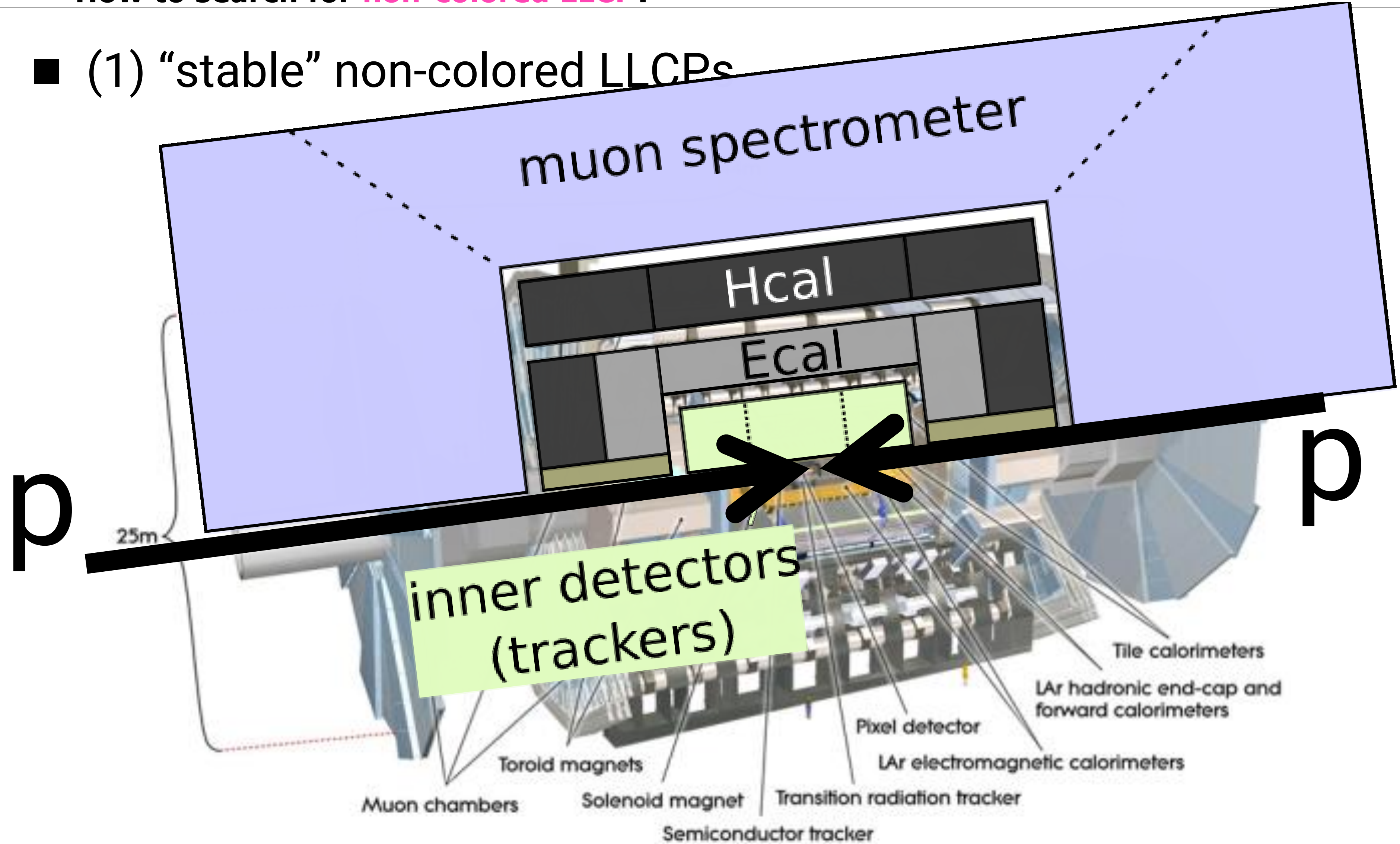

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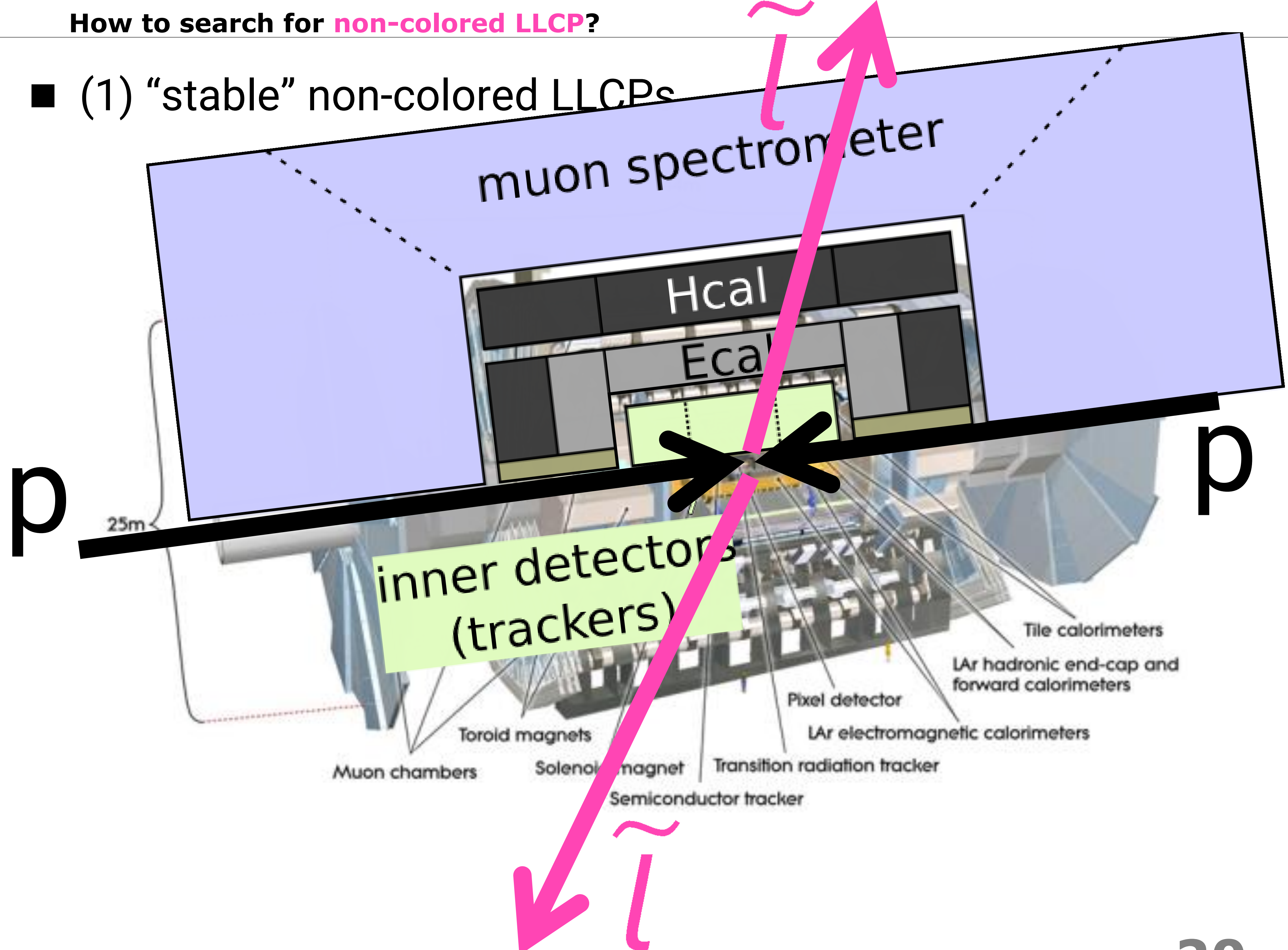
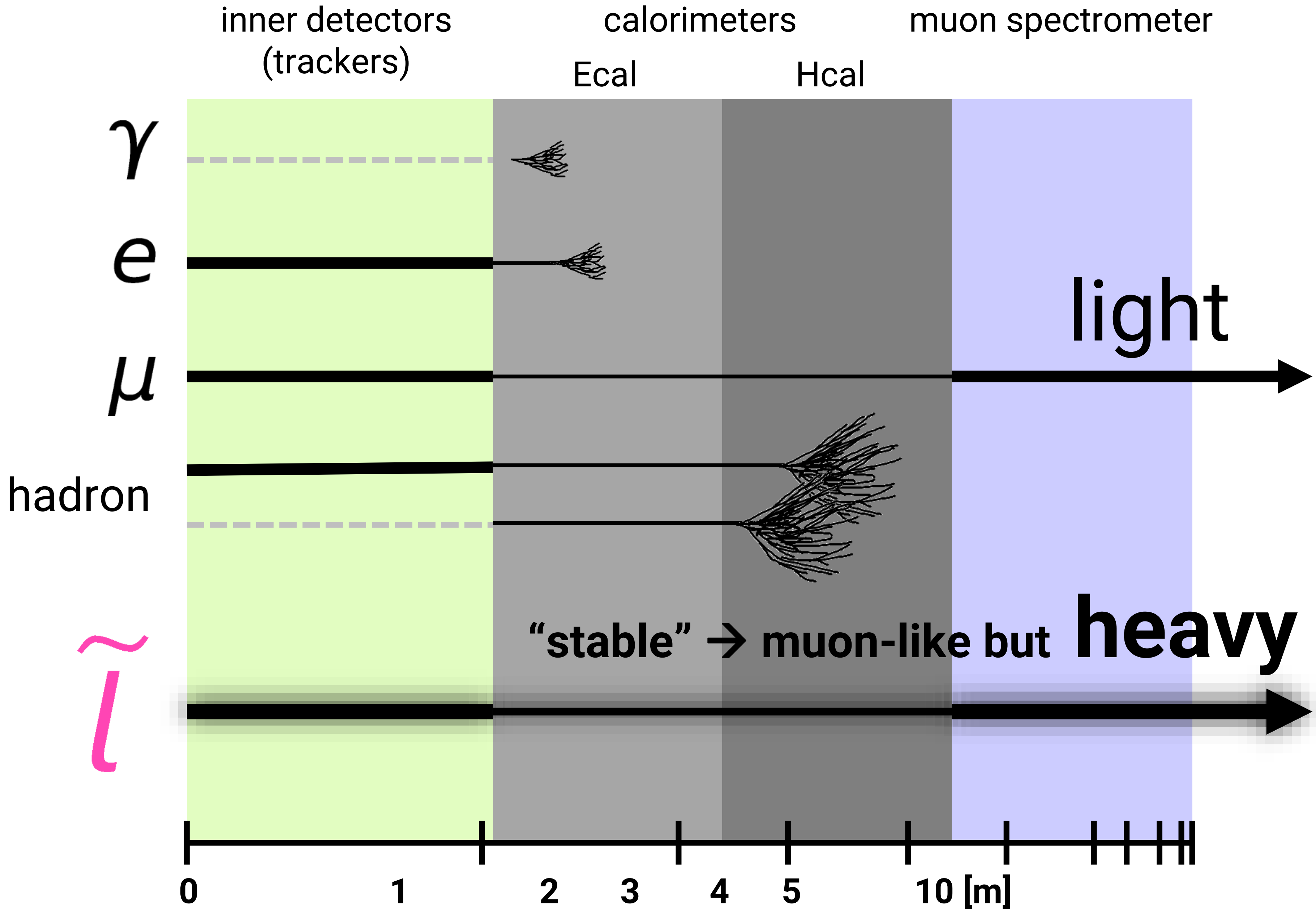




inner detectors
(trackers)
calorimeters
Ecal
Hcal
muon spectrometer
γ
e
μ
hadron
light
"stable" → muon-like but heavy
0
1
2
3
4
5
10 [m]

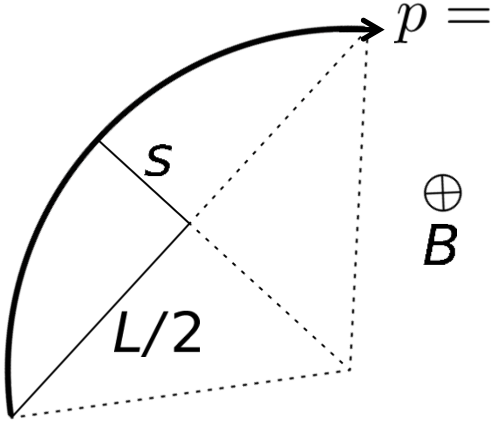
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

momentum & velocity

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

➢ momentum

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



➢ velocity

- TOF [time-of-flight]

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

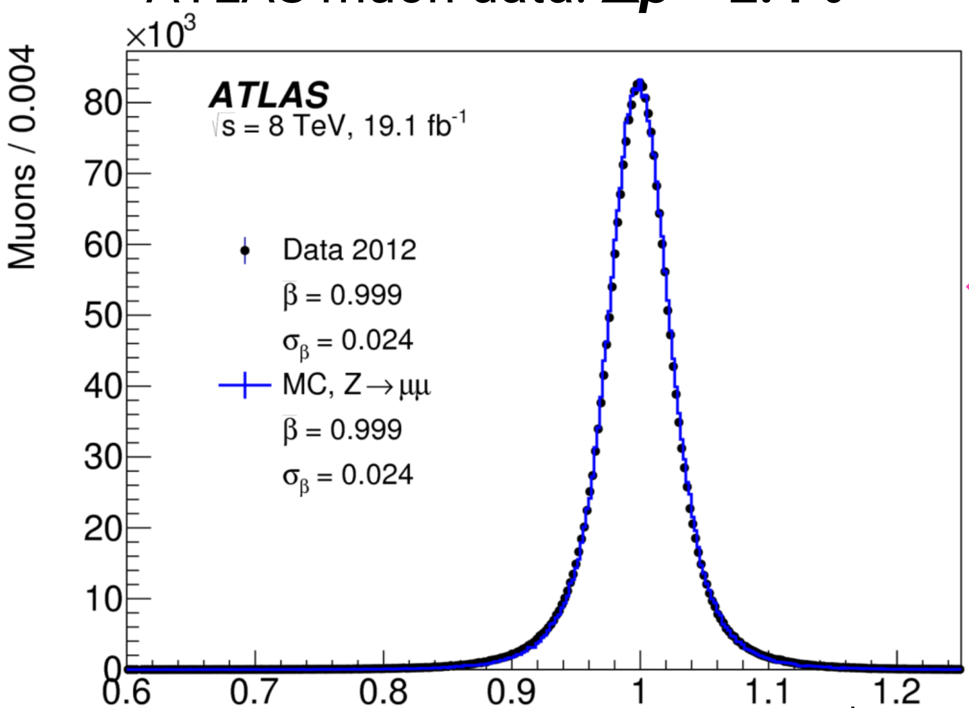
- d*E*/d*x* [ionization energy loss]

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

momentum & velocity

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

ATLAS muon data: **Δβ = 2.4%**



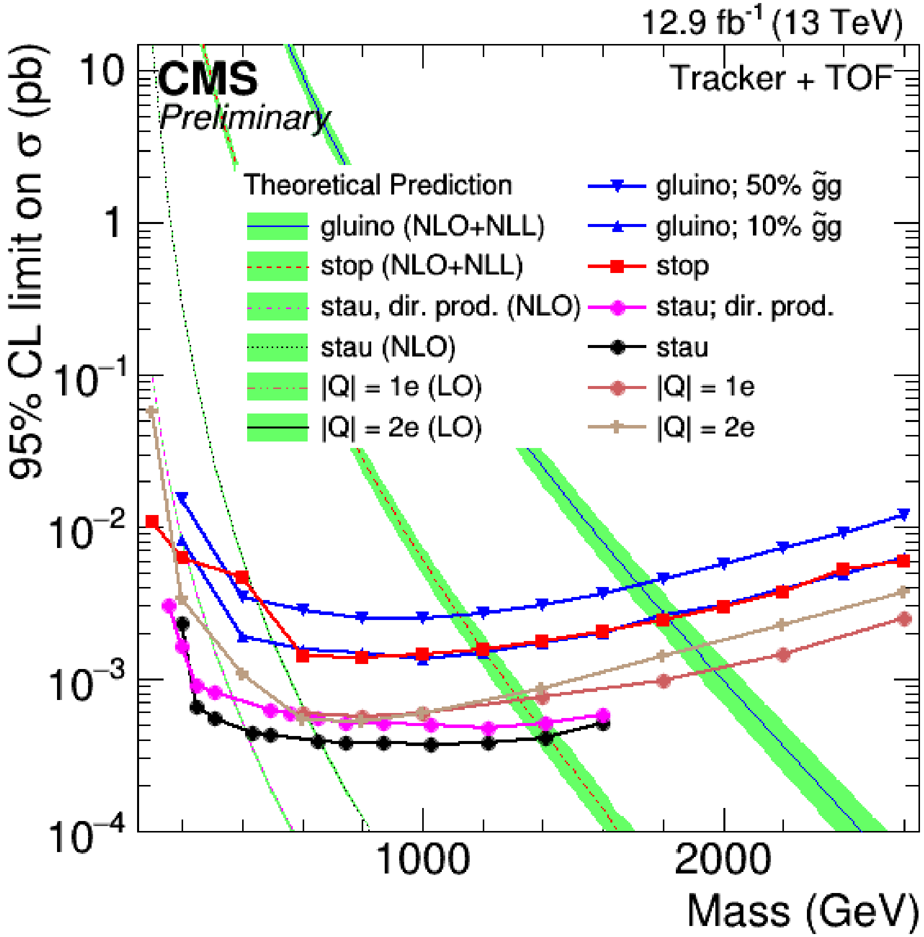
$\beta^{\text{obs}} =: \hat{\beta}$

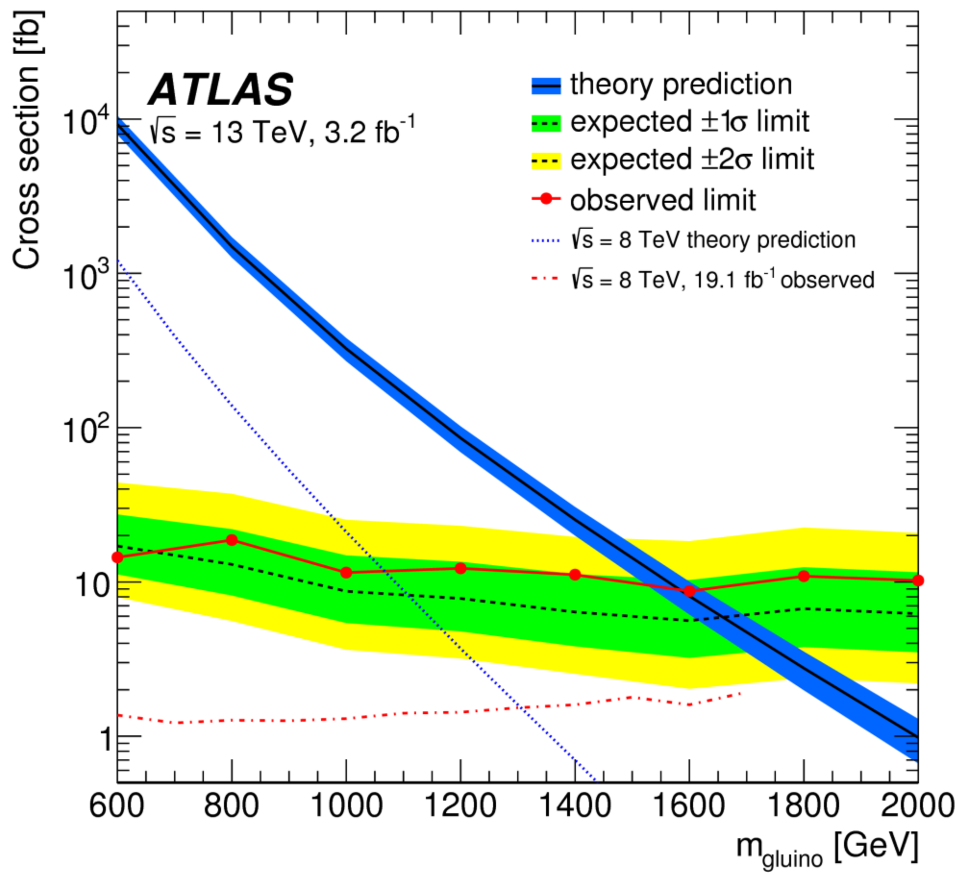
➢ velocity

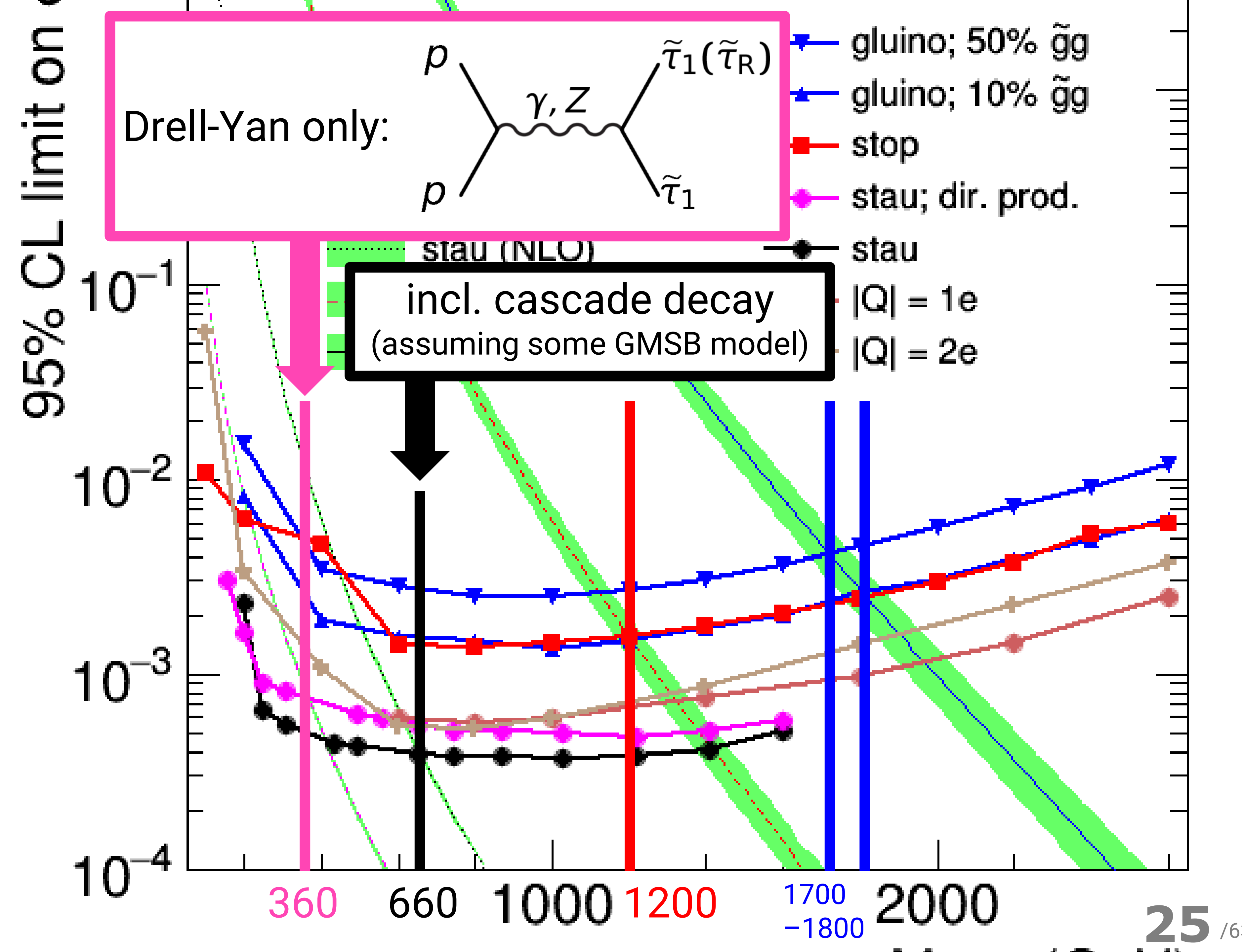
- TOF [time-of-flight]

