הטכניון
מכון טכנולוגי לישראל
TECHNION
Israel Institute of Technology

LLCP at FCC-hh & FCC-he

Sho IWAMOTO（岩本　祥） [Technion, Israel → Padova, Italia]

27 Aug. 2017
SI2017-ph @ Fuji-Yoshida

Based on

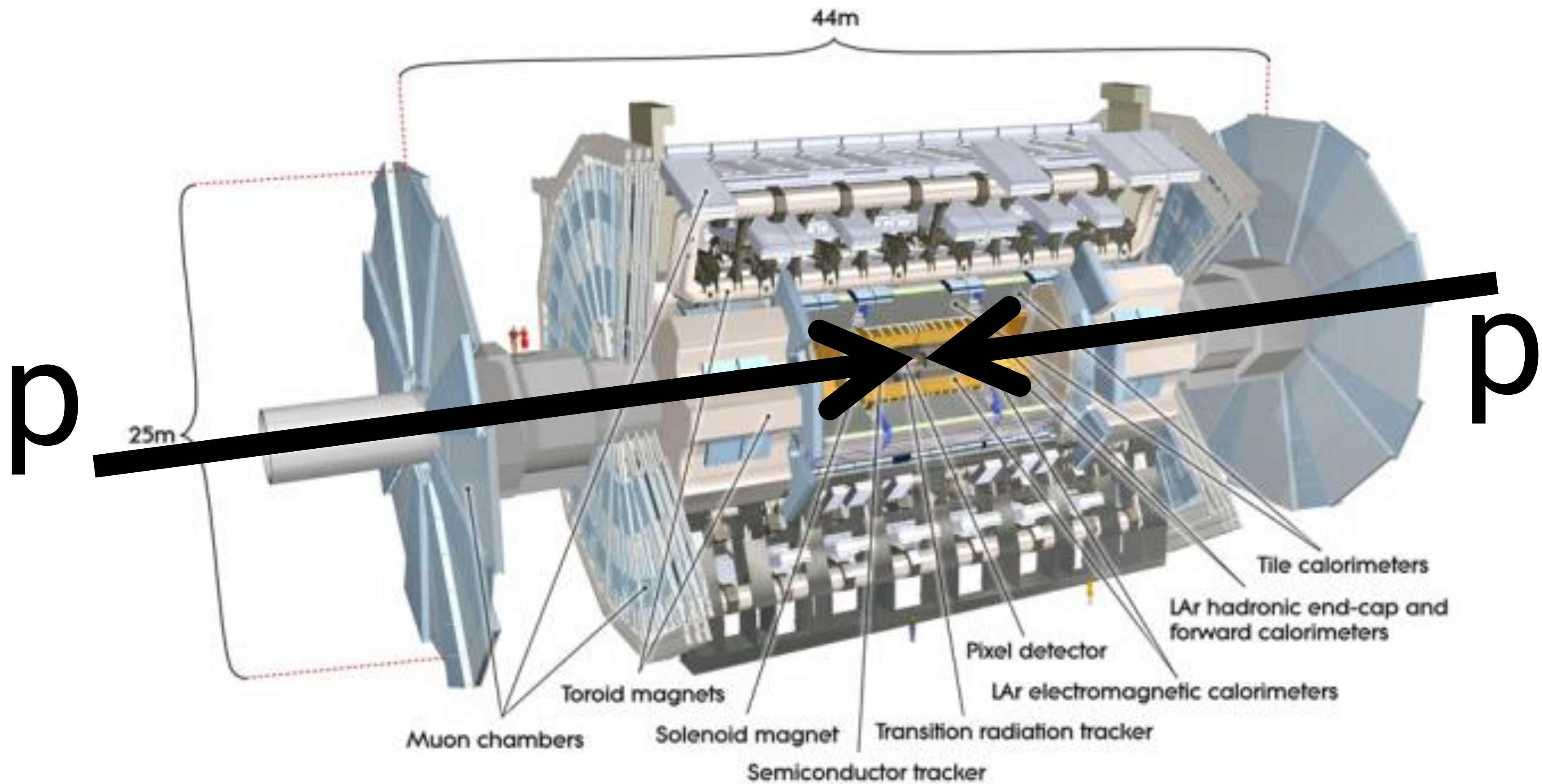
hh: Jonathan. L. Feng, ***S.I.***, Yael Shadmi, Shlomit Tarem [1505.02996]

(collected in FCC-hh report [1606.00947])