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

- dE/dx [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)
10
1
10−1
10−2
10−3
10−4
1000
2000
Mass (GeV)

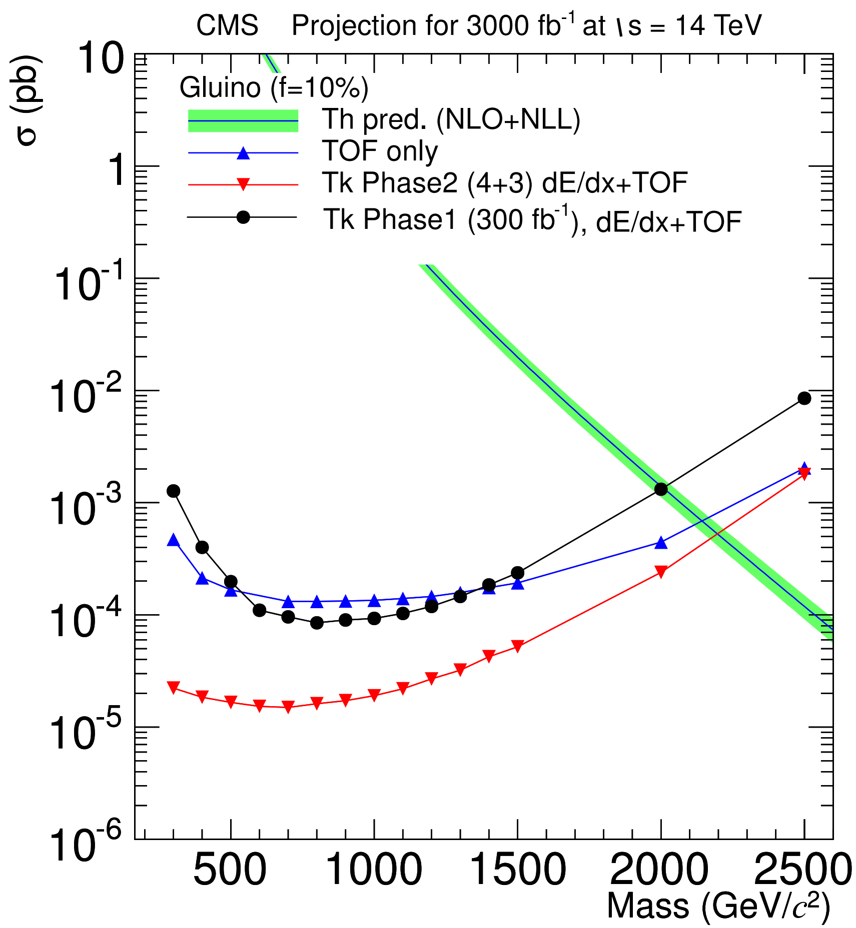

ATLAS
√s = 13 TeV, 3.2 fb-1
theory prediction
expected ±1σ limit
expected ±2σ limit
observed limit
√s = 8 TeV theory prediction
√s = 8 TeV, 19.1 fb-1 observed
Cross section [fb]
10^4
10^3
10^2
10
1
600
800
1000
1200
1400
1600
1800
2000
m_gluino [GeV]

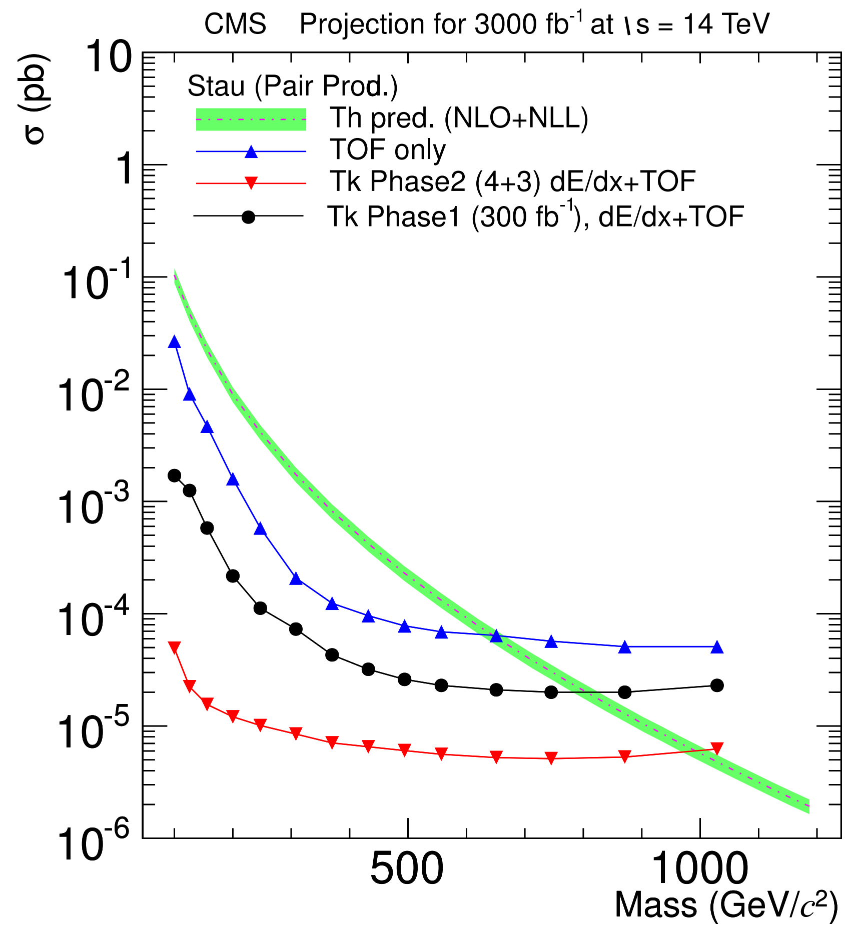


95% CL limit on σ
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Drell-Yan only:
p
p
γ, Z
$\tilde{\tau}_1(\tilde{\tau}_R)$
$\tilde{\tau}_1$
incl. cascade decay
(assuming some GMSB model)
gluino; 50% $\tilde{g}g$
gluino; 10% $\tilde{g}g$
stop
stau; dir. prod.
stau
|Q| = 1e
|Q| = 2e
stau (NLO)
360
660
1000
1200
1700
−1800
2000

HL-LHC

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

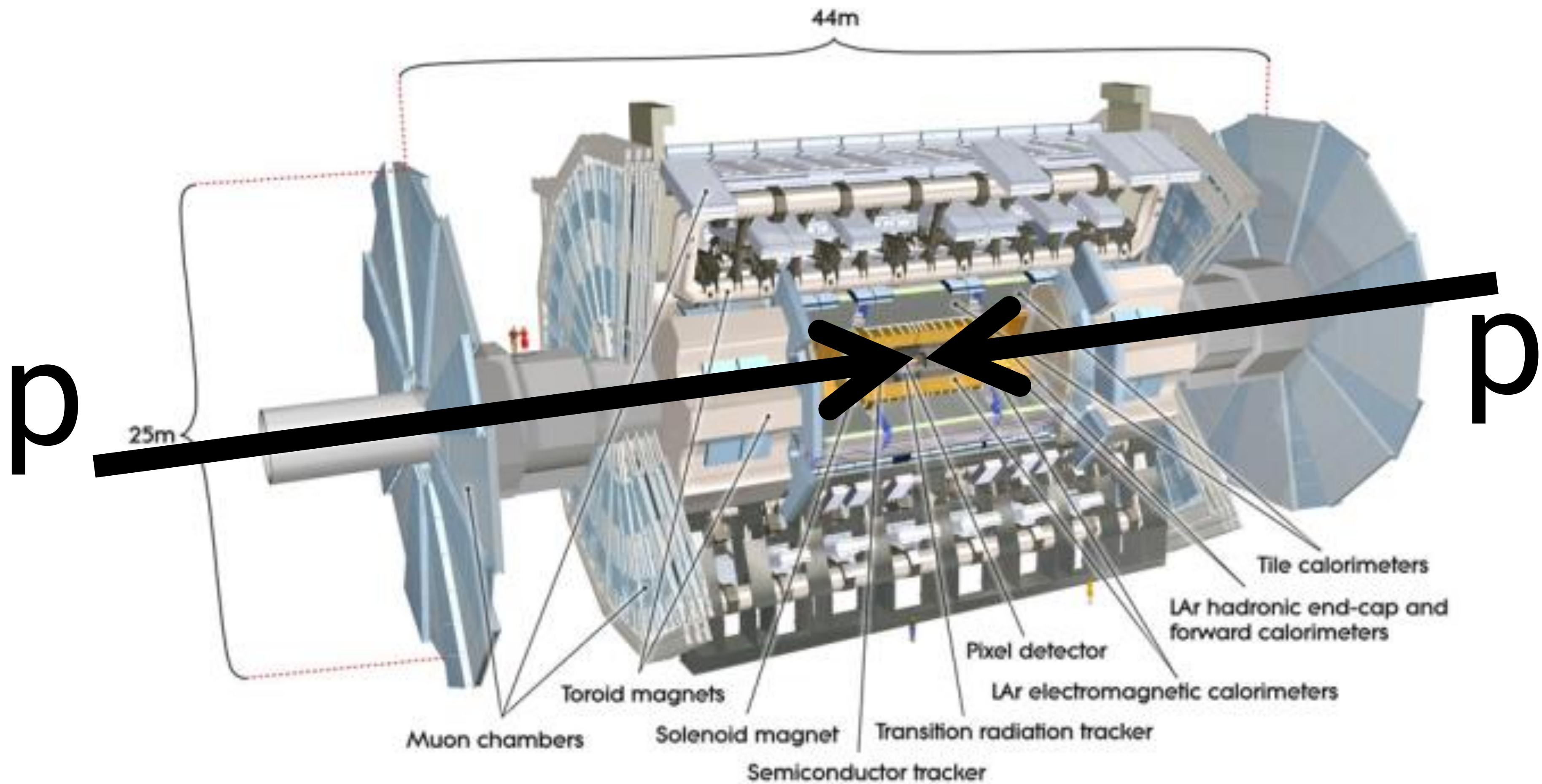




	current	HL-LHC
gluino:	1.7 TeV	→ 2.2 TeV?
stop:	1.2 TeV	→ 1.7 TeV?
stau (GMSB):	660 GeV	→ 1.2 TeV?
stau (DY):	360 GeV	→ 1.0 TeV?

(or discovery?)

- (2) “in-flight decay” non-colored LLCPs



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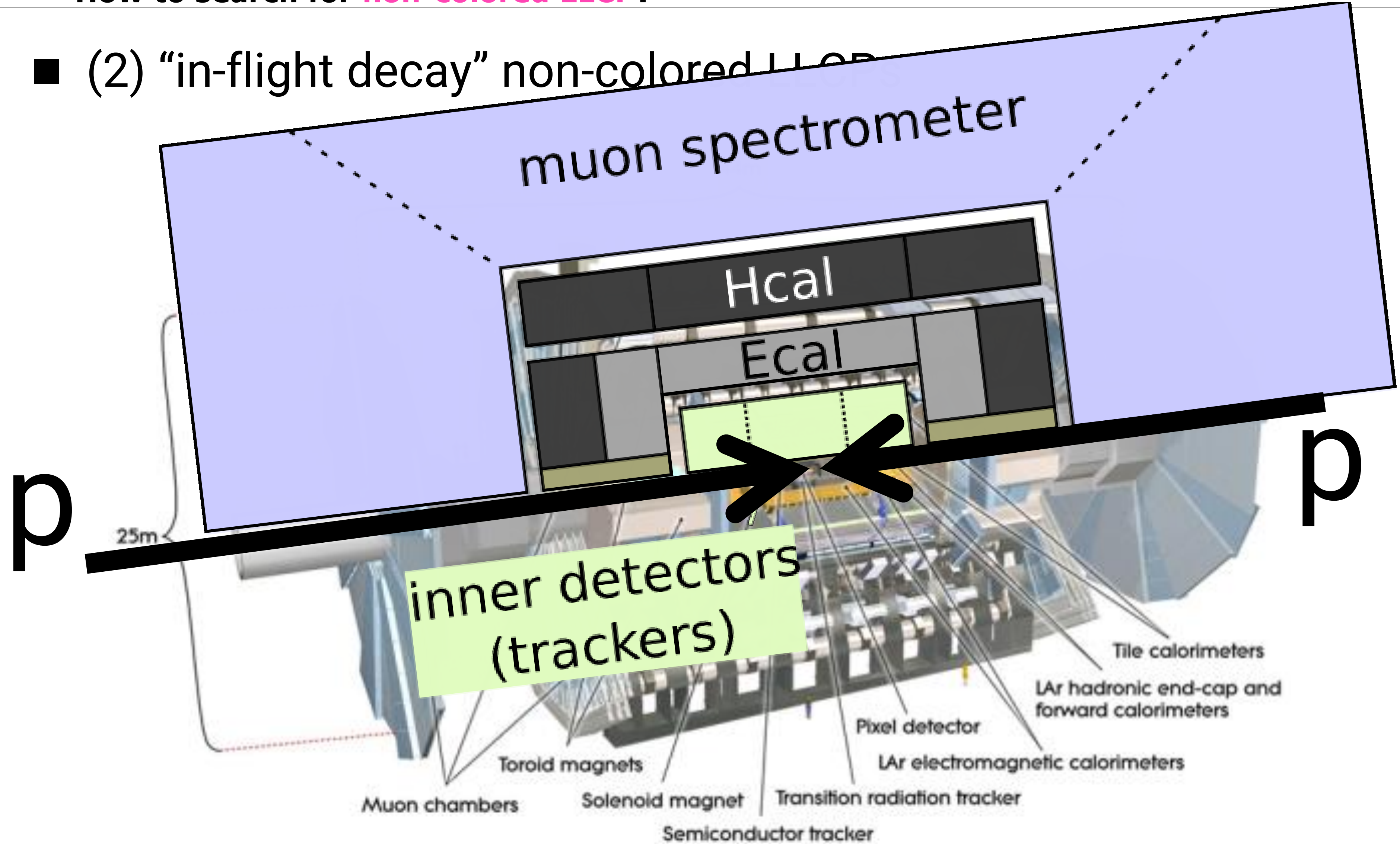

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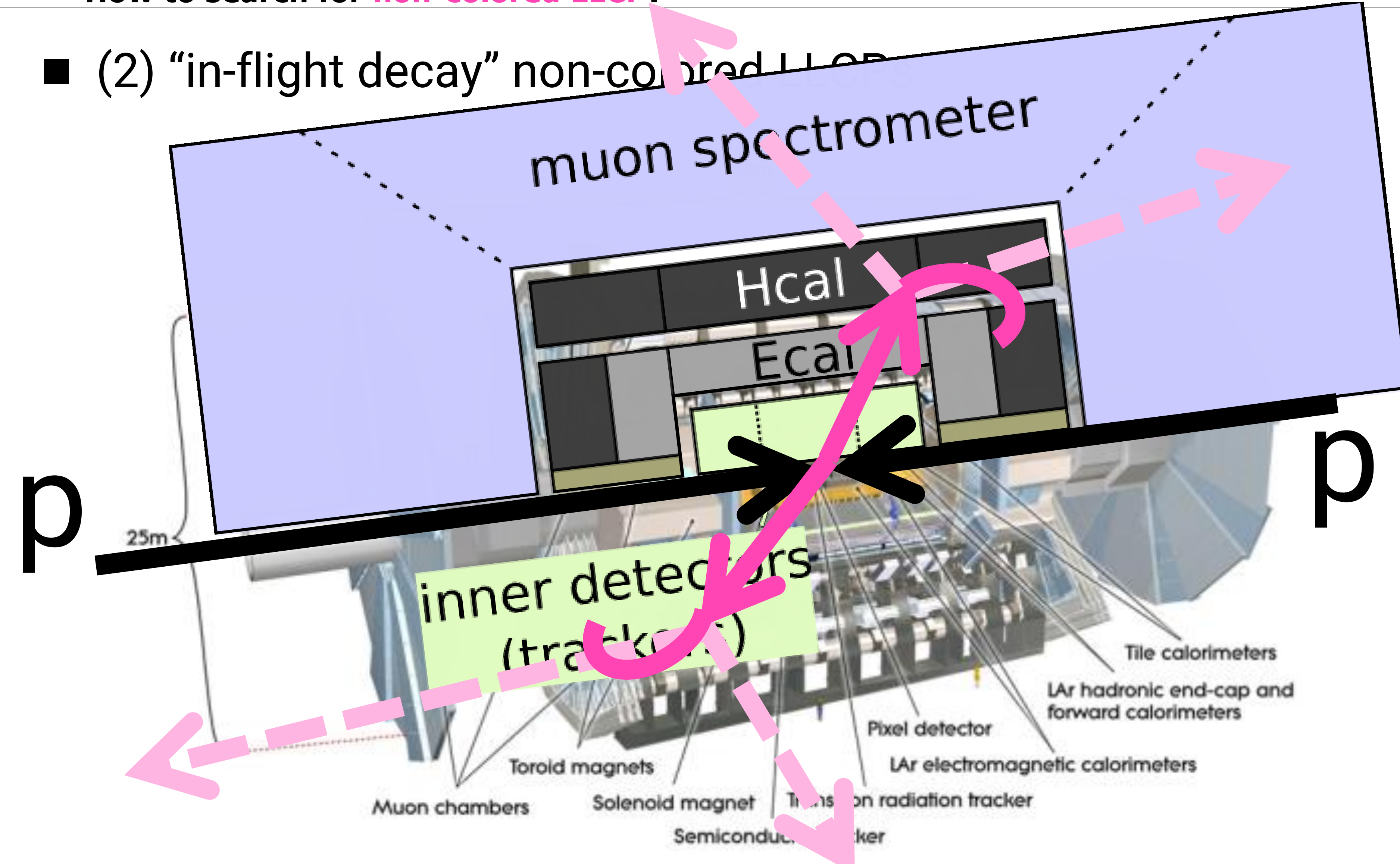

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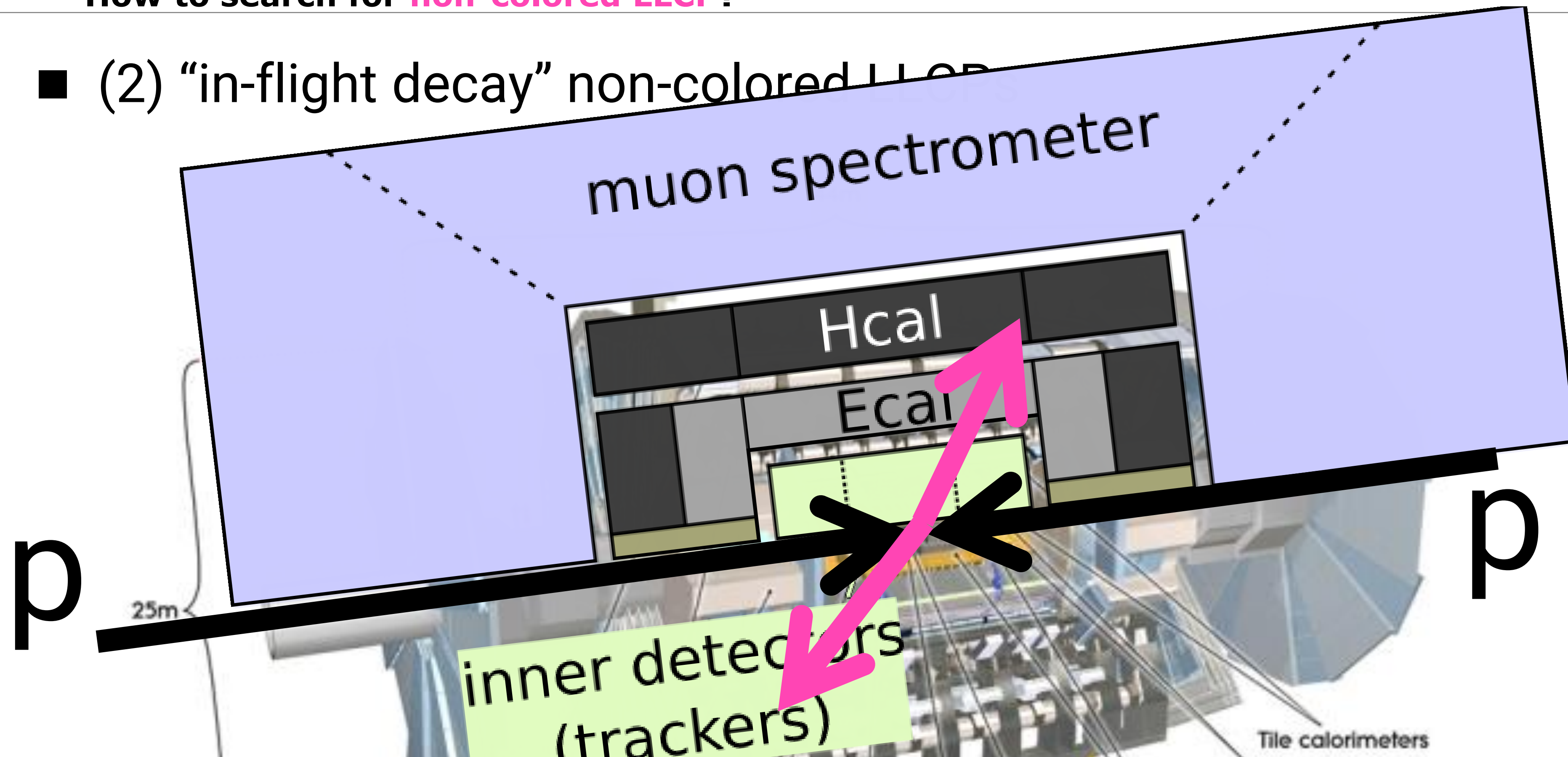
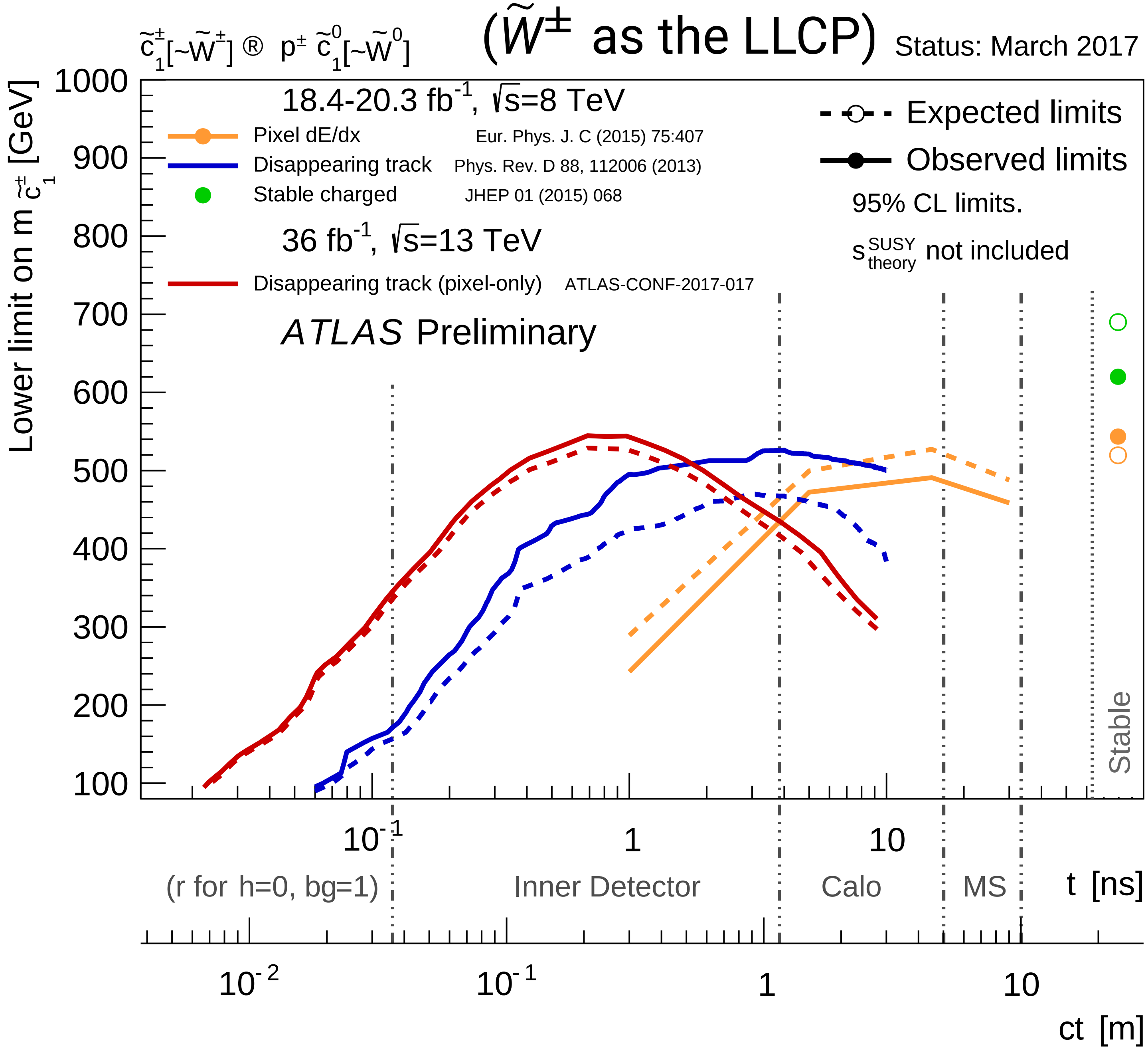


"in-flight decay" LLCPs
= disappearing tracks



c̃±1[~W̃±] ® p± c̃01[~W̃0]
(W̃± as the LLCP)
Status: March 2017
18.4-20.3 fb-1, √s=8 TeV
Pixel dE/dx
Eur. Phys. J. C (2015) 75:407
Disappearing track
Phys. Rev. D 88, 112006 (2013)
Stable charged
JHEP 01 (2015) 068
36 fb-1, √s=13 TeV
Disappearing track (pixel-only)
ATLAS-CONF-2017-017
ATLAS Preliminary
Expected limits
Observed limits
95% CL limits.
σSUSY theory not included
Lower limit on m c̃±1 [GeV]
1000
900
800
700
600
500
400
300
200
100
Stable
10-1
1
10
(τ for η=0, βγ=1)
Inner Detector
Calo
MS
τ [ns]
10-2
10-1
1
10
cτ [m]

1. LLCPs

- Introduction & Motivations
- How to search? & Current bounds

2. Future colliders (FCC-hh and FCC-he)

3. LLCP searches at FCC-hh

4. LLCP searches at FCC-he

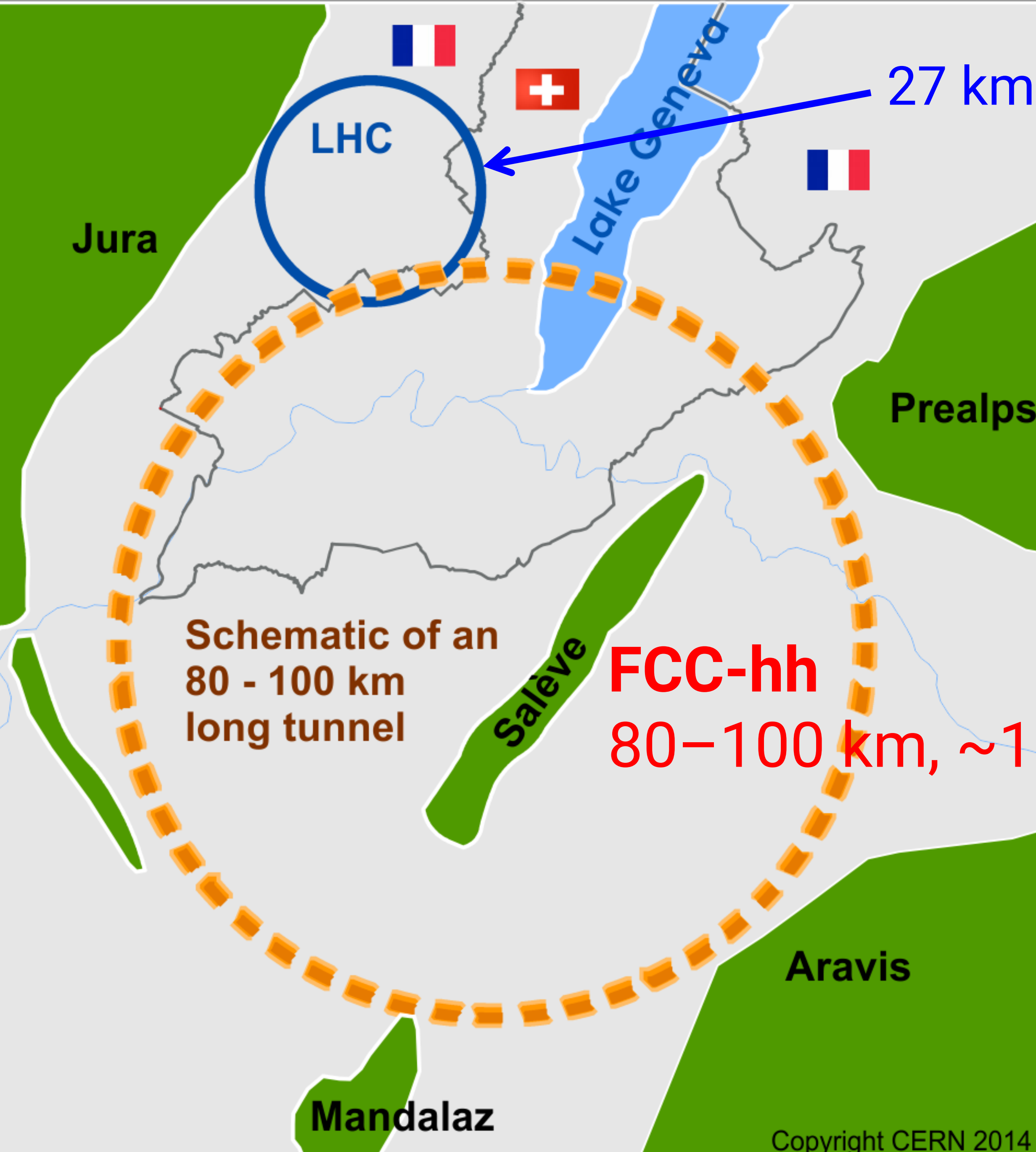
Based on

hh: Jonathan L. Feng, SI, Yael Shadmi, Shlomit Tarem [1505.02996]

(collected in FCC-hh report [1606.00947])

he: Kechen Wang, SI, Monica D'Onofrio, Georges Azuelos [17??.?????]

(subgroup in BSM@ep collaboration)



27 km, 8.3 T, beam = 7 TeV

* **HE-LHC**
  27 km, 16 T
  beam = 13.5 TeV

FCC-hh

80–100 km, ~16 T, beam = 50 TeV

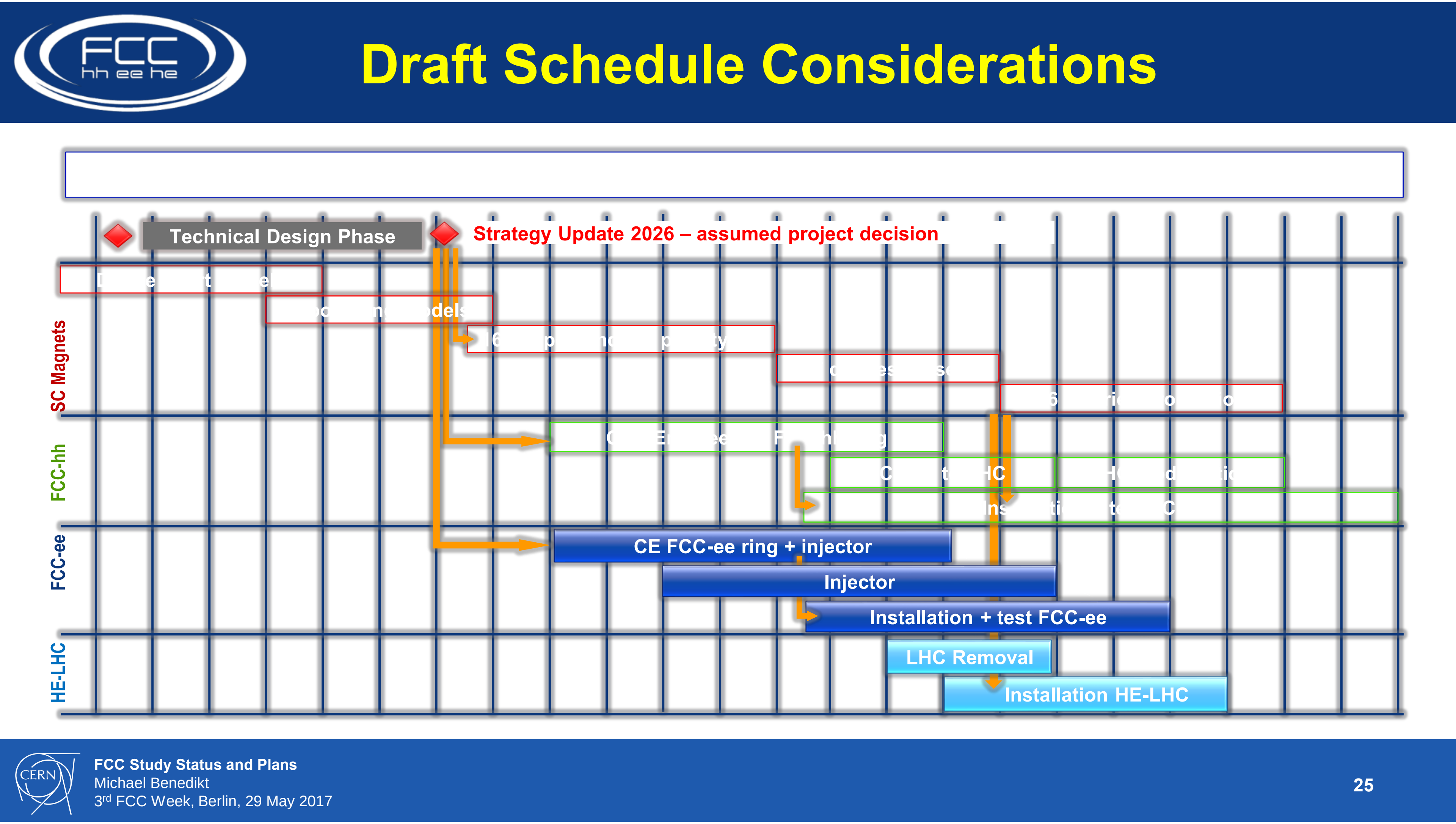
($\int \mathcal{L}$ = 5–10 ab^{-1})

(FCC-ee as a potential first step)

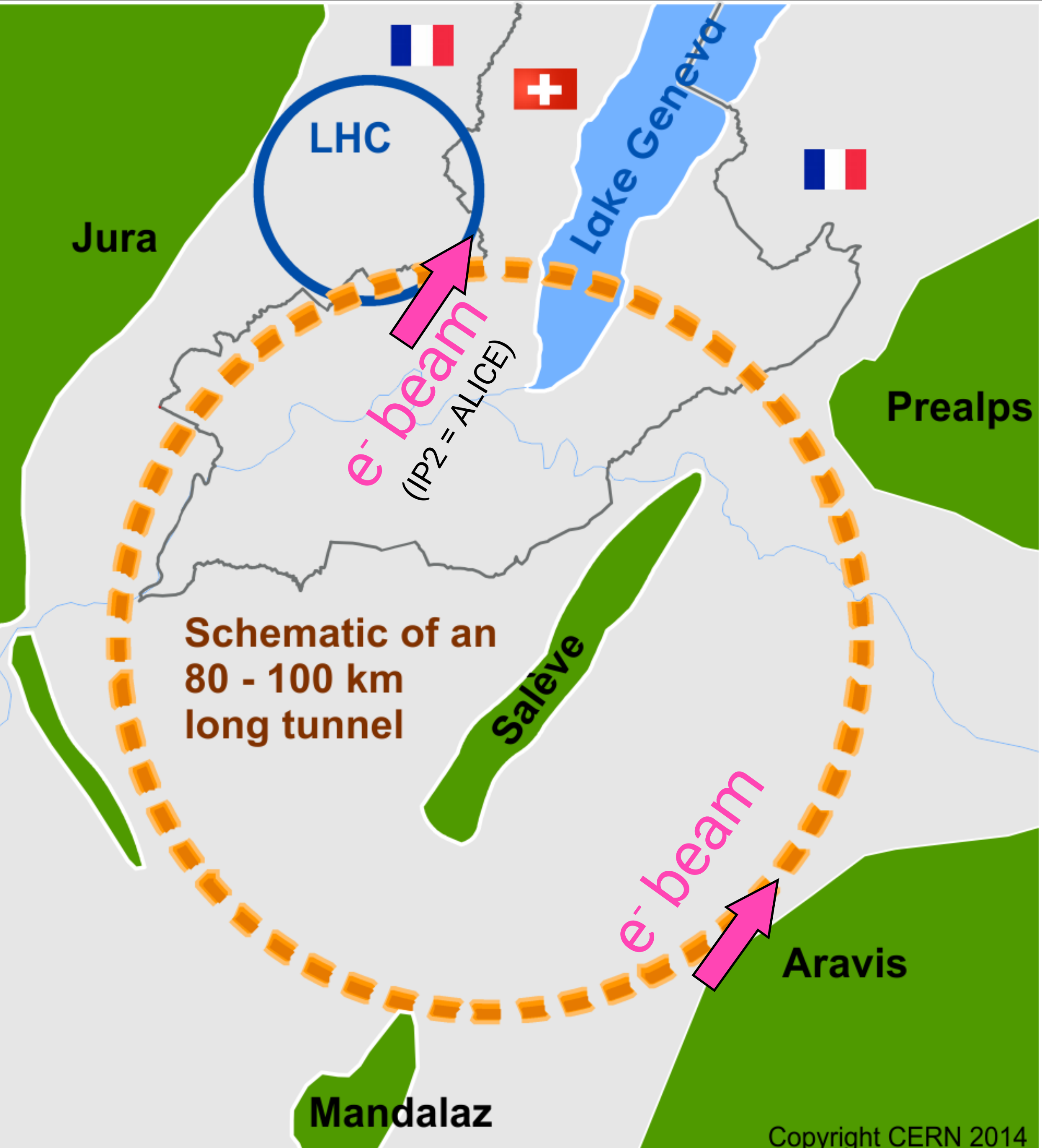
→ CDR in 2018

[conceptual design report]

Magnet R&D: 20+ years



From M. Benedikt's talk @ 3rd FCC Week, 29 May 2017



LHC + e⁻ beam = LHeC

FCC-hh + e⁻ beam = FCC-he

E_e = 60 GeV (140 GeV?)

from "Energy Recovery Linacs"

$\sqrt{s}_{\text{LHeC}} = 2 \times 0.65\,\text{TeV}$

$\sqrt{s}_{\text{FCC-he}} = 2 \times 1.73\,\text{TeV}$

$(\int \mathcal{L}_{\text{FCC-he}} \sim 1\,\text{ab}^{-1})$

- Mar 2015 : FCC week 2015 @ Washington D.C.
- Apr 2016 : FCC week 2016 @ Rome
- Jan 2017 : FCC physics workshop @ CERN
- May 2017 : FCC week 2017 @ Berlin
- Sep 2017 : LHeC/FCC-eh workshop @ CERN
- Jan 2018 : FCC physics workshop @ CERN
- Apr 2018 : FCC week 2018 @ Amsterdam

1. LLCPs

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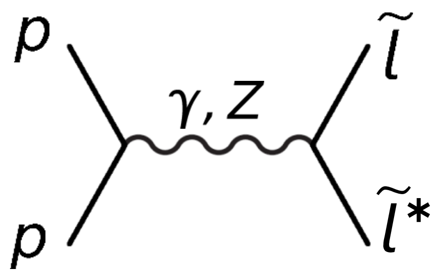
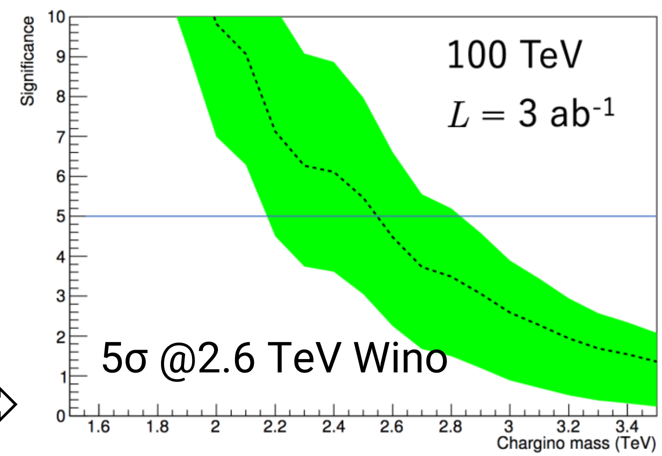
■ LLCPs at FCC-hh $\simeq$ LLCPs at LHC

- ➢ same production mechanism; just with a higher energy.
  - e.g., $\tilde{l}$ → Drell−Yan process (or from cascade decay)





[R. Sawada's talk in FCC week 2017]

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    - $\Delta L/\Delta t$ (time-of-flight)

- ➢ Two extras:
  - muon radiative energy loss
  - LLCP momentum resolutions

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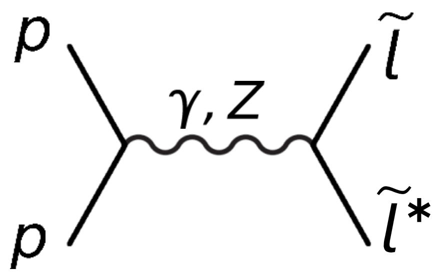

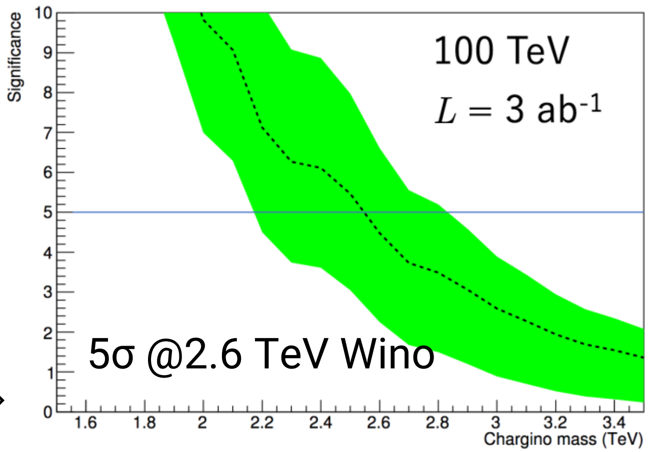

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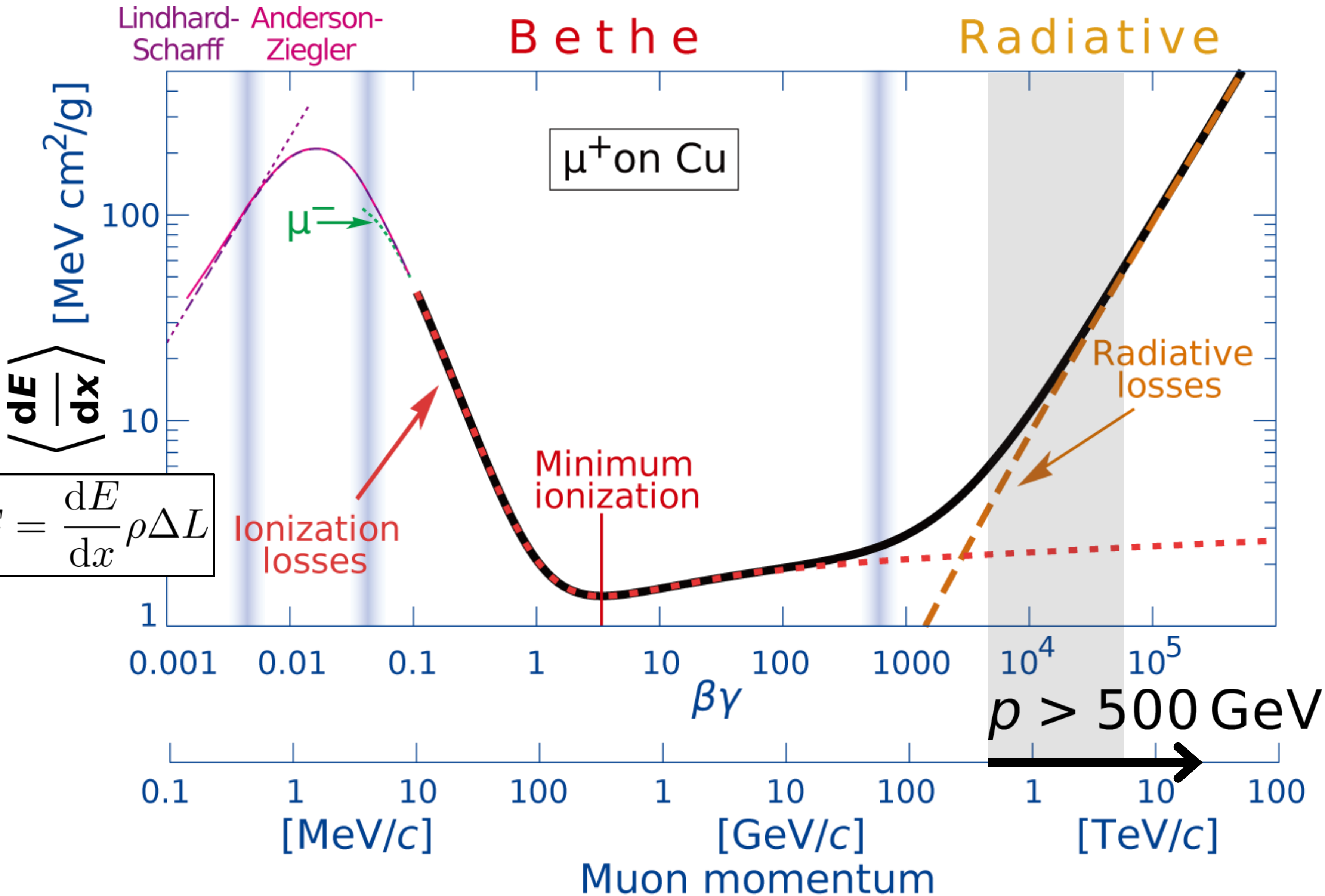