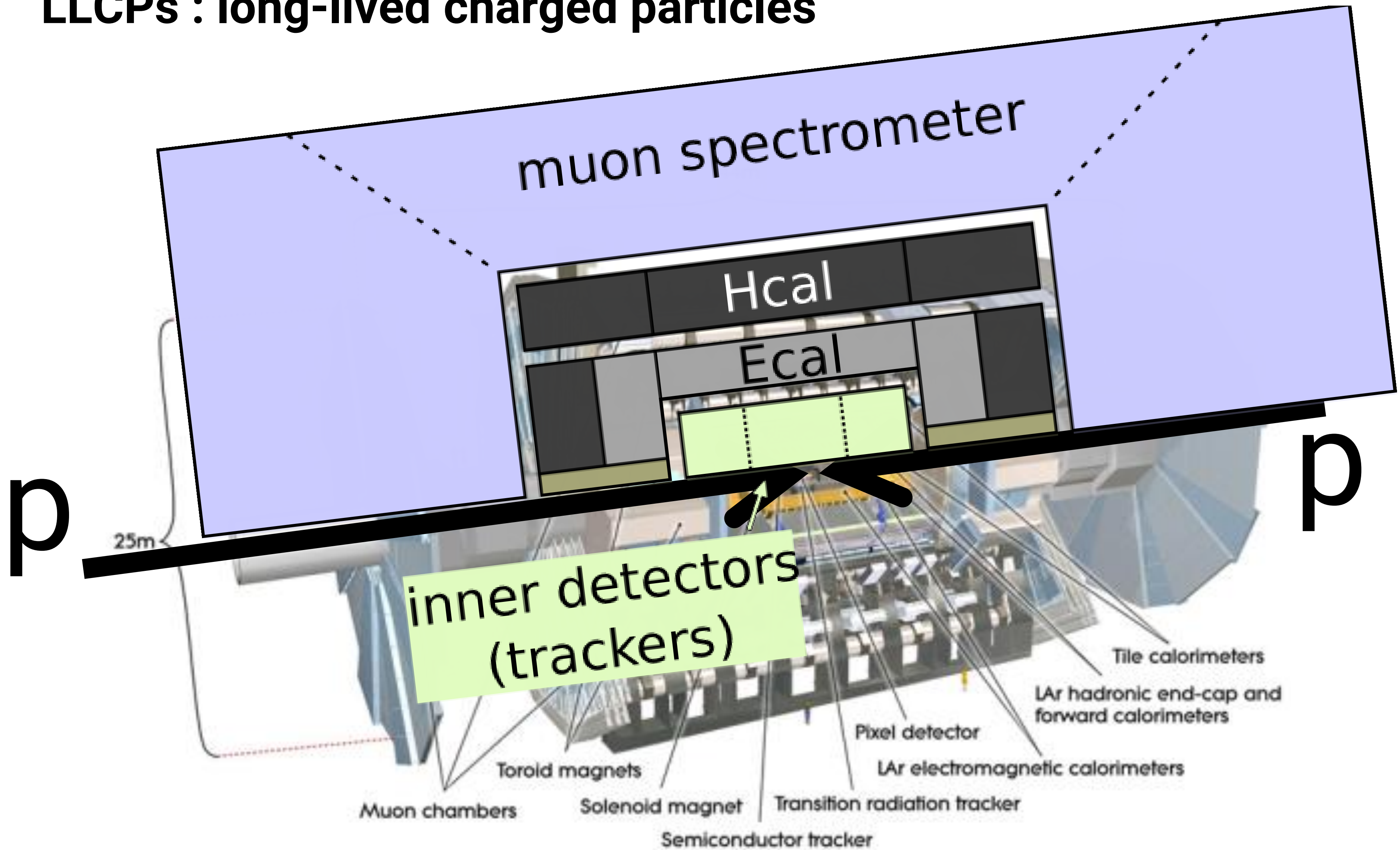
he: Kechen Wang, ***S.I.***, Monica D’Onofrio, Georges Azuelos [17??.?????]

(subgroup in BSM@ep collaboration)