$$\Delta E = \frac{\mathrm{d}E}{\mathrm{d}x}\rho\Delta L$$

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

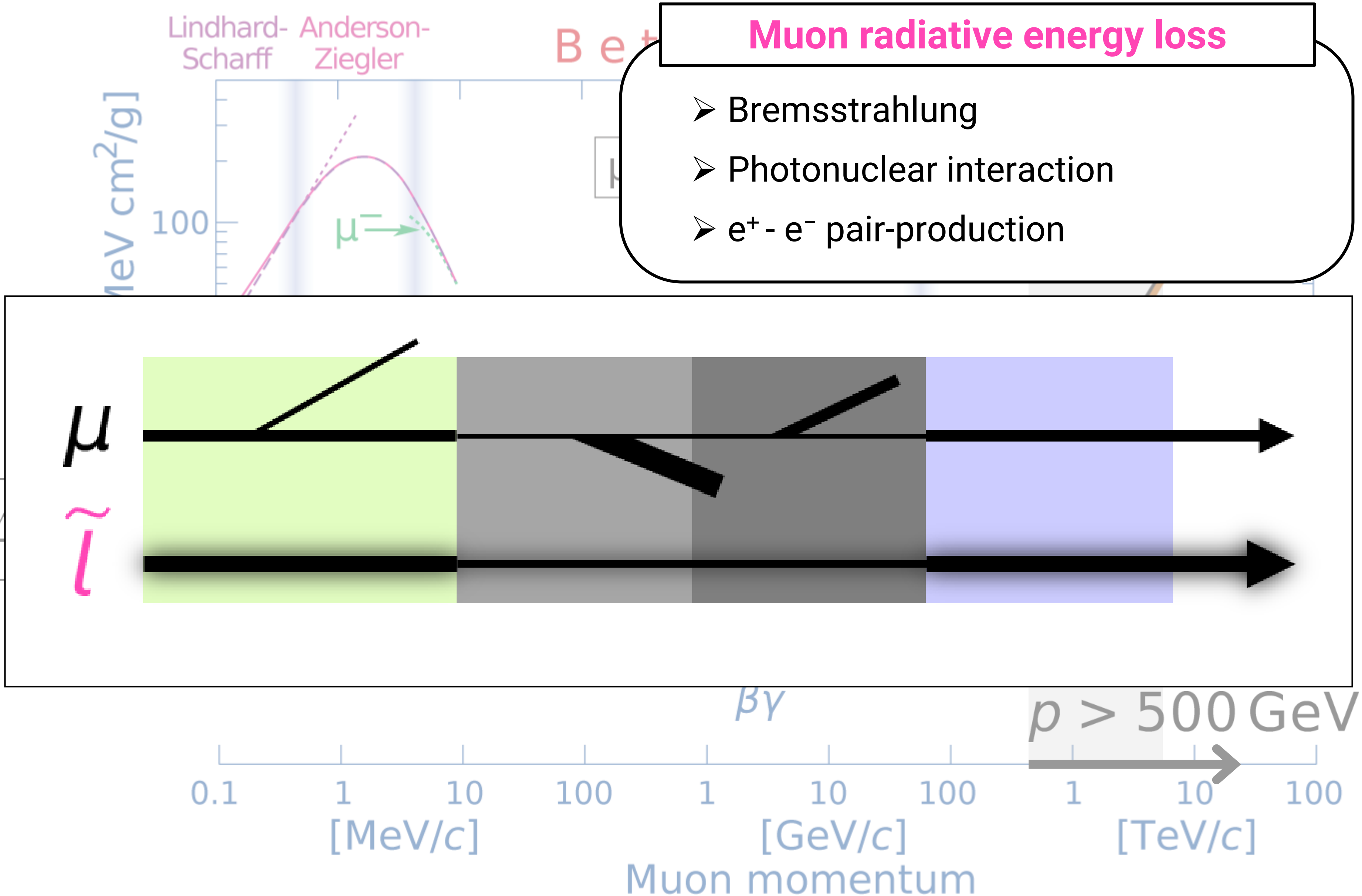

Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
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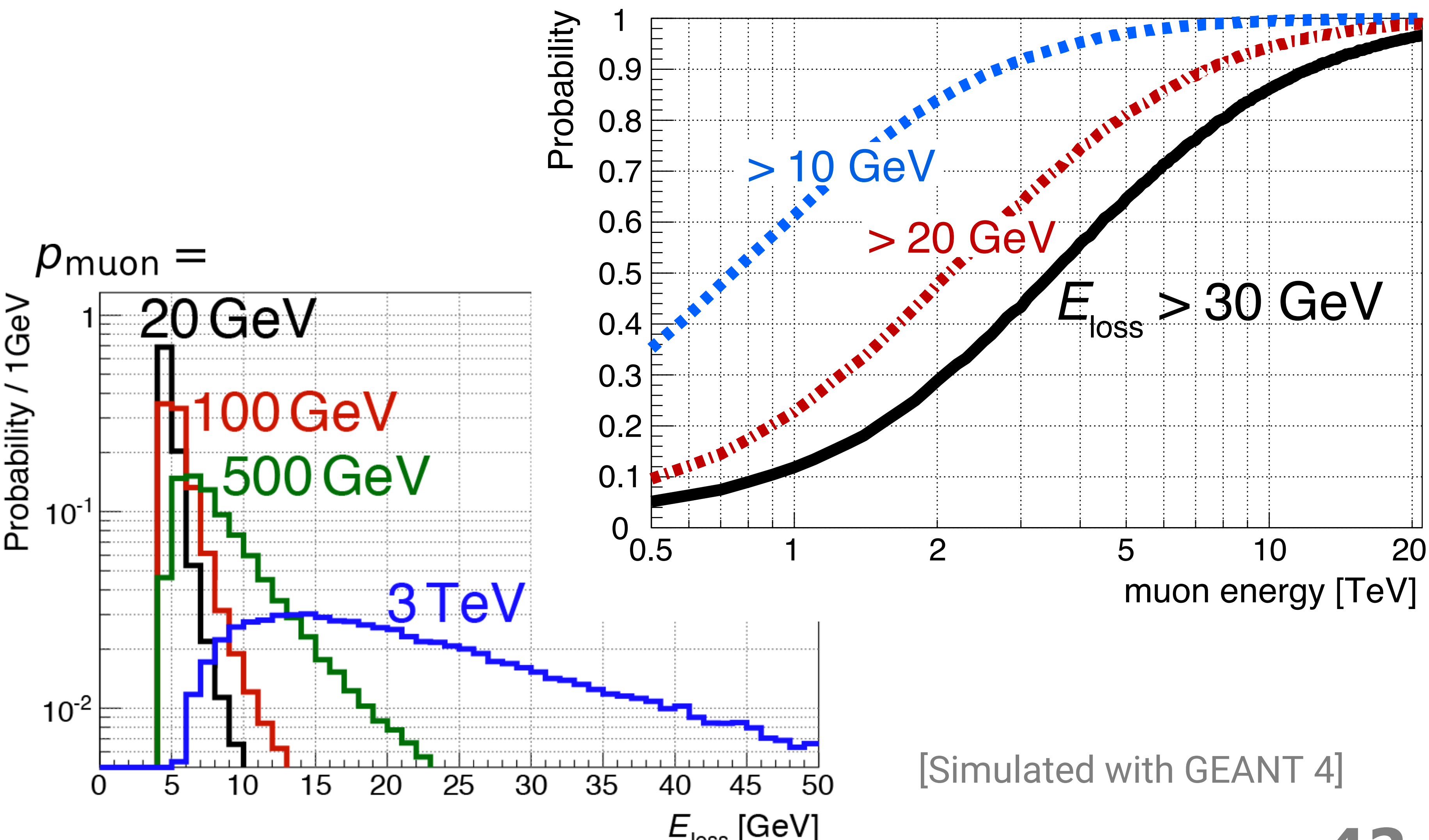
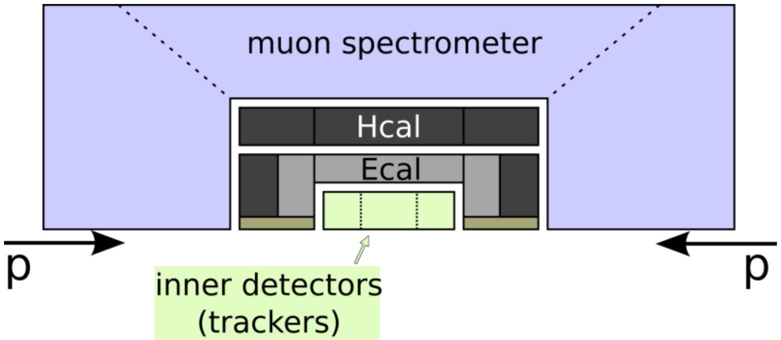
“calorimeter”: approximated by iron (Fe) with 3m thickness.

→ 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

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

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

- 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	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
$(\because\ 0.82^2 = 0.66)$

- $|\eta| < 2.4$
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- $E_{\mathrm{loss}} < 30\,\mathrm{GeV}$

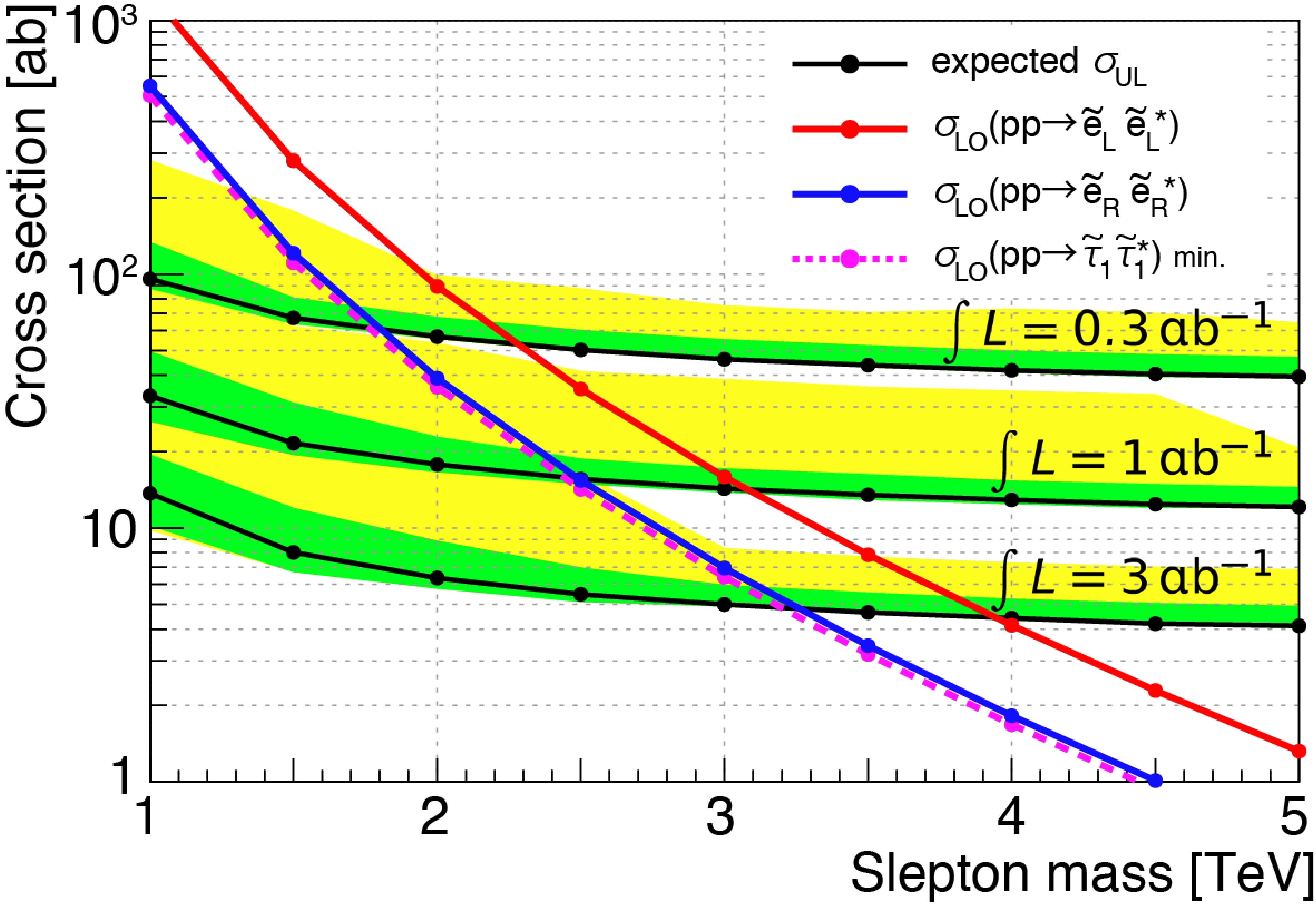
Event categorization $(\int L = 1\,\mathrm{ab}^{-1})$

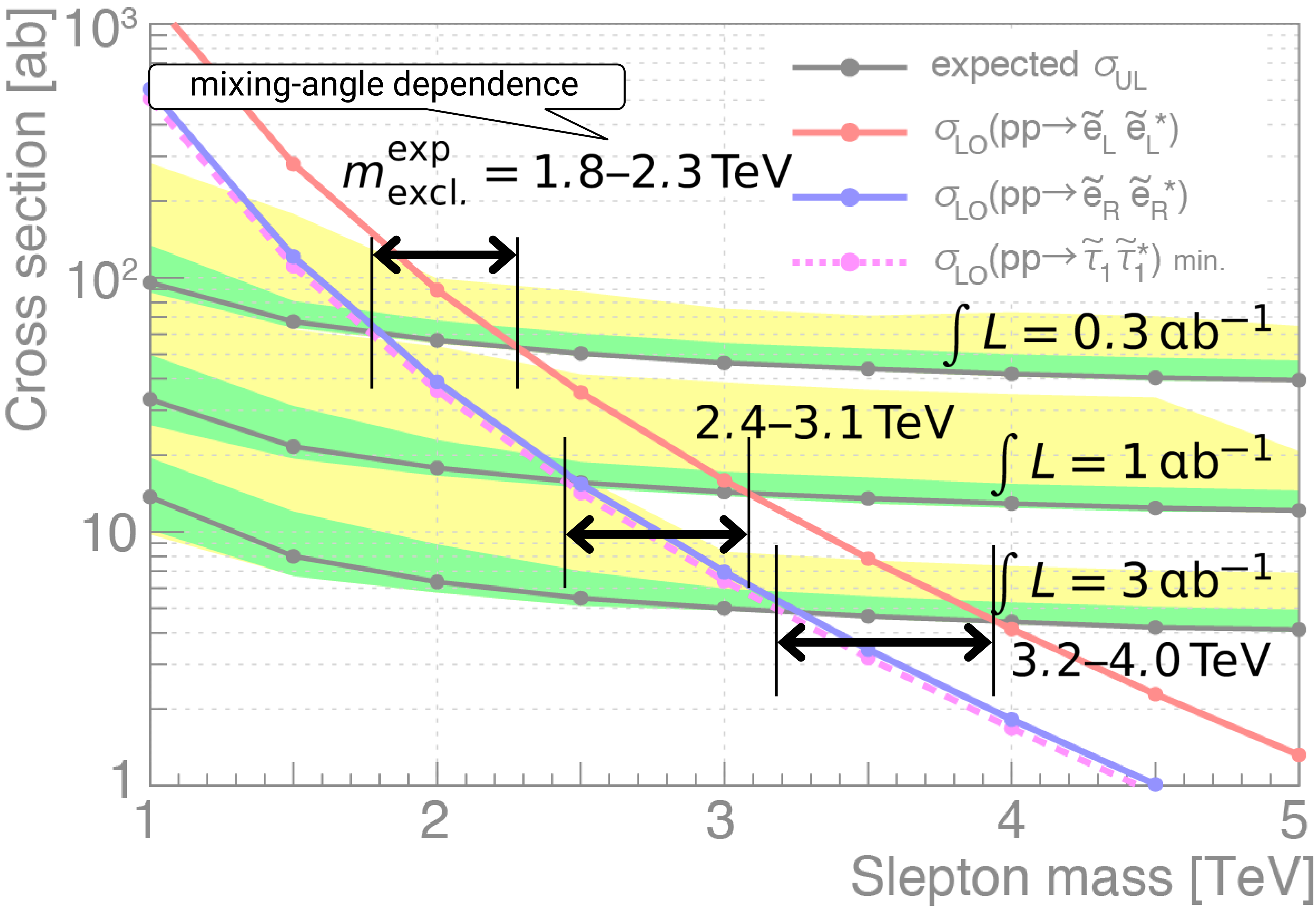
	1 TeV	3 TeV	BKG
$N_{\mathrm{LLCP}} = 0$	483	1.34	(a lot)
$N_{\mathrm{LLCP}} = 1$	378	4.46	2.78×10^5
$N_{\mathrm{LLCP}} = 2$	424	10.1	34.6

SR

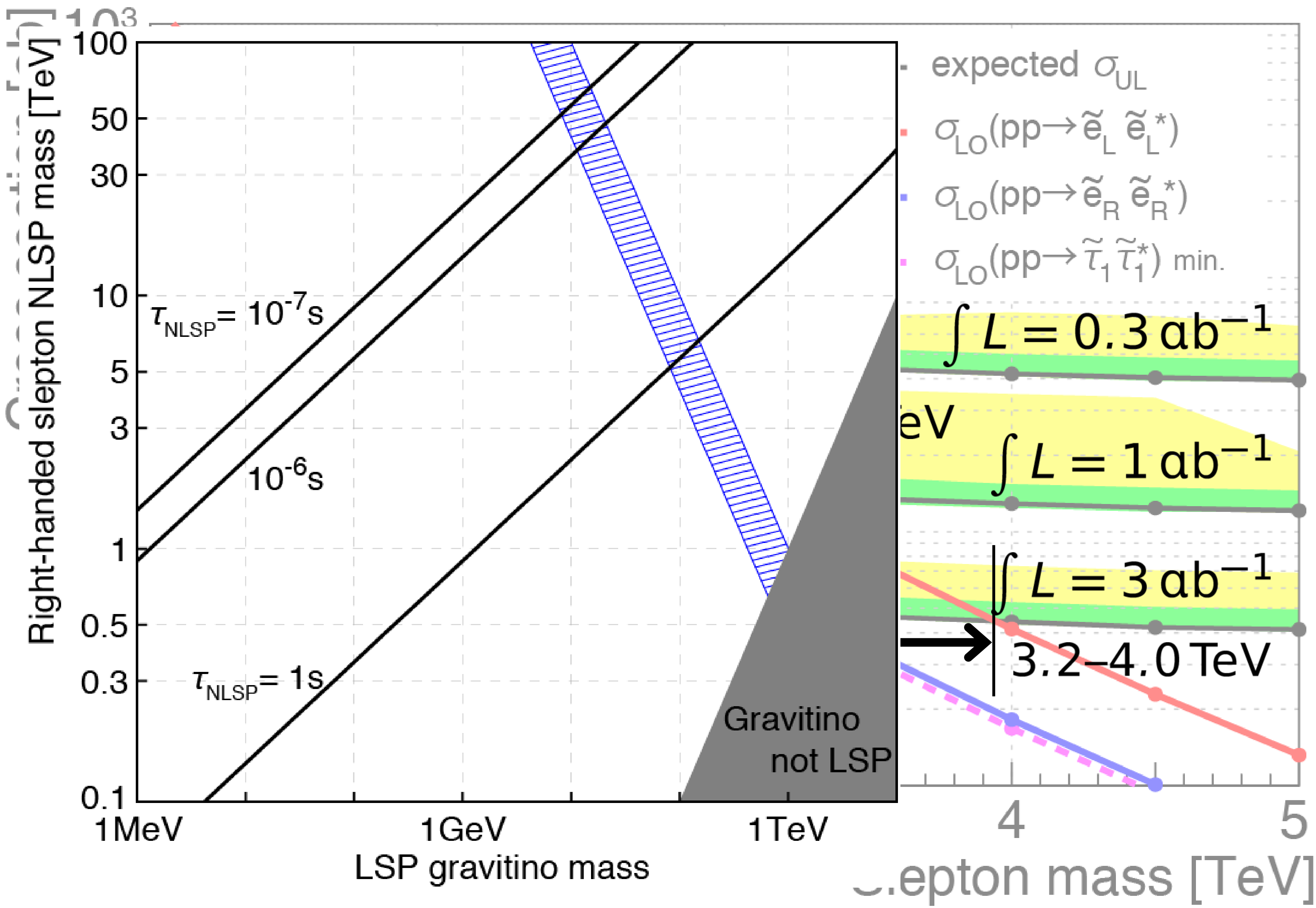
- Event selection
  - two $\tilde{l}$-candidates

Feng, SI, Shadmi, Tarem [1505.02996]




Cross section [ab]
10³
10²
10
1
mixing-angle dependence
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.
$m^{\rm exp}_{\rm excl.} = 1.8\text{–}2.3$ TeV
2.4–3.1 TeV
3.2–4.0 TeV
$\int L = 0.3\,{\rm ab}^{-1}$
$\int L = 1\,{\rm ab}^{-1}$
$\int L = 3\,{\rm ab}^{-1}$
1
2
3
4
5
Slepton mass [TeV]

 Feng, SI, Shadmi, Tarem [1505.02996]



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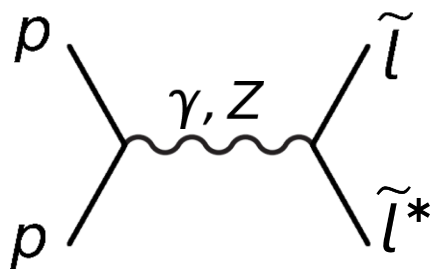

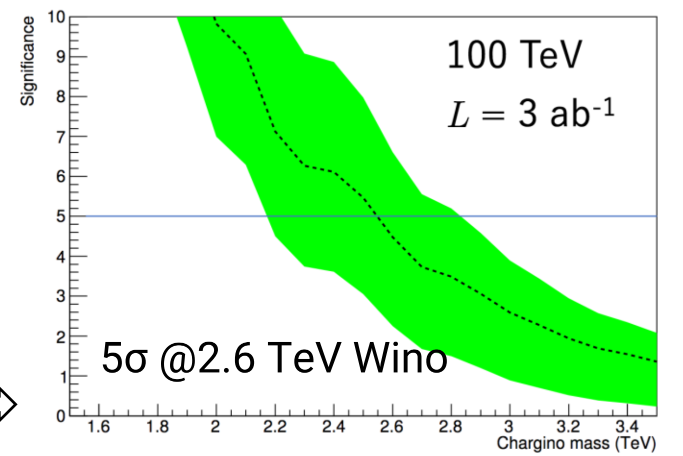

[Ryu Sawada's talk in FCC week 2017]

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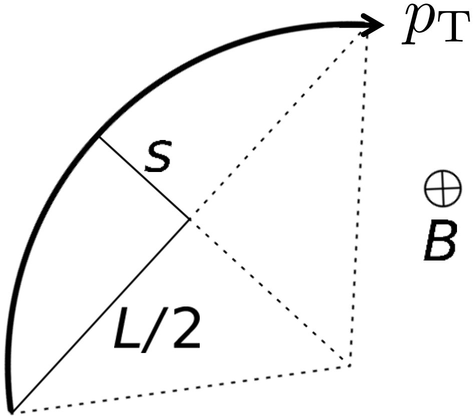
  - **LLCP momentum resolutions**

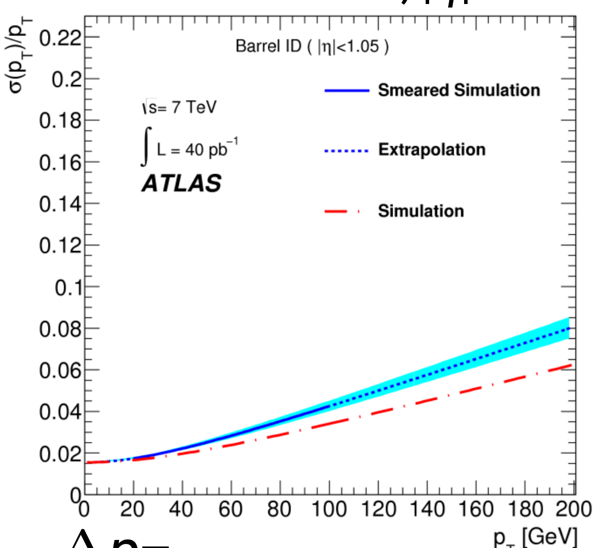


$$p_{\mathrm{T}} = \frac{L^2}{8s}|q|B \Longrightarrow \Delta p_{\mathrm{T}} = \frac{L^2|q|B}{8}\frac{\Delta s}{s^2} = \frac{8\Delta s}{L^2|q|B}\cdot p_{\mathrm{T}}^2$$

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

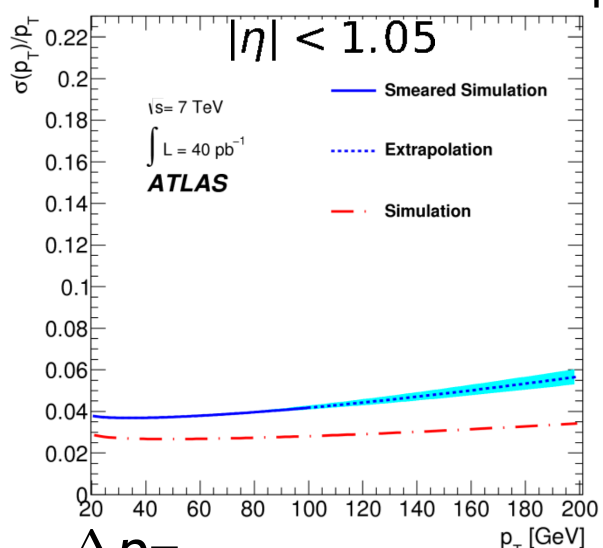
ATLAS 7 TeV results on muon momentum resolution

Inner Detector, $|\eta|<1.05$

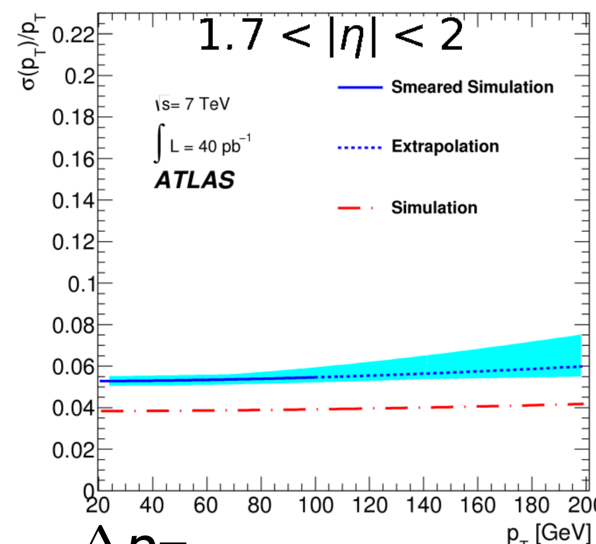


$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.38 p_{\mathrm{T}}/\mathrm{TeV}$$

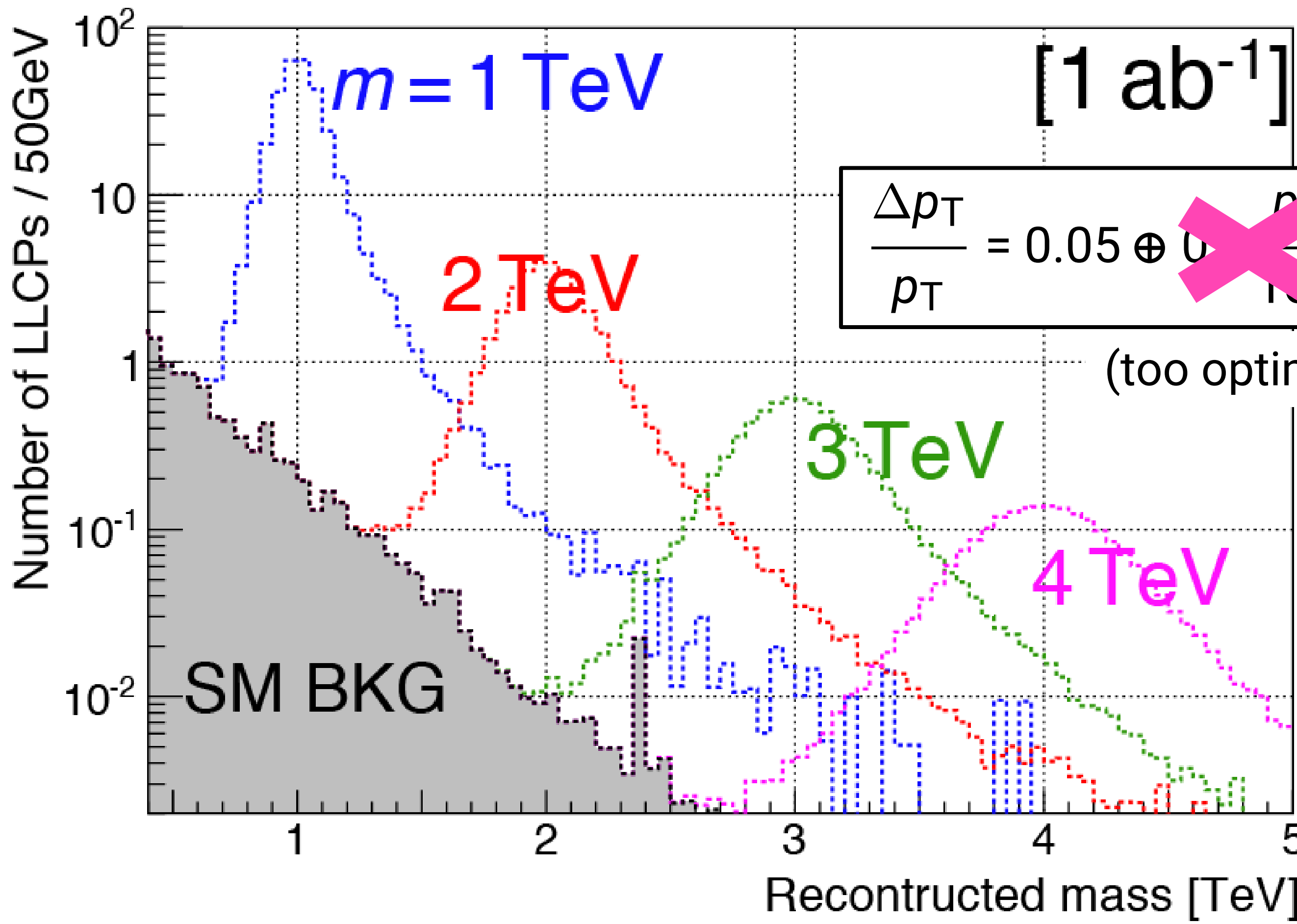
Muon Spectrometer



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



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



$\frac{\Delta p_T}{p_T} = 0.05 \oplus 0.\ldots \frac{p_T}{\text{TeV}}$ (too optimistic)

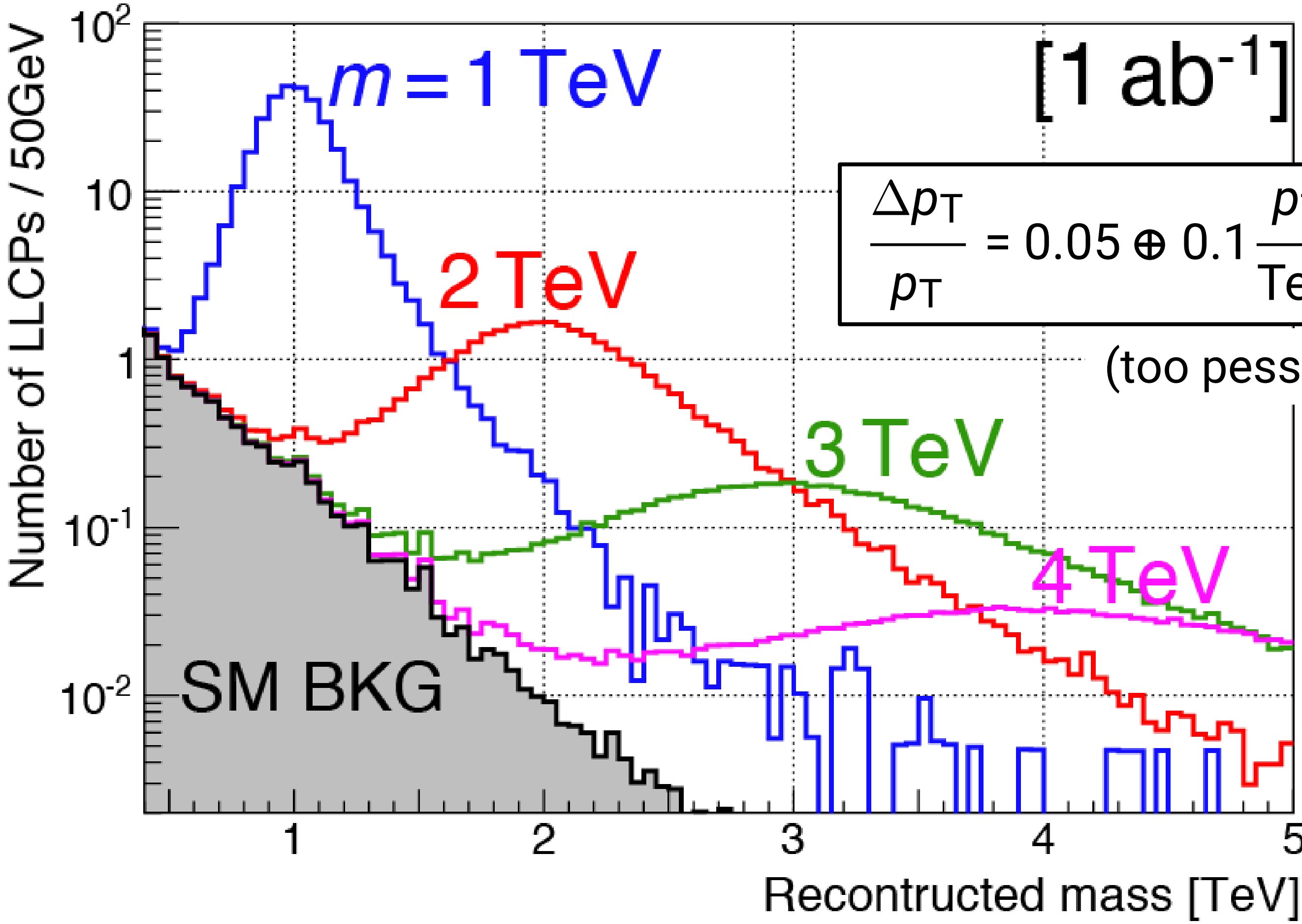
$\left(= \frac{p}{\beta\gamma} = \frac{p_T \cosh\eta}{\beta\gamma} \right)$

FCC-hh trk. goal: 10–20% @ 10 TeV

(Michele Selvaggi's talk in FCC physics workshop)

cf. ATLAS 7 TeV commissioning:

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



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

(too pessimistic?)

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

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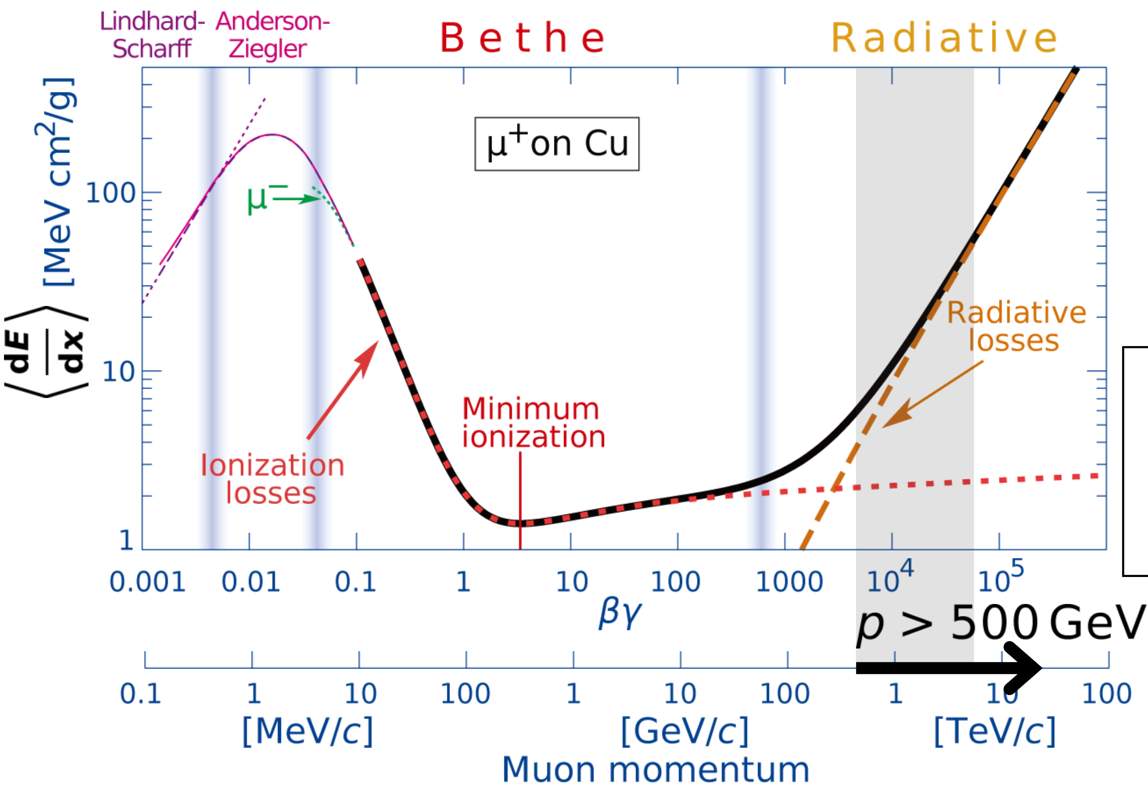
- 100 TeV FCC-hh mass reach (Drell–Yan $\tilde{l}$ or $\tilde{\tau}$)

	$0.3ab^{-1}$	$1ab^{-1}$	$3ab^{-1}$
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"**



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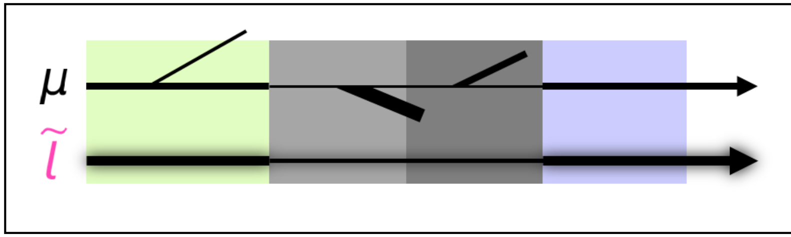

→ **34%** of BKG reduction

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   - **Introduction & Motivations**
   - **How to search? & Current bounds**
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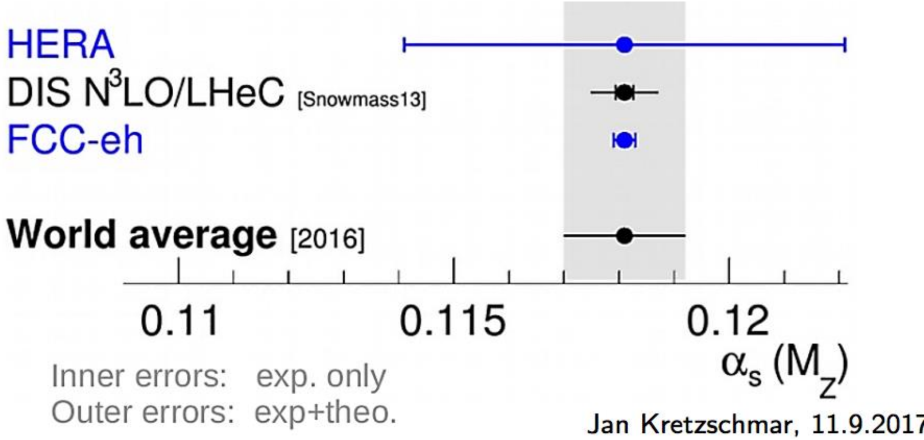
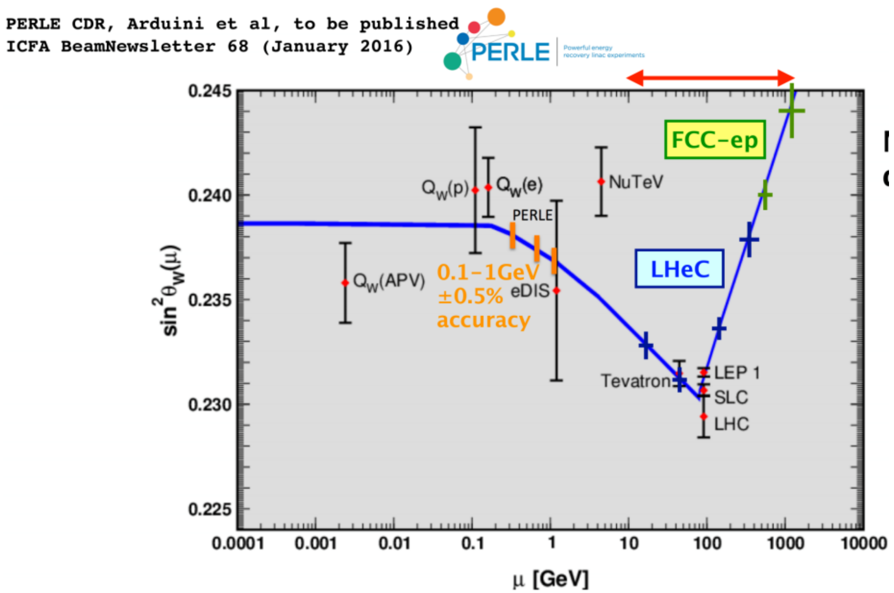
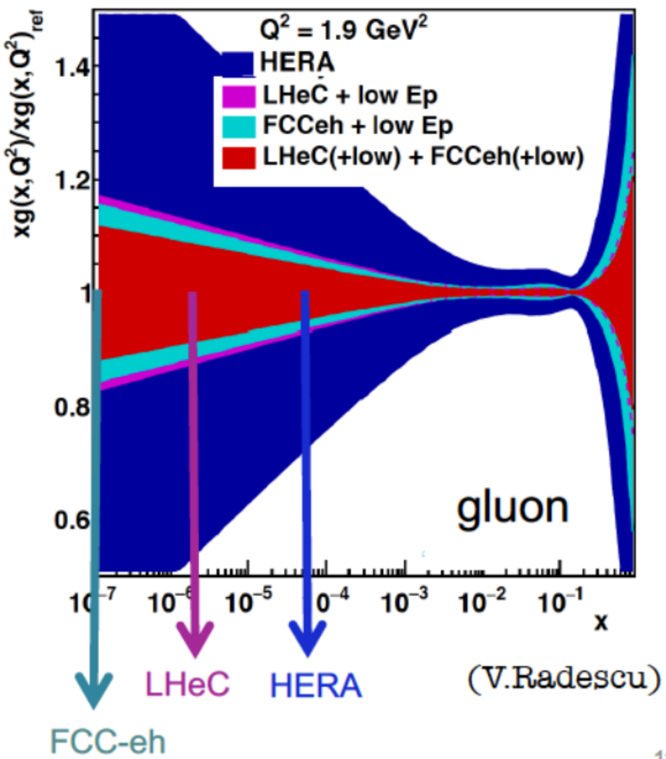
(subgroup in BSM@ep collaboration)

- FCC-he targets:
  - **PDFs & strong coupling**
  - Higgs & Electroweak physics
  - QCD (heavy quark PDFs)
  - low-*x* physics (non-linear QCD?) : $x < 10^{-6}$







- What's MORE?

Any power to New Physics? → BSM ep team

- BSM ep team

★ Direct Searches

- Leptoquarks: limits, quantum # & couplings
- Contact interactions: eeqq
- Anomalous gauge couplings: VVV
- Vector boson scattering
- BSM in the top sector
- RPC SUSY: DM, sleptons
- RPV SUSY: neutralinos, squarks
- BSM Higgs: exotic (invisible) decay; H^+, H^{++}
- Sterile neutrinos

[from a talk by Kechen Wang @ FCC week 2017]

- Dark Mattter
  - 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

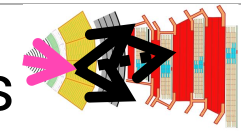
  $\tilde{\tau}$-LLCP

  - super-WIMP scenario
    → $\tilde{l} >$ O(1) TeV

  $\tilde{l}$-LLCP

- Li problem
  - MSSM $\tilde{\tau}$ with
    $m_{\tilde{\tau}} \sim 400$ GeV
    $\Delta(m_{\tilde{\tau}} - m_{\text{LSP-DM}}) \sim 100$ MeV

  $\tilde{\tau}$-LLCP



- Simple MSSM models
  - Pure-Wino dark matter **60mm**
  - Pure-Higgsino dark matter **7mm**

⇩

$\tilde{\chi}^{\pm}$ long-lived because of small δm
($\delta m > 0$)

(but DM underabundant
for "observable" region)

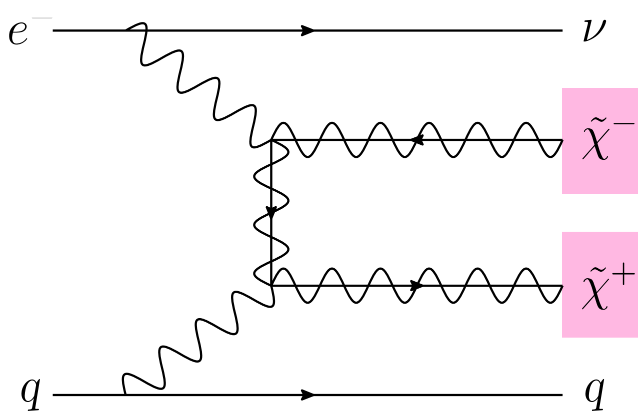
- Other MSSM models
  - Gauge-Mediation (keV $\tilde{G}$)
  - R-parity violation

with $\tilde{l}$ -LSP

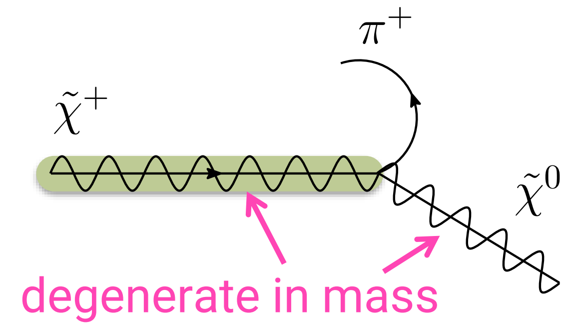
⇨ $\tilde{l}$ long-lived **any cτ**
because of tiny couplings.

However, the simplest scenarios have tiny cross sections; less promising than LHC.