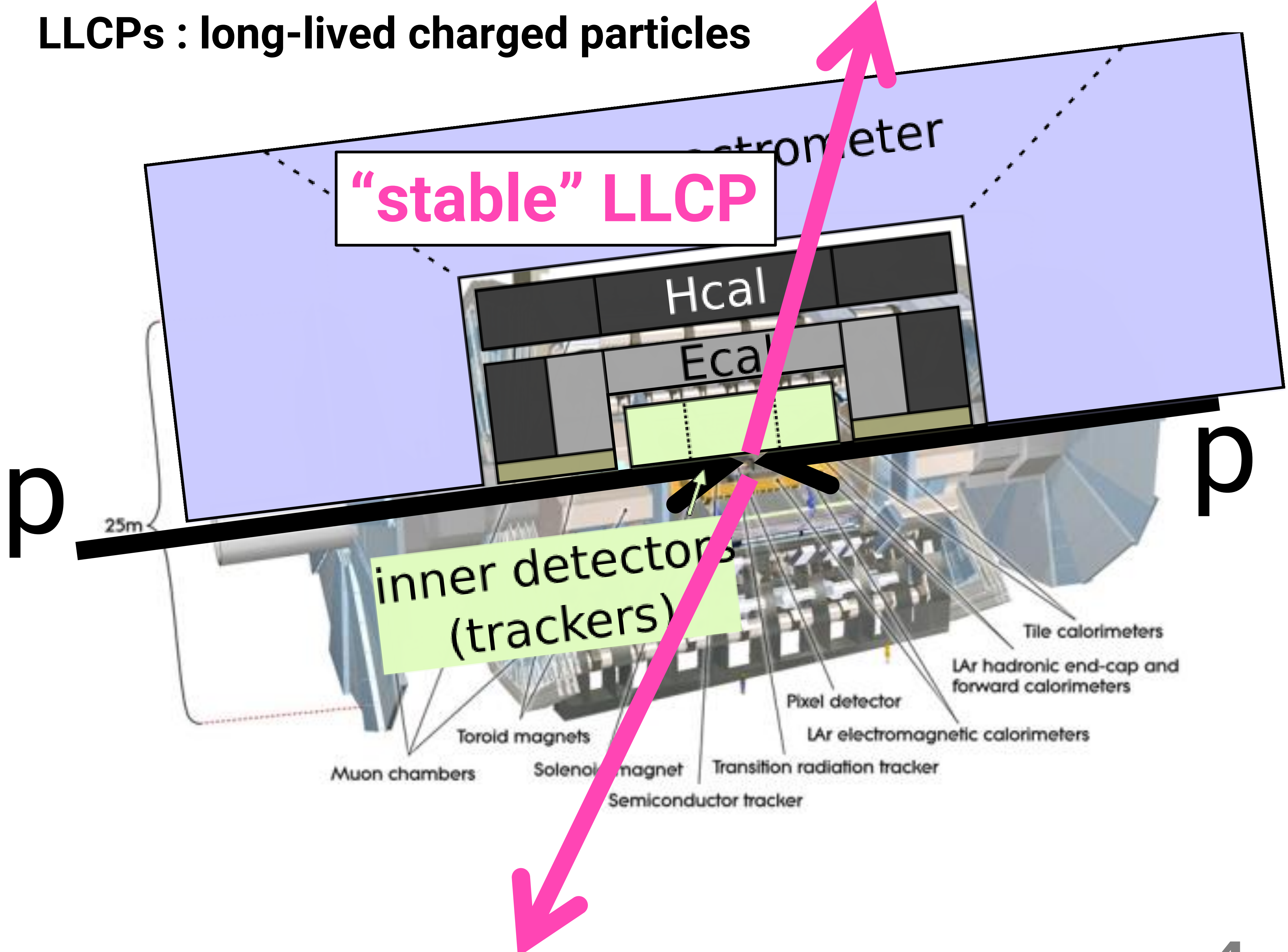
LLCPs : long-lived charged particles



LLCPs : long-lived charged particles



LLCPs : long-lived charged particles



LLCPs : long-lived charged particles

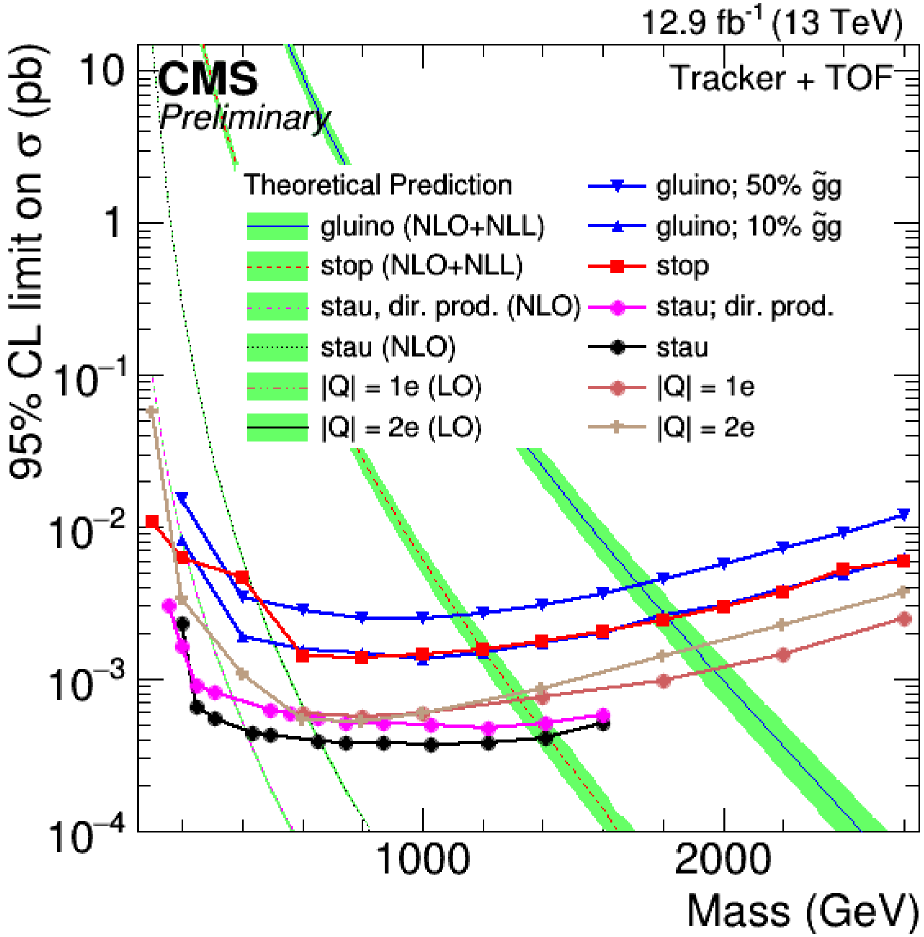