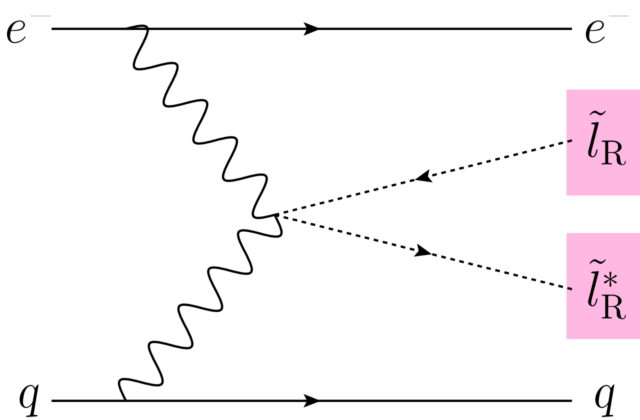
- Simplest models: 4-body production; $\sigma < 1$ fb … (´・ω・`)
  - Pure-Wino / Pure-Higgsino LSP



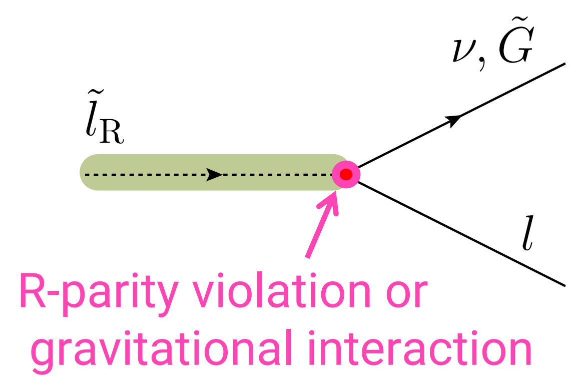
disappearing track



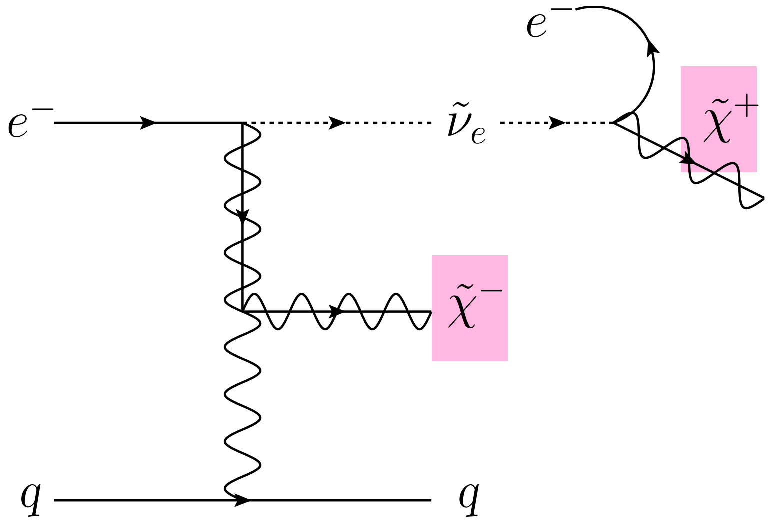
  - Slepton LSP



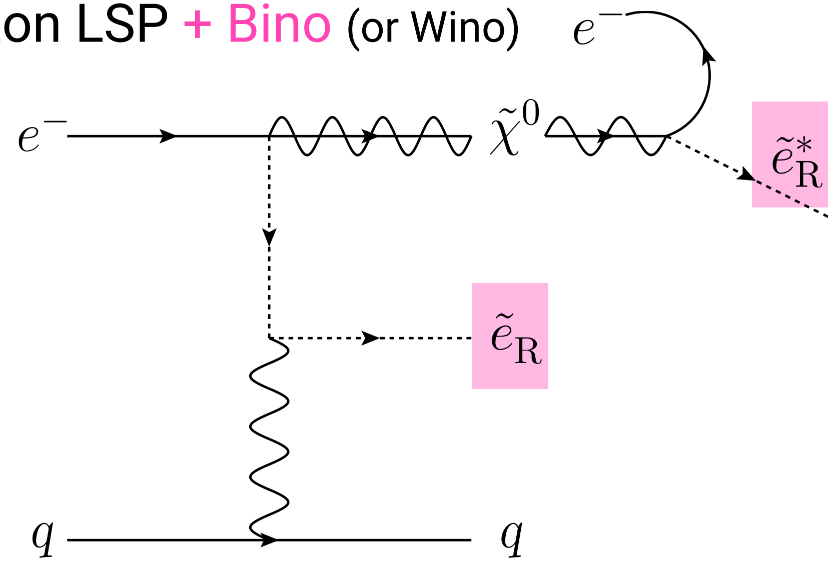
disappearing track (or "kink")



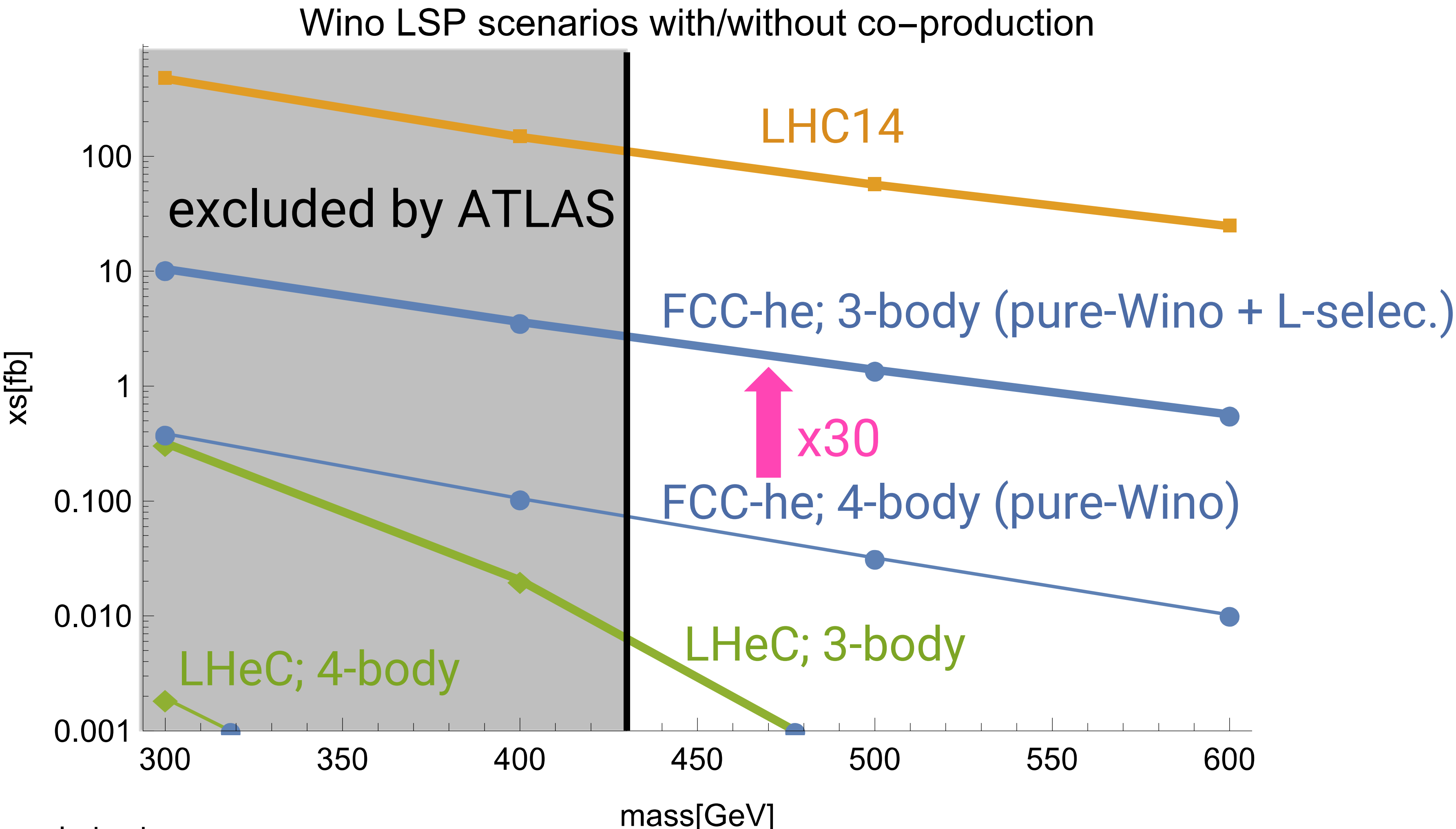
- Introducing co-LSP allows **3-body** production
  - Pure-Wino ~~/ Pure-Higgsino LSP~~ + left-handed selectron



  - Slepton LSP + Bino (or Wino)



- **Nominal production cross section** (without acceptances / efficiencies)

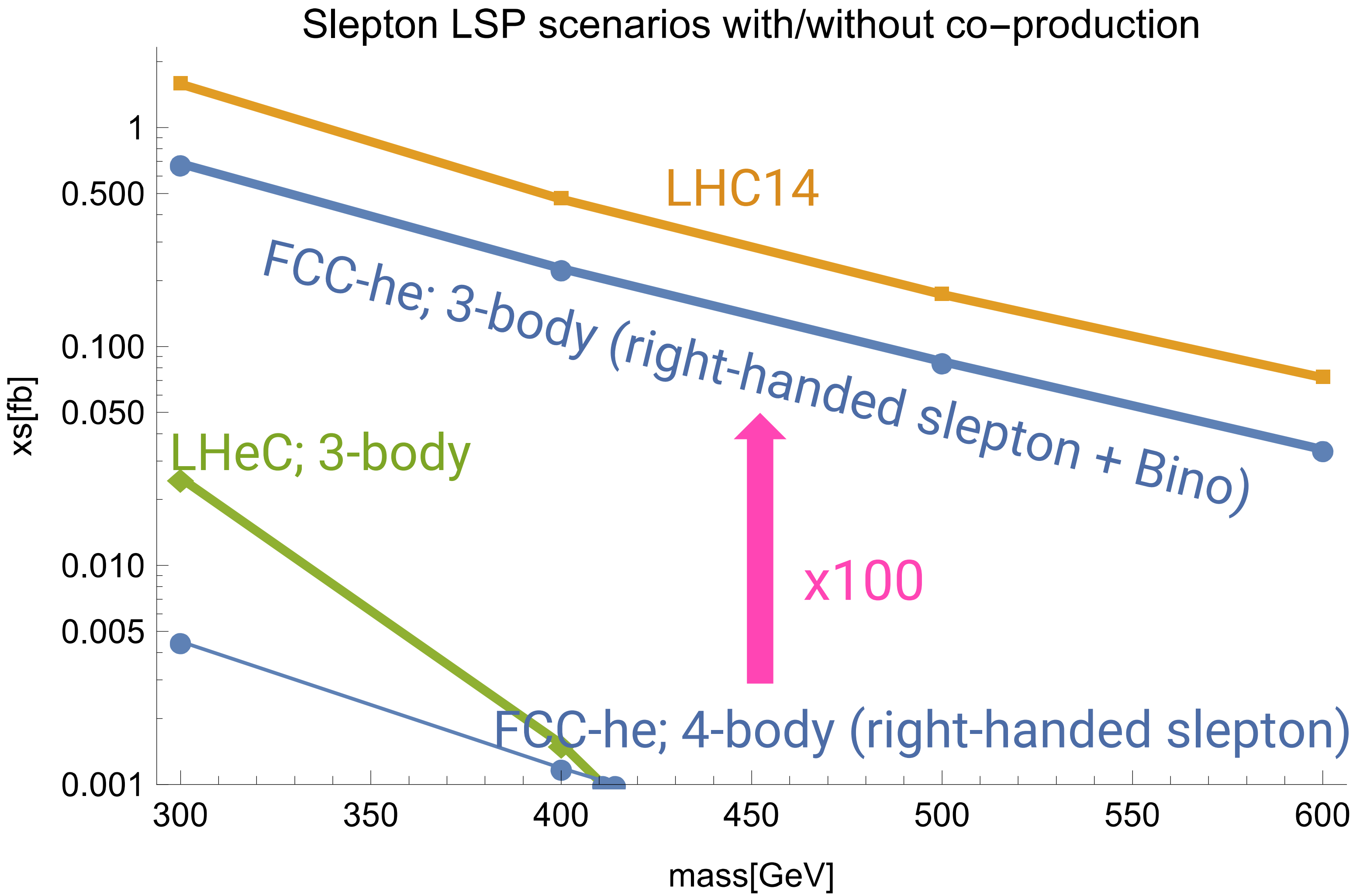


With no polarization.

Shaded region is excluded by ATLAS (13TeV, 36/fb)

"3-body" model assumes $m_{\tilde{e}_\mathrm{L}} = m_{\tilde{\chi}_1^0} + 9$ GeV

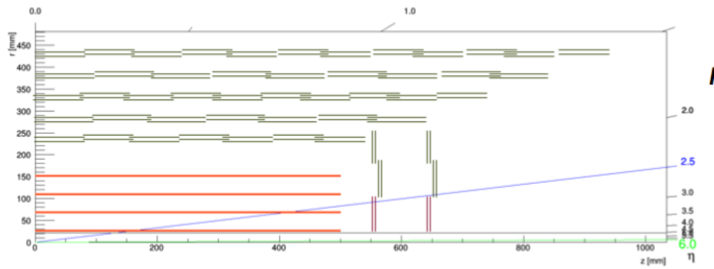
- Nominal production cross section (without acceptances / efficiencies)

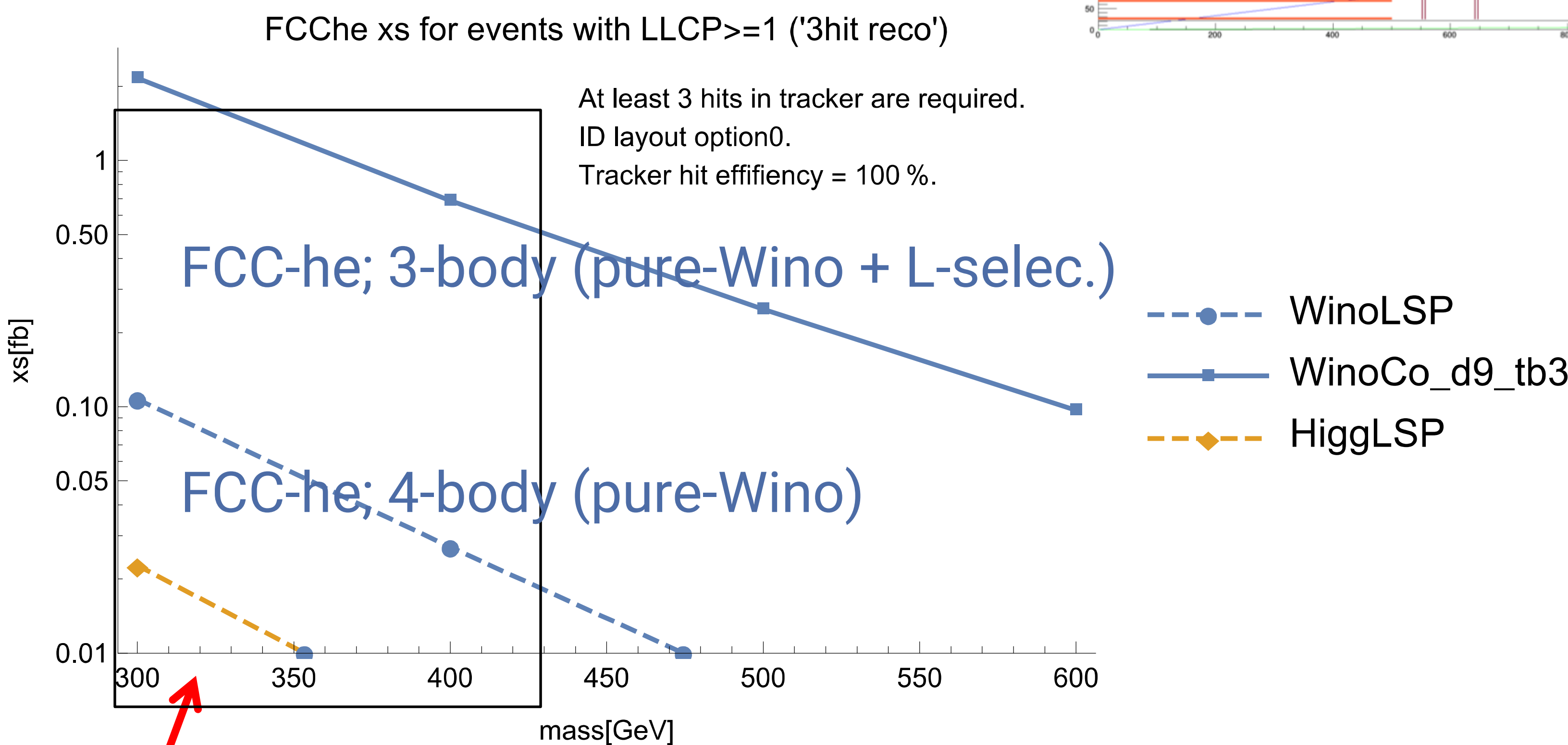


With no polarization.

"3-body" model assumes $m_{\tilde{\chi}_1^0} = m_{\tilde{e}} + 1\,\mathrm{GeV}$

LLCPs are required to decay after 3 layers of IDs.
(=~ to leave 3 hits in ID)





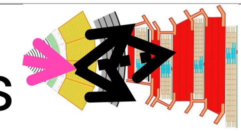
Higgsino-only scenario: less promising because of smaller $c\tau$.

With no polarization.

Shaded region is excluded by ATLAS (13TeV, 36/fb)

"3-body" process assumes $m_{\tilde{e}_L} = m_{\tilde{\chi}_1^0} + 9$ GeV.

- **"Wino+slep" model is promising.**
- **reco eff. is governed by the innermost layers**
  → closer / more-precise layers would help a lot.



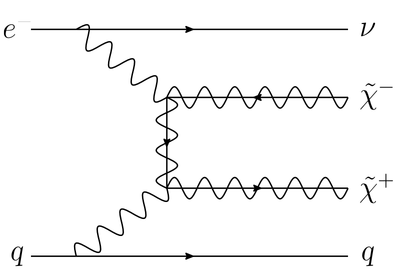
"single SUSY particle"

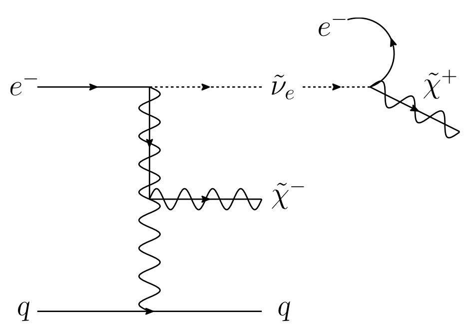
→ tiny σ due to 4-body process; HL-LHC will be better.

If with another sparticle for **3-body "co-production"**

→ FCC-he will be competitive with HL-LHC.

- Pure-Wino LSP + $\tilde{e}_L$
- Slepton LSP + Bino (or Wino)





- Simple MSSM models
  - Pure-Wino dark matter **60mm**
  - ~~Pure-Higgsino dark matter **7mm**~~

lifetime too short

→ trying to improve by identifying daughter particles…

- Other MSSM models
  - Gauge-Mediation (keV $\tilde{G}$)
  - R-parity violation

with $\tilde{l}$ -LSP

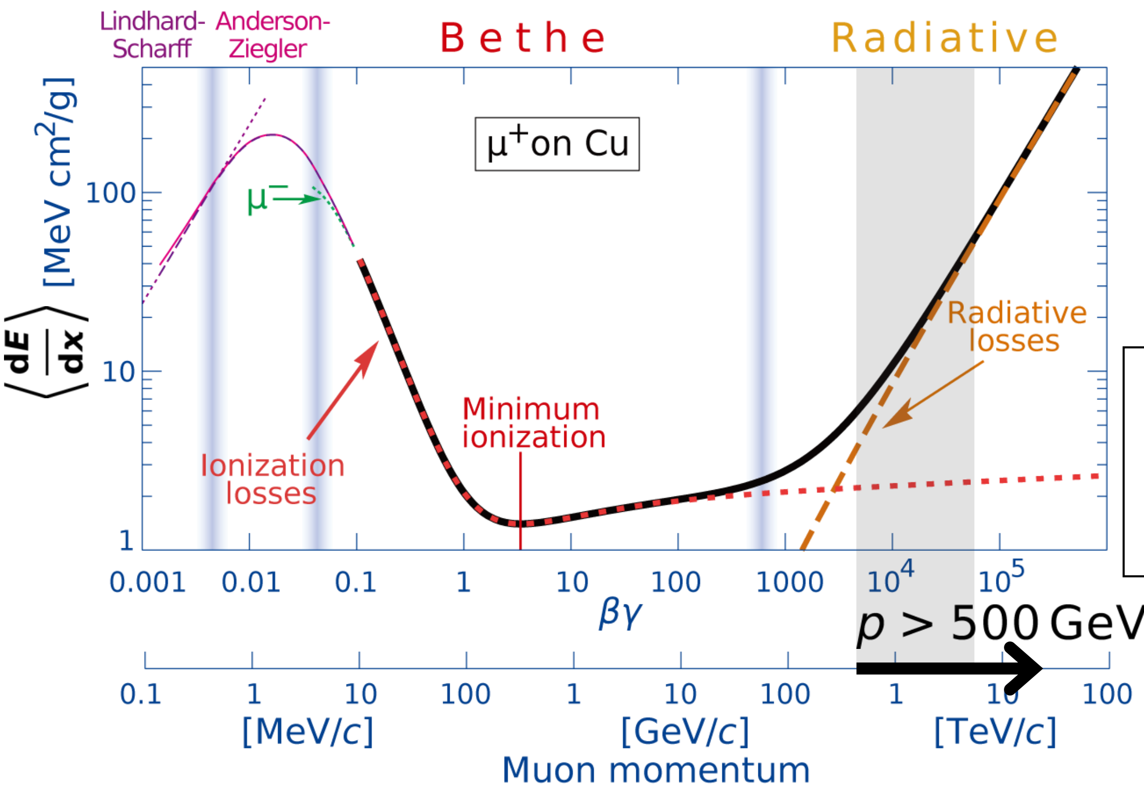
any $c\tau$

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

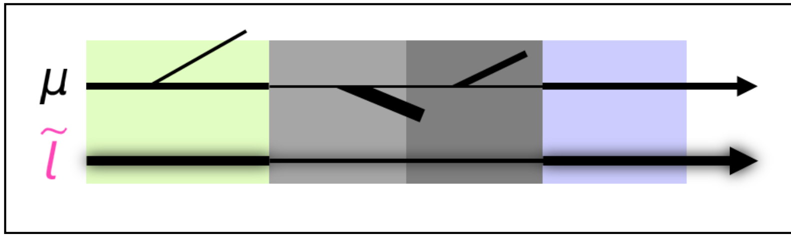
	$0.3ab^{-1}$	$1ab^{-1}$	$3ab^{-1}$
Exclusion	1.8–2.3	2.4–3.1	3.2–4.0
Discovery	1.6–2.2	2.3–3.0	3.1–4.0

in TeV

- **"Muon radiative energy loss"**

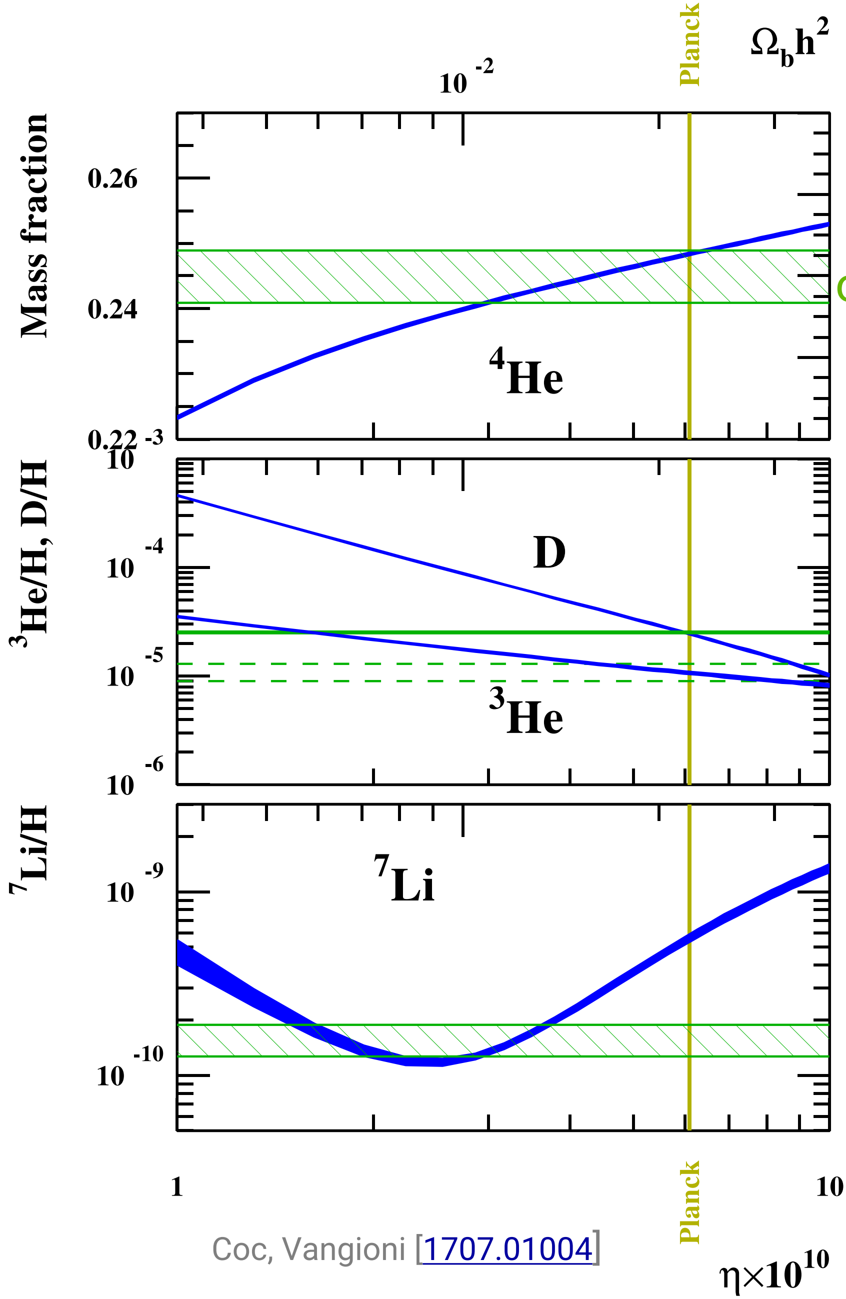


- Bremsstrahlung
- Photonuclear interaction
- e^+-e^- pair-production



→ **34%** of BKG reduction

Lithium problem



BBN theory
observation

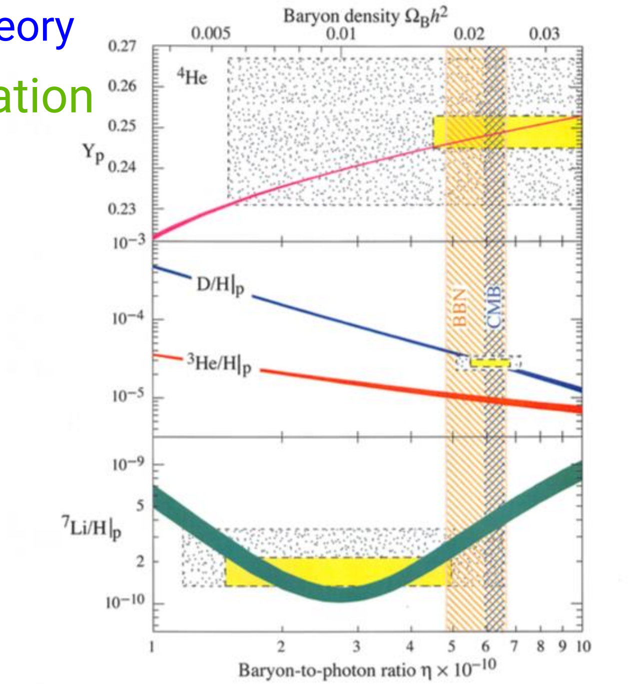


Figure 20.1: The abundances of ^{4}He, D, ^{3}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis — the bands show the 95% CL range. Boxes indicate the observed light element abundances (smaller boxes: $\pm2\sigma$ statistical errors; larger boxes: $\pm2\sigma$ statistical *and* systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN concordance range (both at 95% CL). Color version at end of book.

Coc, Vangioni [1707.01004]

- Dark Matter (especially to am...)
  - 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

    Harigaya, Kaneta, Matsumoto [1403.0715], Ellis, Olive, Zheng [1404.55..] etc.
  - super-WIMP scenario
    → $\tilde{l} > O(1)$ TeV (as we see soon.)

non-colored LLCP

… covered in this talk

(slepton $\tilde{l}$ / stau $\tilde{\tau}$ as benchmarks)

[1606.00947]

colored LLCP

(→ hadronize: "R-hadron")

- Li problem
  - MSSM $\tilde{\tau}$ with
    $m_{\tilde{\tau}} \sim 400$ GeV
    $\Delta(m_{\tilde{\tau}} - m_{\text{LSP-DM}}) \sim$

"Extrapolations"

$\tilde{g}$(-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(?)

Why β>0.4? (slepton dE/dx)

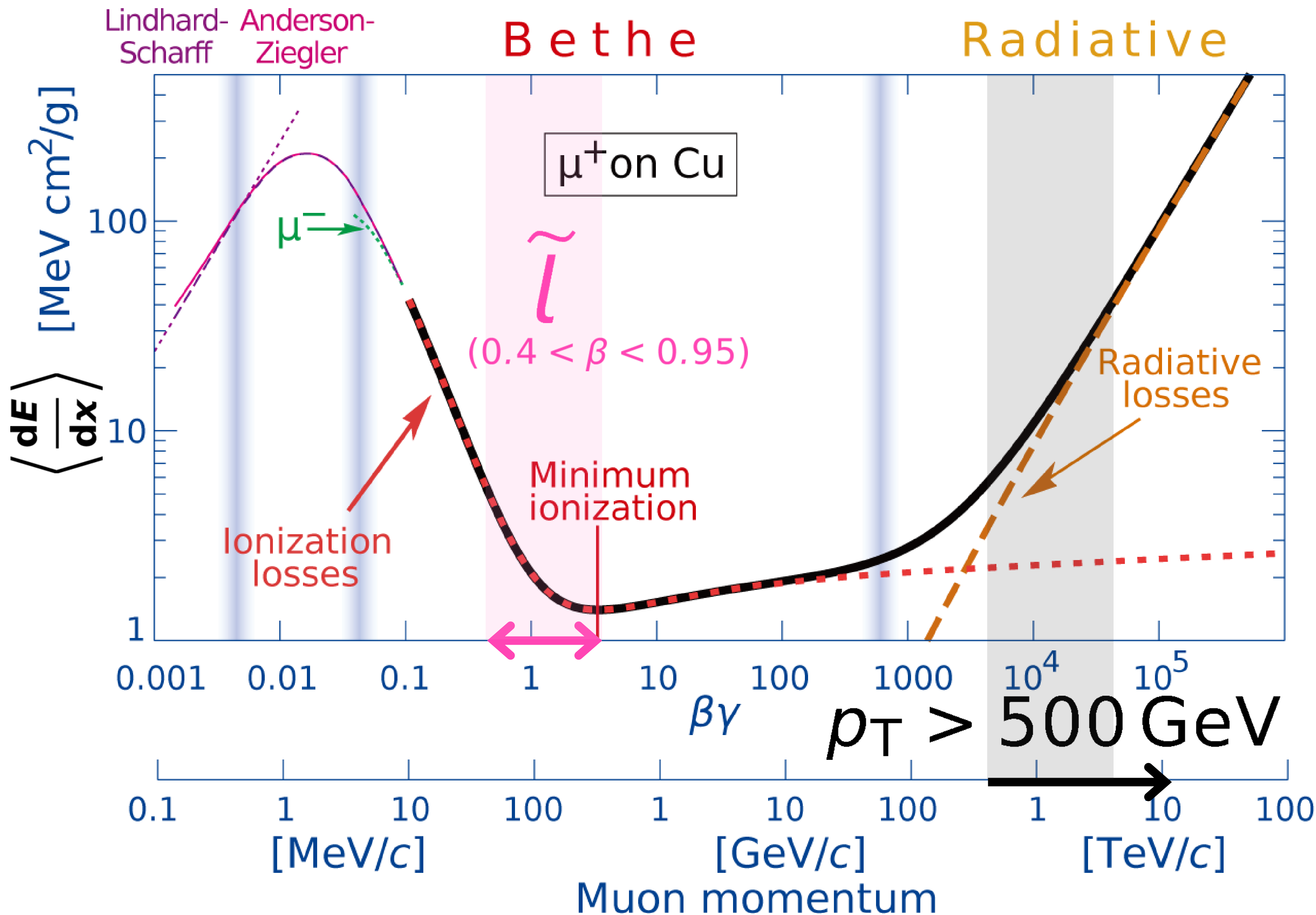


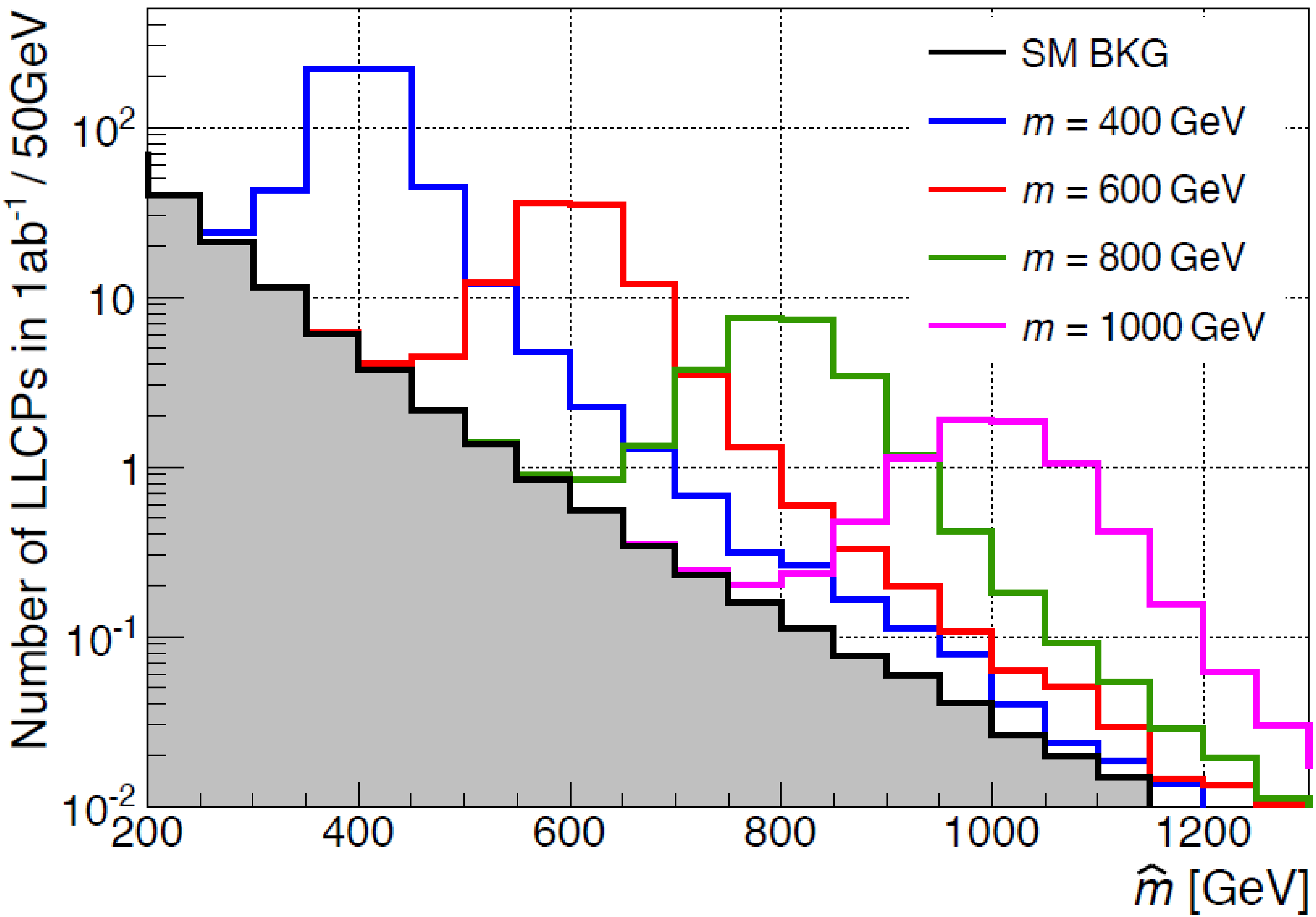
Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

HL-LHC

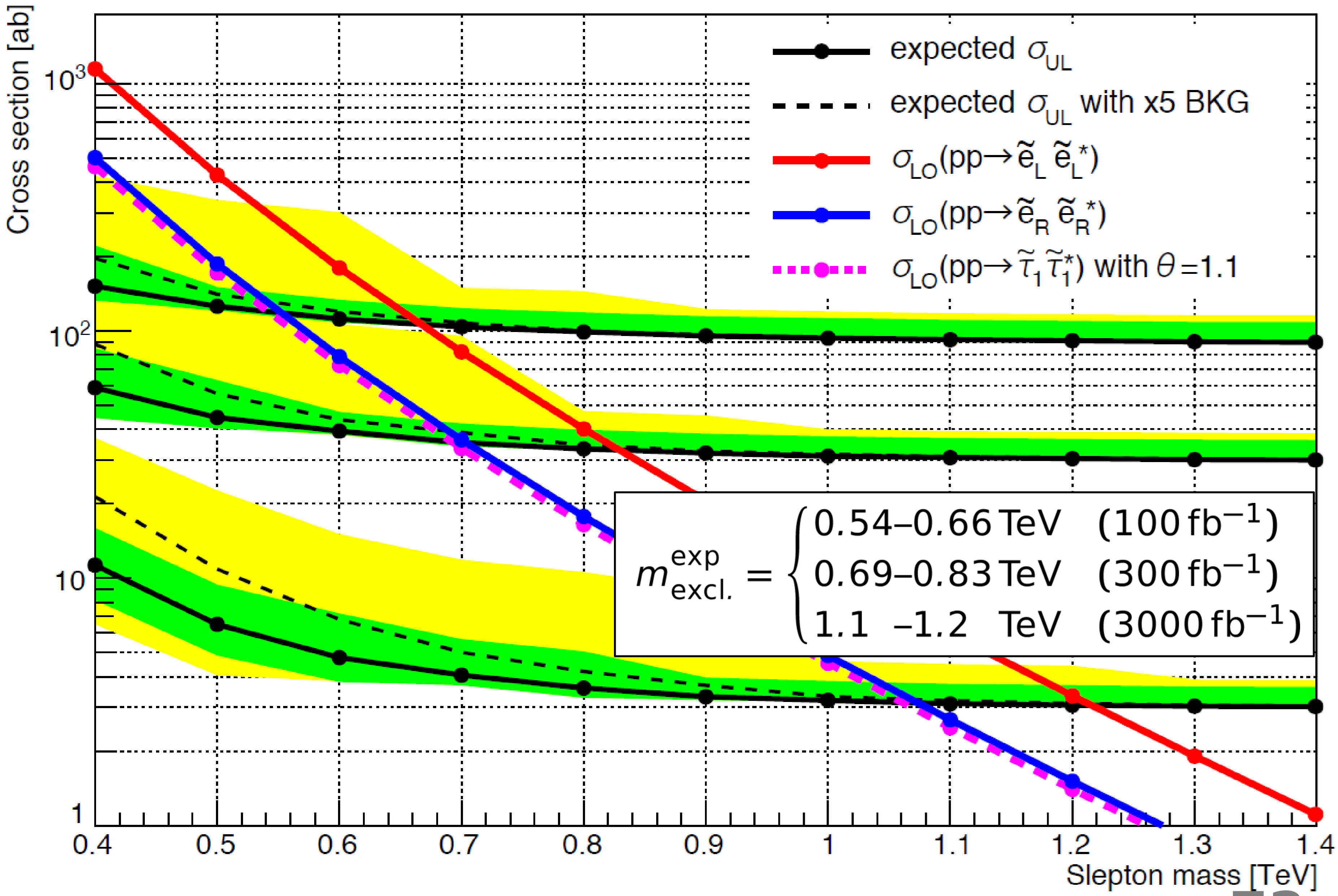
- Detector
  - similar to ATLAS/CMS
  - β-resolution same as ATLAS (resolution: 2.4%)
- Signal: Madgraph5 + Pythia6 + Delphes3 (calculated at the LO)
- BKG: "Snowmass 2013" BKG set for **14** TeV (publicly available)
- Pile-up not considered

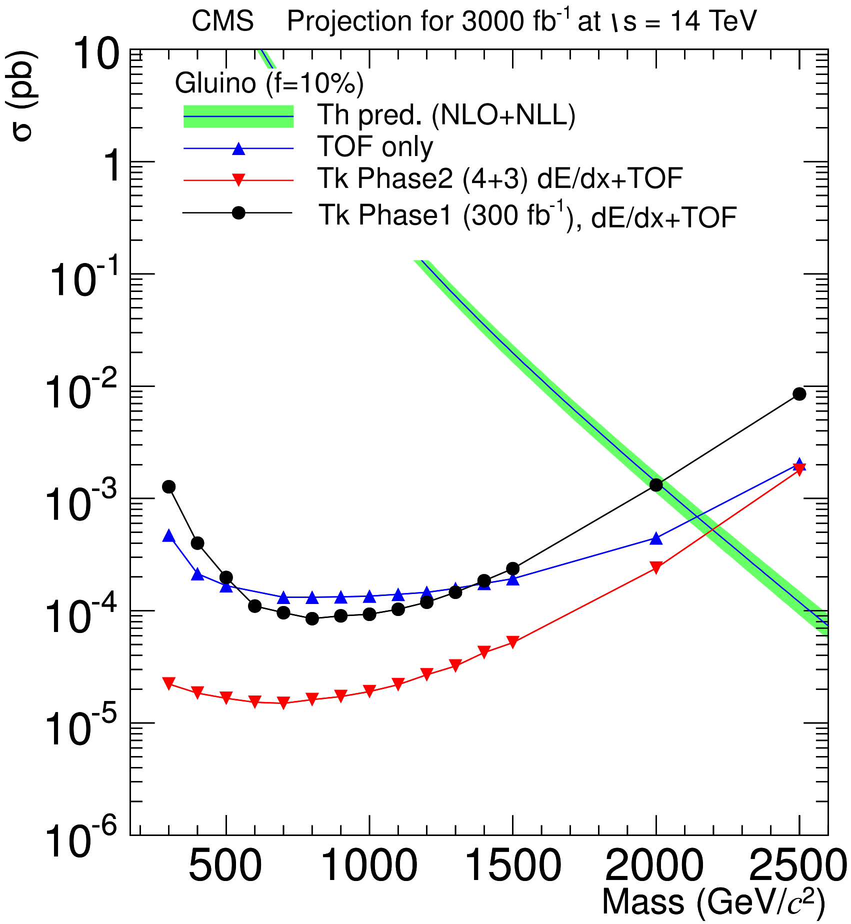
- $\tilde{l}$-selection flow

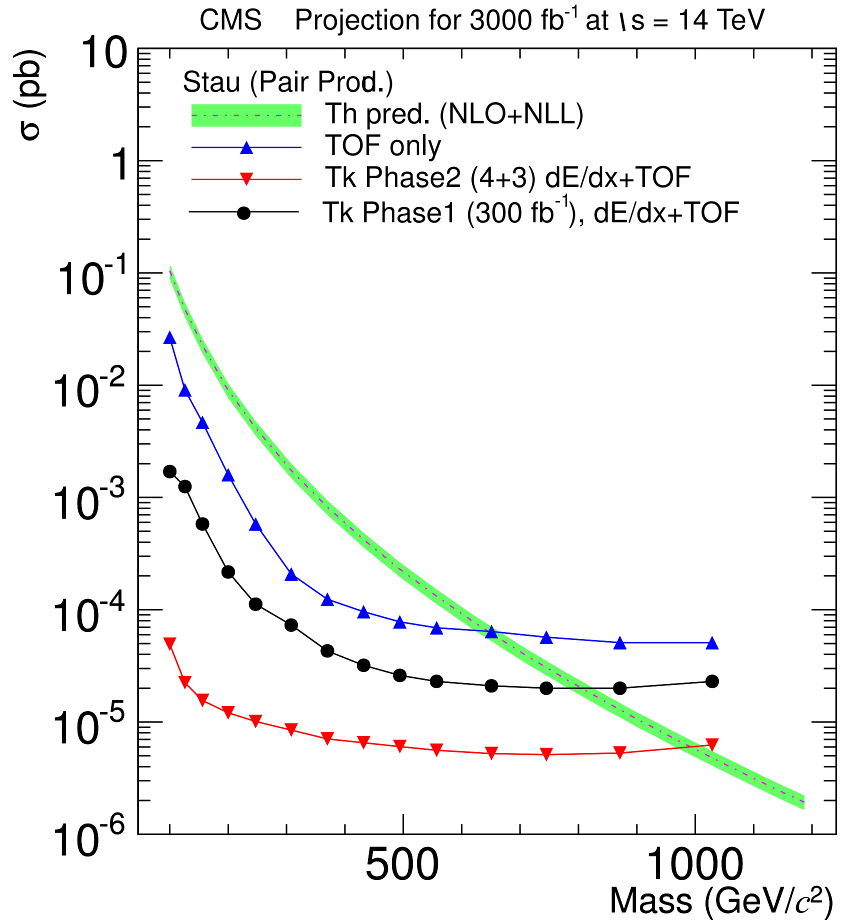
  reconstructed "muon" w.
  - $p_T >$ **100** GeV
  - $|\eta| < 2.4$
  - $0.3 < \hat{\beta} < 0.95$
  - ~~$E_{\rm loss} < 30\,{\rm GeV}$~~
- Event selection
  - two $\tilde{l}$-candidates