"stable" LLCP

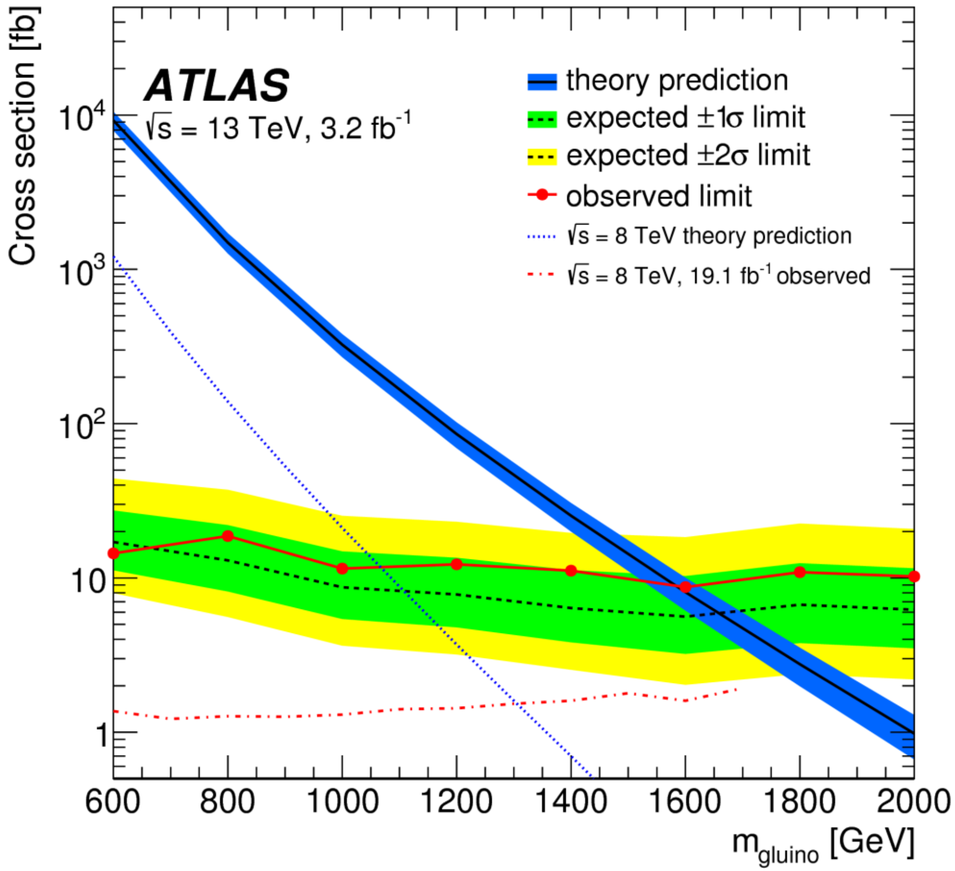
- passes the detector like a muon.
- is much heavier than a muon.

- Background = muons
- distinguishable by measuring the mass.

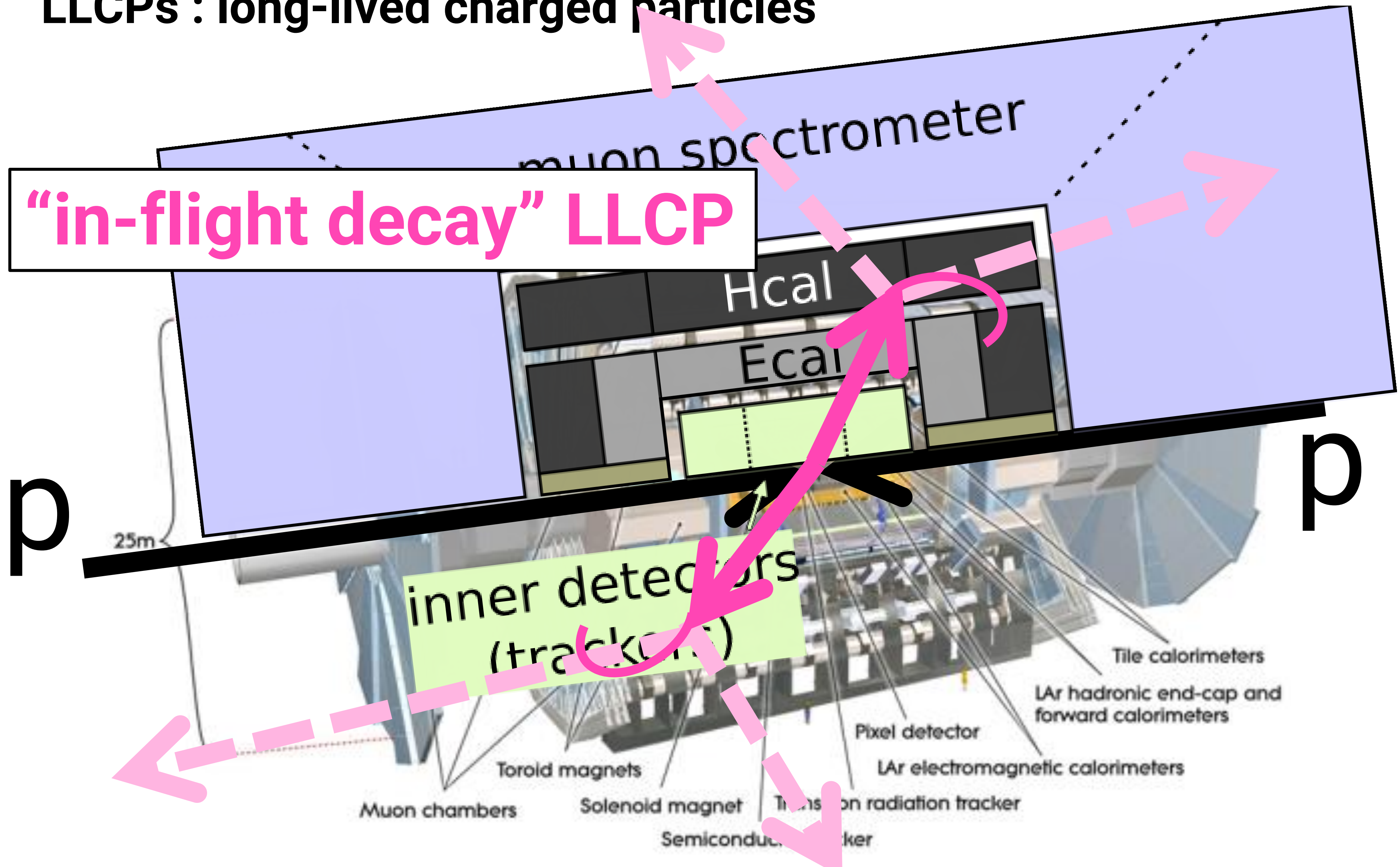
= measuring the velocity.