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

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

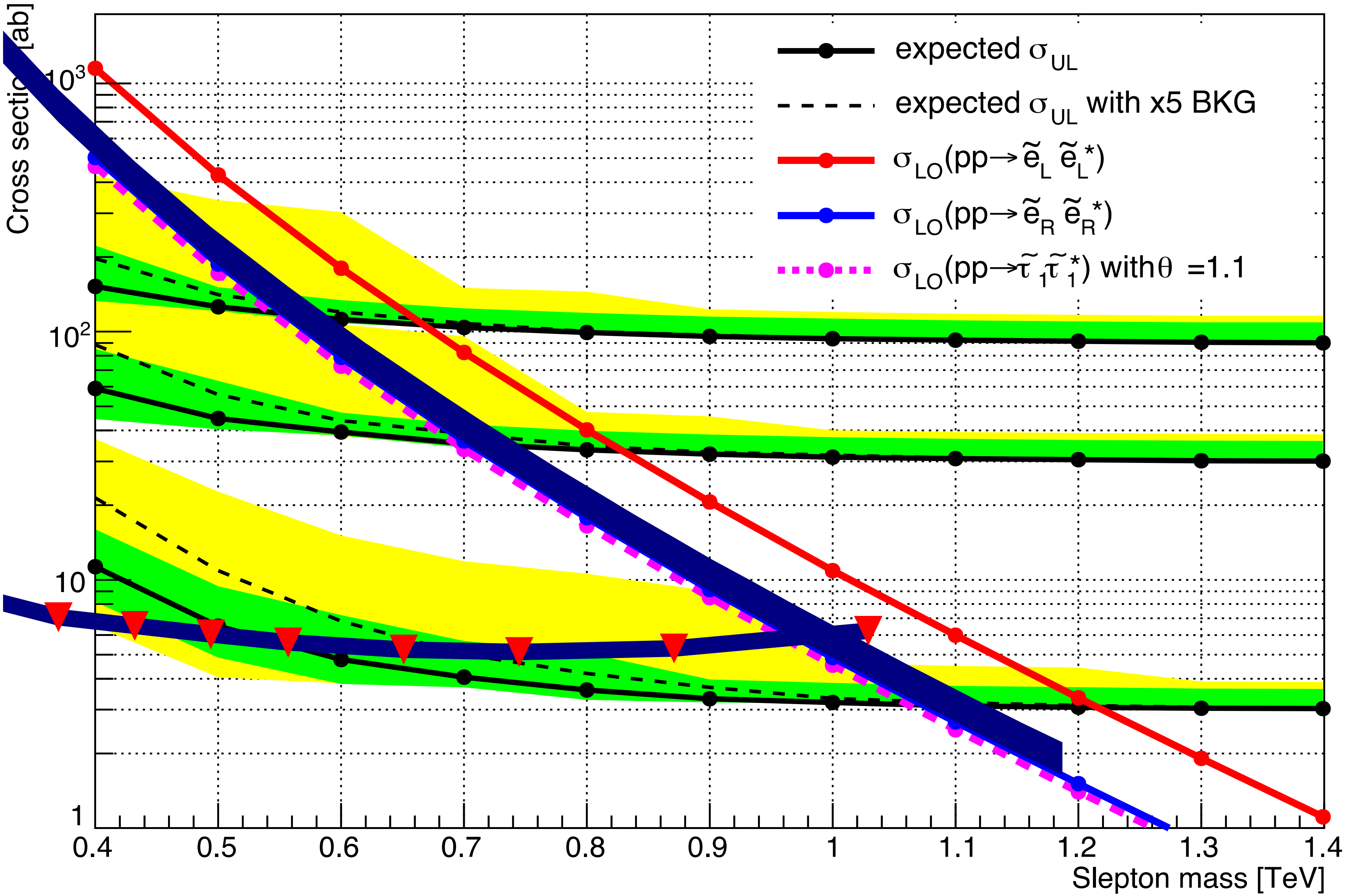




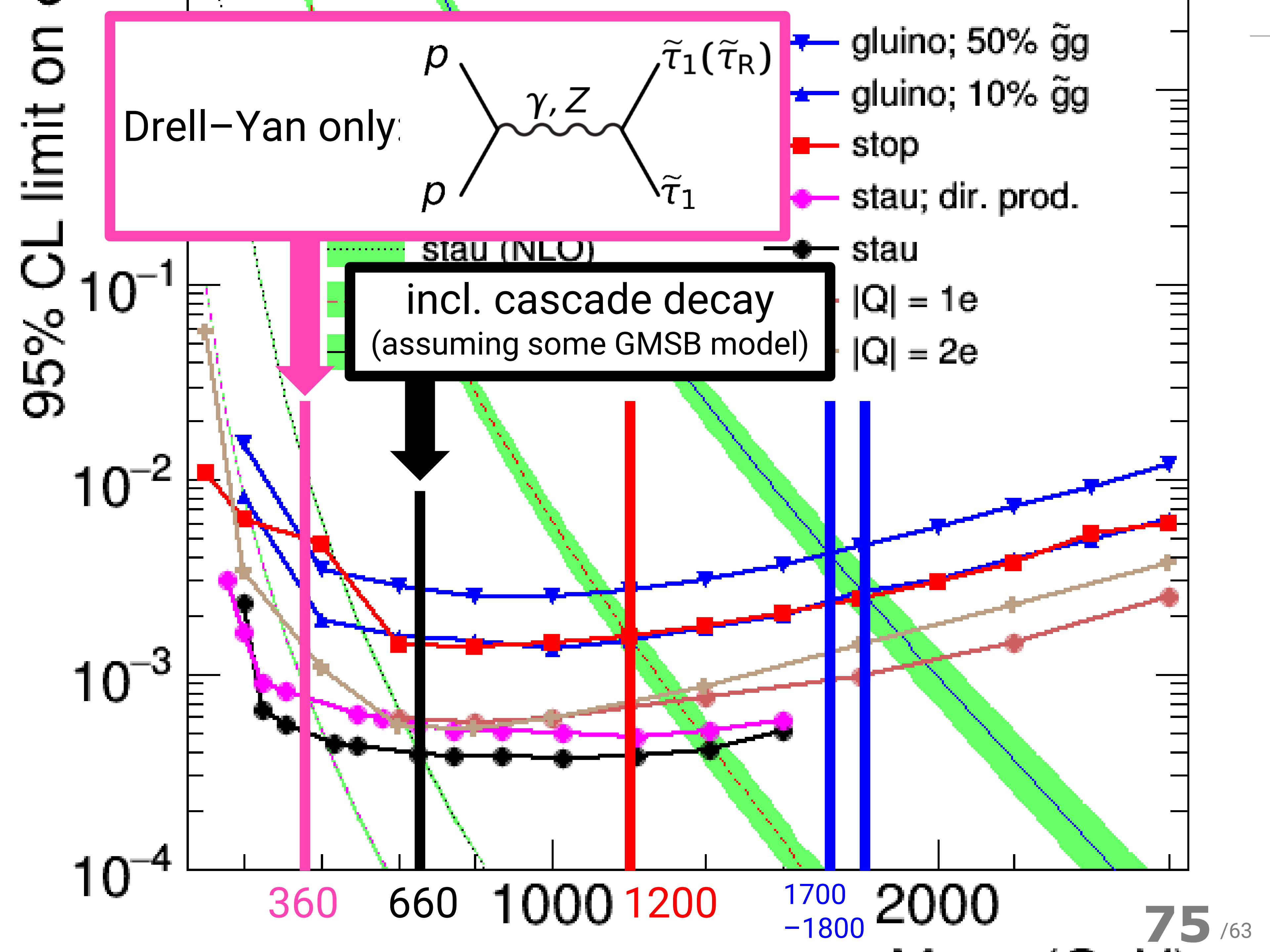


	current	HL-LHC
gluino:	1.7 TeV	→ 2.2 TeV?
stop:	1.2 TeV	→ 1.7 TeV?
stau (GMSB):	660 GeV	→ 1.2 TeV?
stau (DY):	360 GeV	→ 1.0 TeV?

(or discovery?)



Cross section [ab]
10^3
10^2
10
1
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
Slepton mass [TeV]
expected σ_{UL}
expected σ_{UL} with x5 BKG
$\sigma_{LO}(pp\to\tilde{e}_L\tilde{e}_L^*)$
$\sigma_{LO}(pp\to\tilde{e}_R\tilde{e}_R^*)$
$\sigma_{LO}(pp\to\tilde{\tau}_1\tilde{\tau}_1^*)$ with θ =1.1



95% CL limit on σ
Drell−Yan only:
p
p
γ, Z
$\tilde{\tau}_1(\tilde{\tau}_R)$
$\tilde{\tau}_1$
gluino; 50% $\tilde{g}g$
gluino; 10% $\tilde{g}g$
stop
stau; dir. prod.
stau
stau (NLO)
|Q| = 1e
|Q| = 2e
incl. cascade decay
(assuming some GMSB model)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
360
660
1000
1200
1700
−1800
2000

Why β>0.4? (slepton dE/dx)

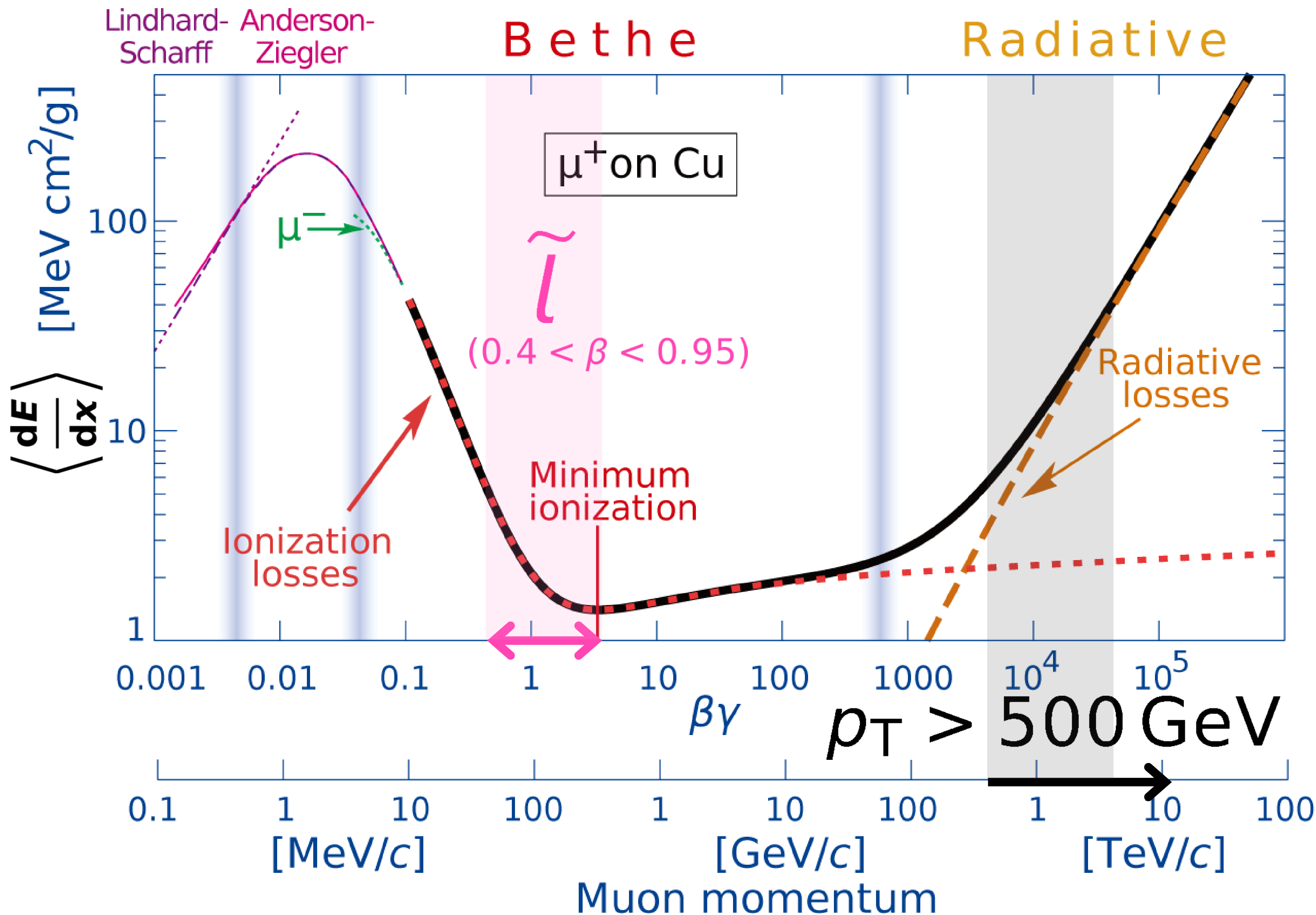
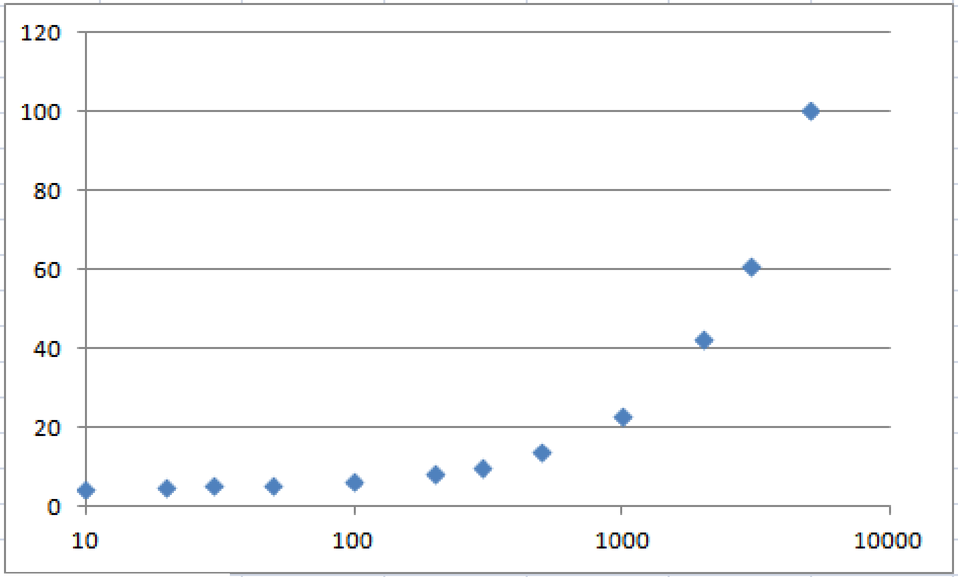
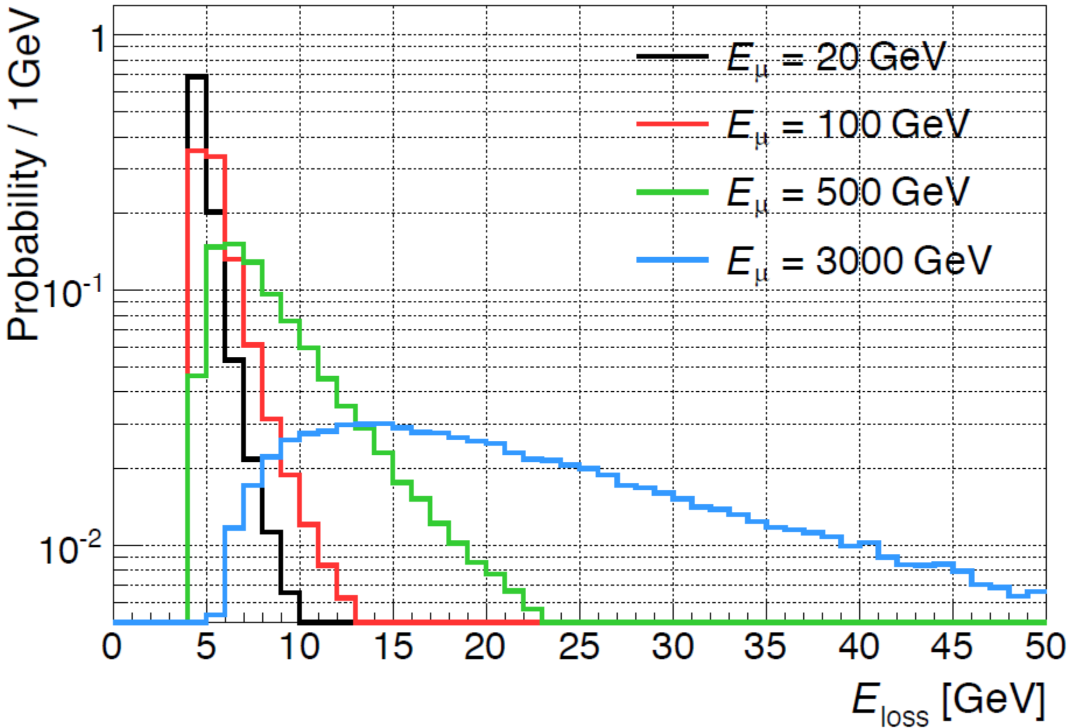


Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

Mean value of E_{loss}?

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

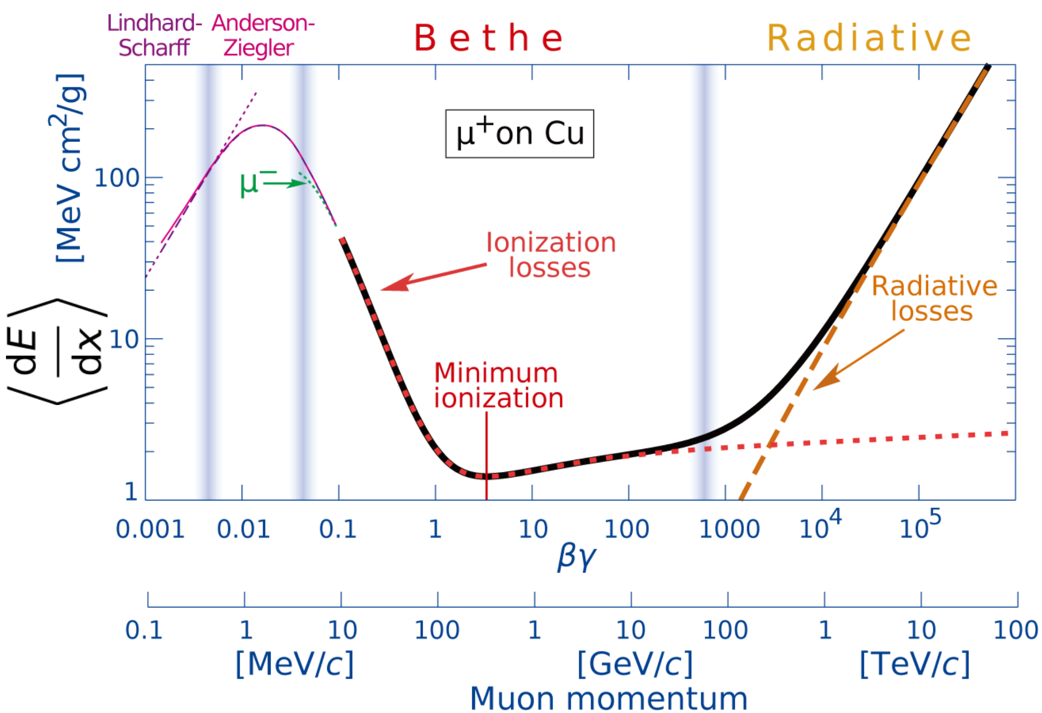
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

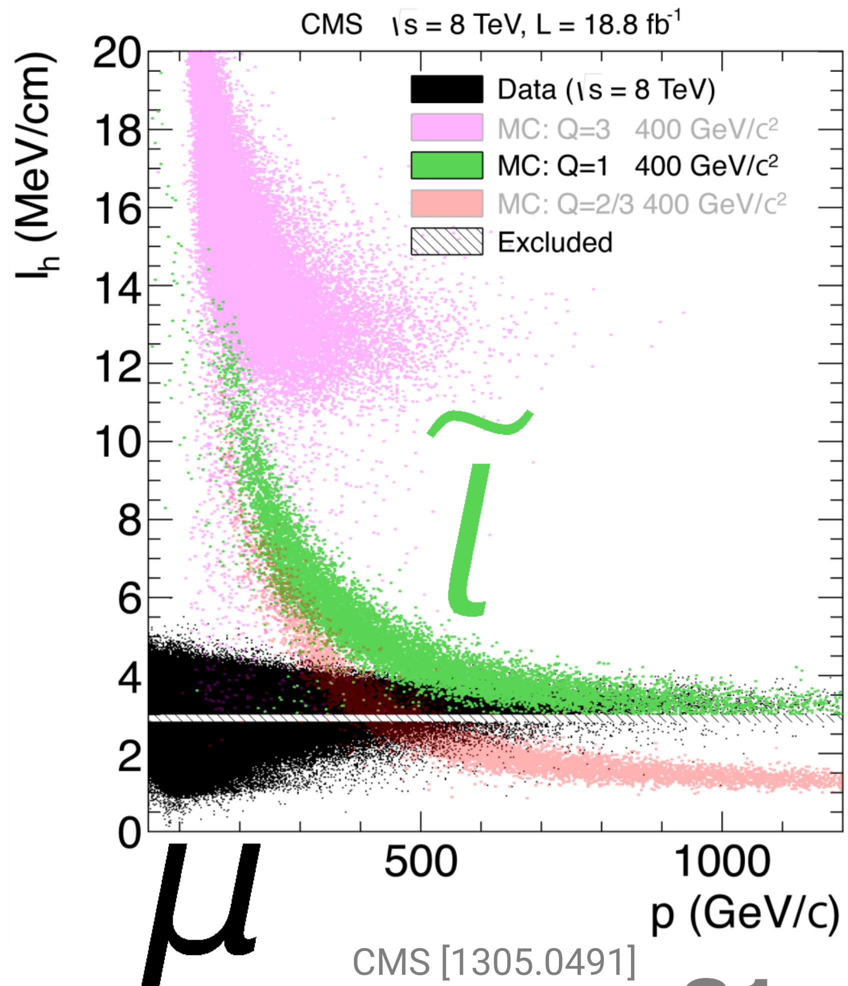
$$I_h = \rho \cdot \frac{\mathrm{d}E}{\mathrm{d}x}\Big|_{\mathrm{estimated}}$$

- TOF : time-of-flight

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

- dE/dx : ionization energy loss

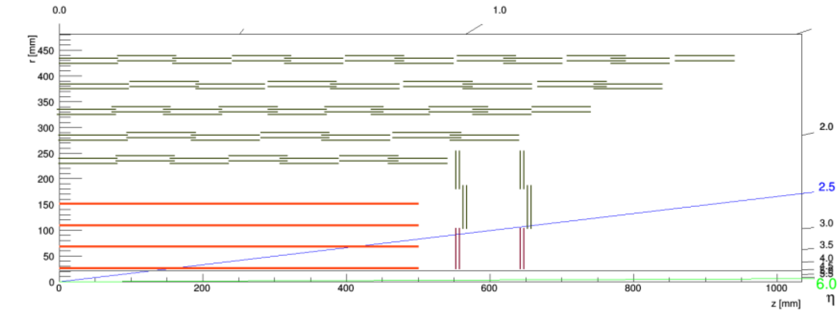




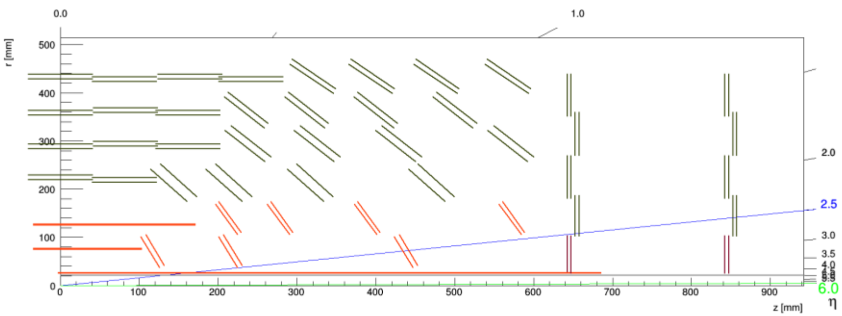
CMS [1305.0491]

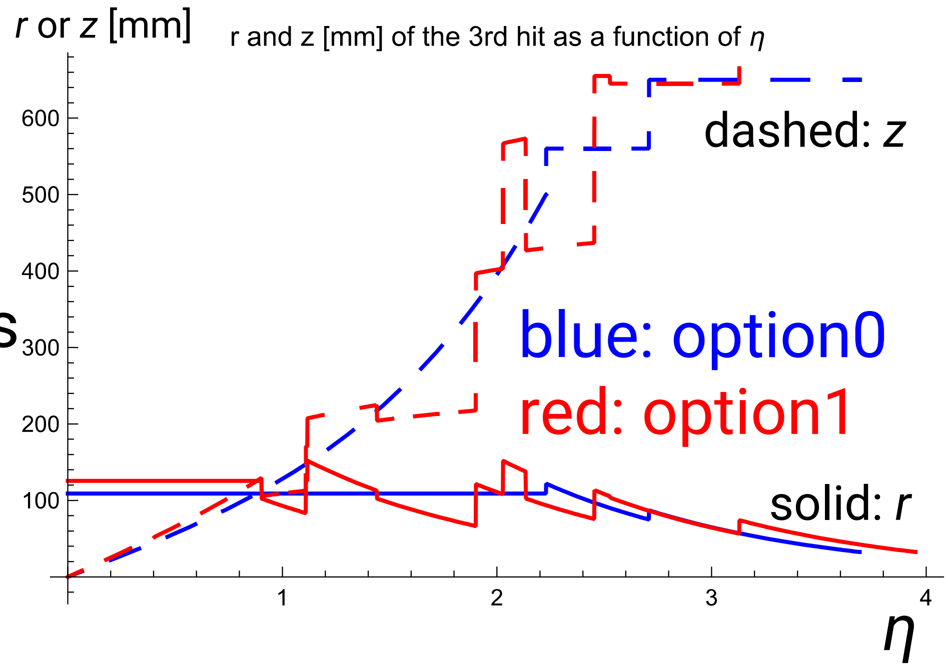
FCC-he ID options

- Option 0 – FCC-Berlin



- Option 1 - tilted endcap-rings





The position of "3rd layer" is not very different. Acceptance will be similar for both options.