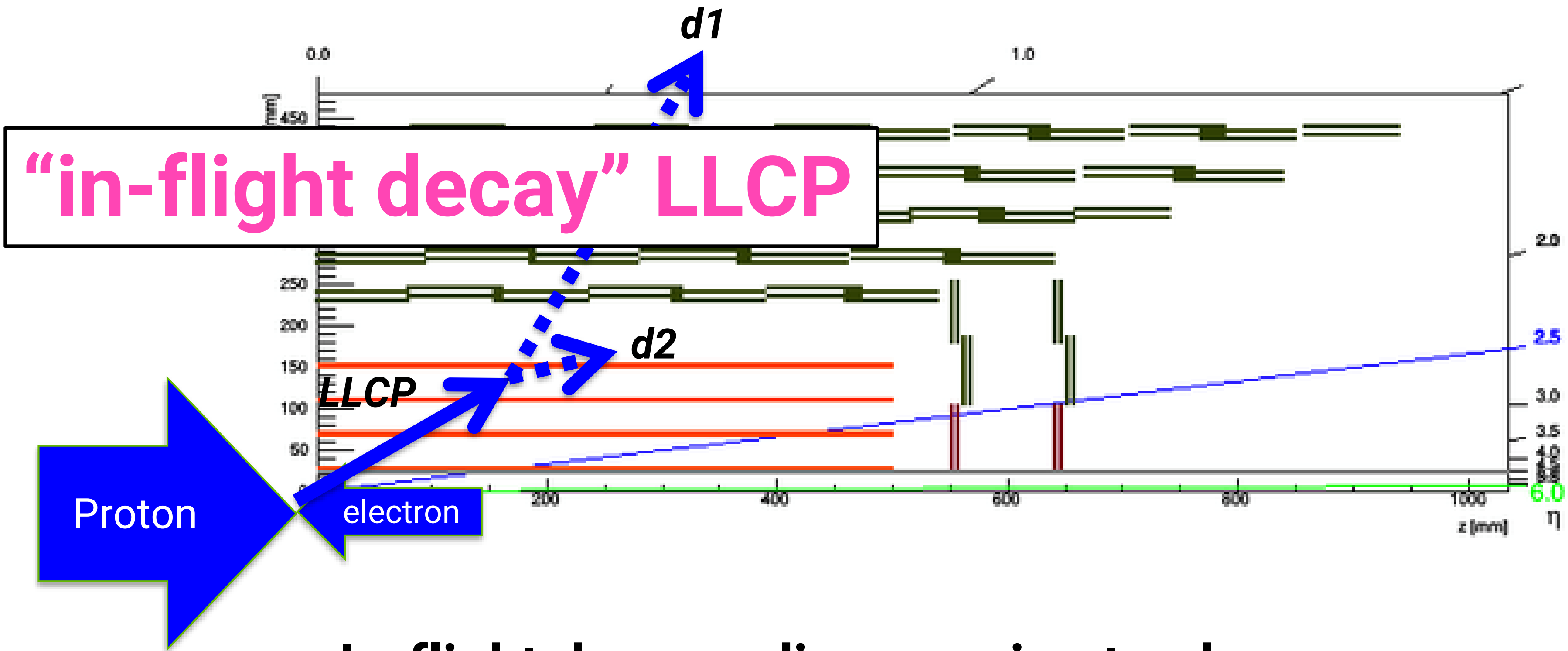
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$


12.9 fb-1 (13 TeV)
CMS
Preliminary
Tracker + TOF
95% CL limit on σ (pb)
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
Mass (GeV)


ATLAS
√s = 13 TeV, 3.2 fb-1
Cross section [fb]
theory prediction
expected ±1σ limit
expected ±2σ limit
observed limit
√s = 8 TeV theory prediction
√s = 8 TeV, 19.1 fb-1 observed
m_gluino [GeV]

LLCPs : long-lived charged particles

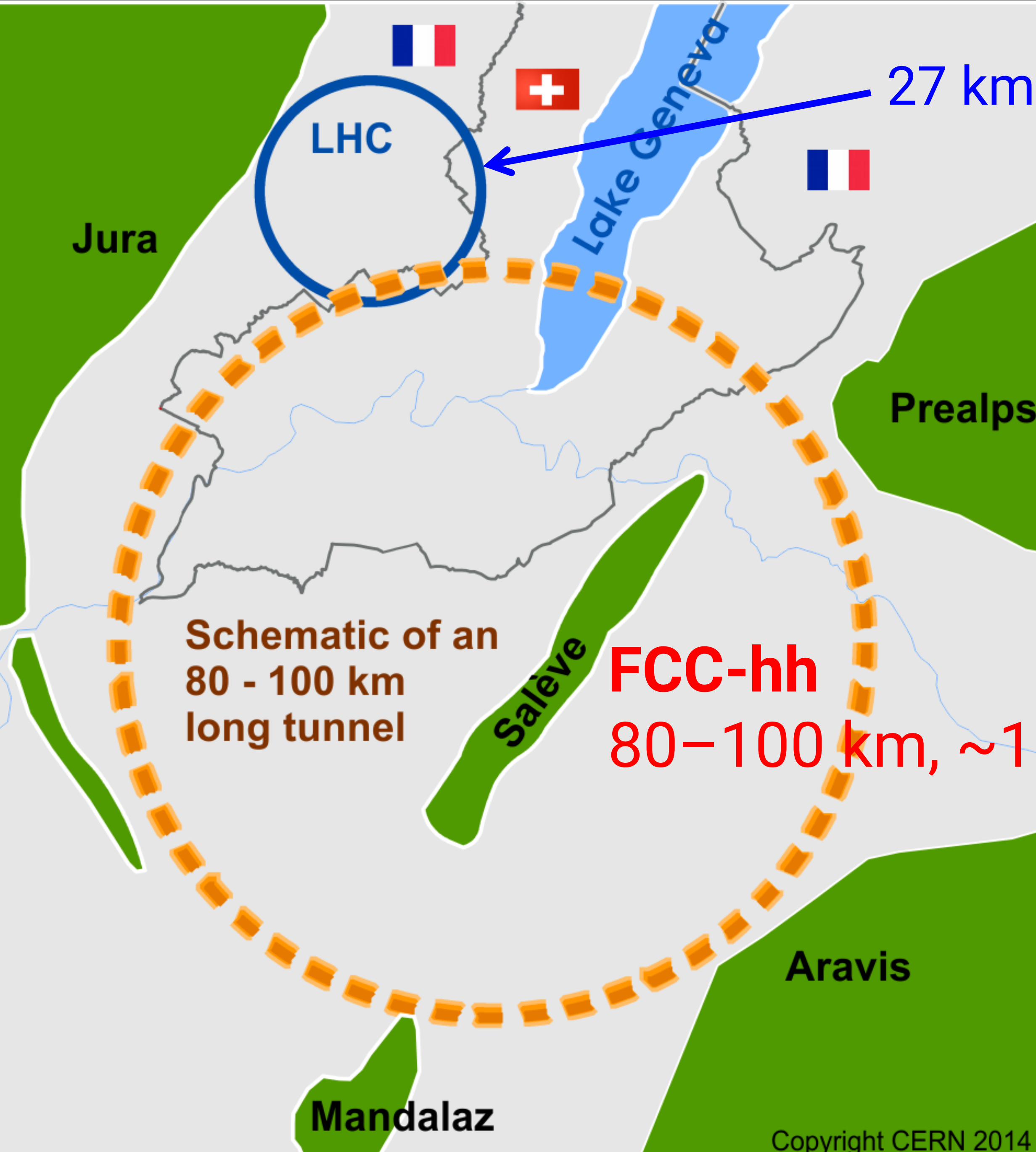




In-flight decay = disappearing track

- 3-4 hits in the inner-most tracker
- and then “missing”

(or a “kink” if the harder daughter ***d1*** is charged)



27 km, 8.3 T, beam = 7 TeV

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

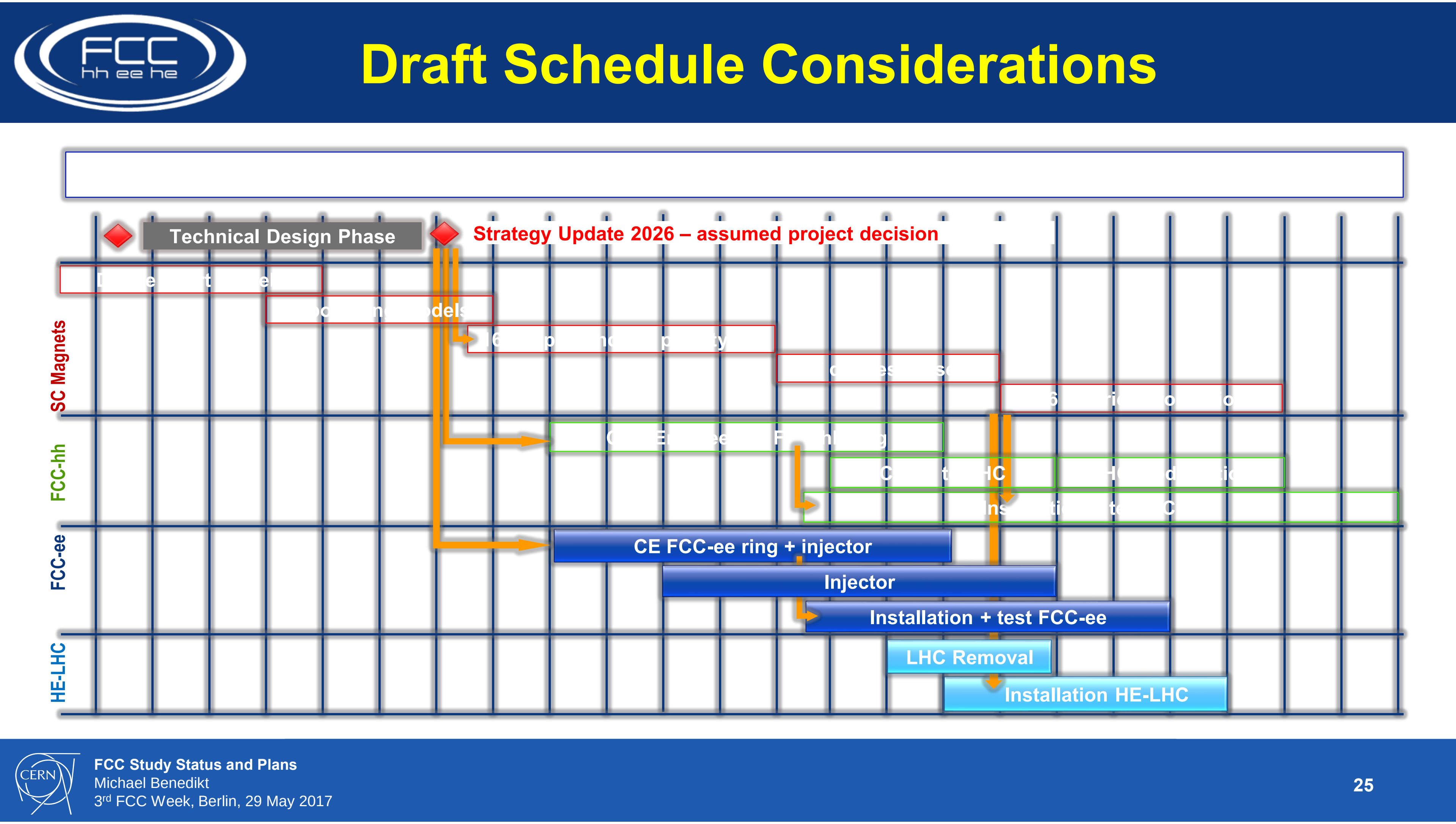
FCC-hh
80–100 km, ~16 T, beam = 50 TeV

($\int \mathcal{L}$ = 5–10 ab^{-1})

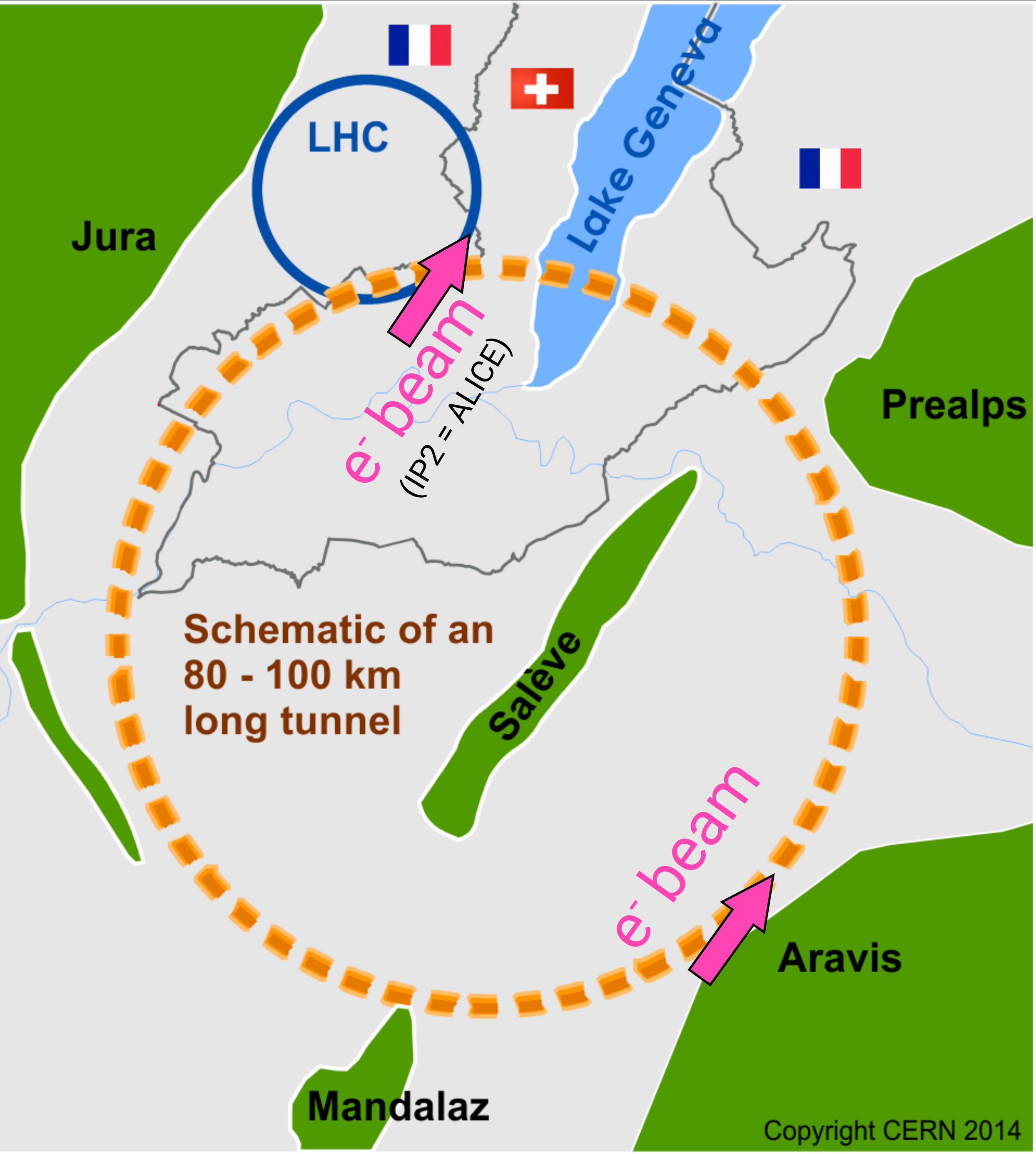
(FCC-ee as a potential first step)

→ CDR in 2018

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"

⇩

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

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

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

Many activities toward CDR

- 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. FCC-hh and FCC-he

2. LLCP searches at FCC-hh

- Motivation: Super-WIMP scenario
- **A new method** to reduce BKG
- Expectation

3. LLCP searches at FCC-he

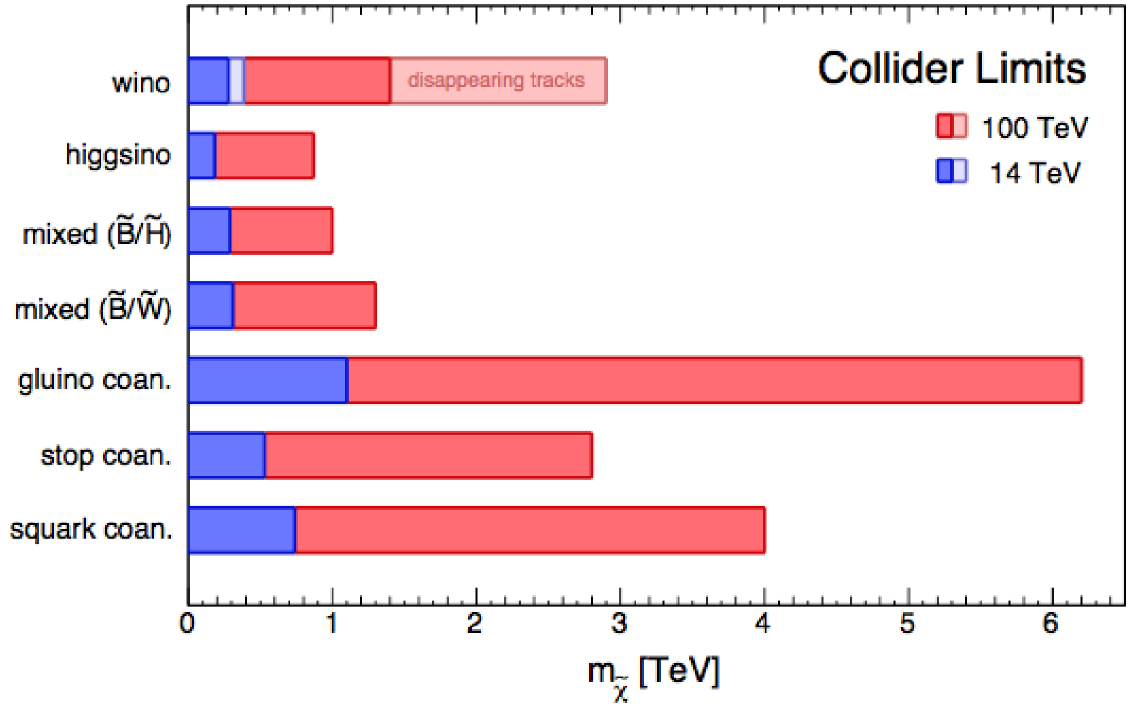
- Scenarios of interest: **what can we do at FCC-he?**
- Expectation

2. LLCP @ FCC-hh

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

(collected in FCC-hh report [1606.00947])

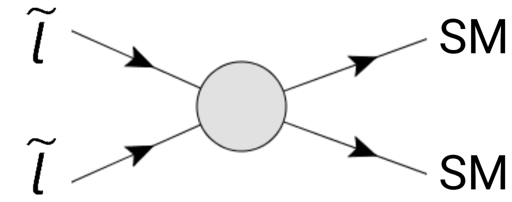
- The era of FCC-hh:
  standard thermal-WIMP scenarios → greatly covered.



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

- Elusive cases:
  - degenerate
  - non-standard

- An example of "non-standard" scenario:
  "super-WIMP"



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

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

frozen-out

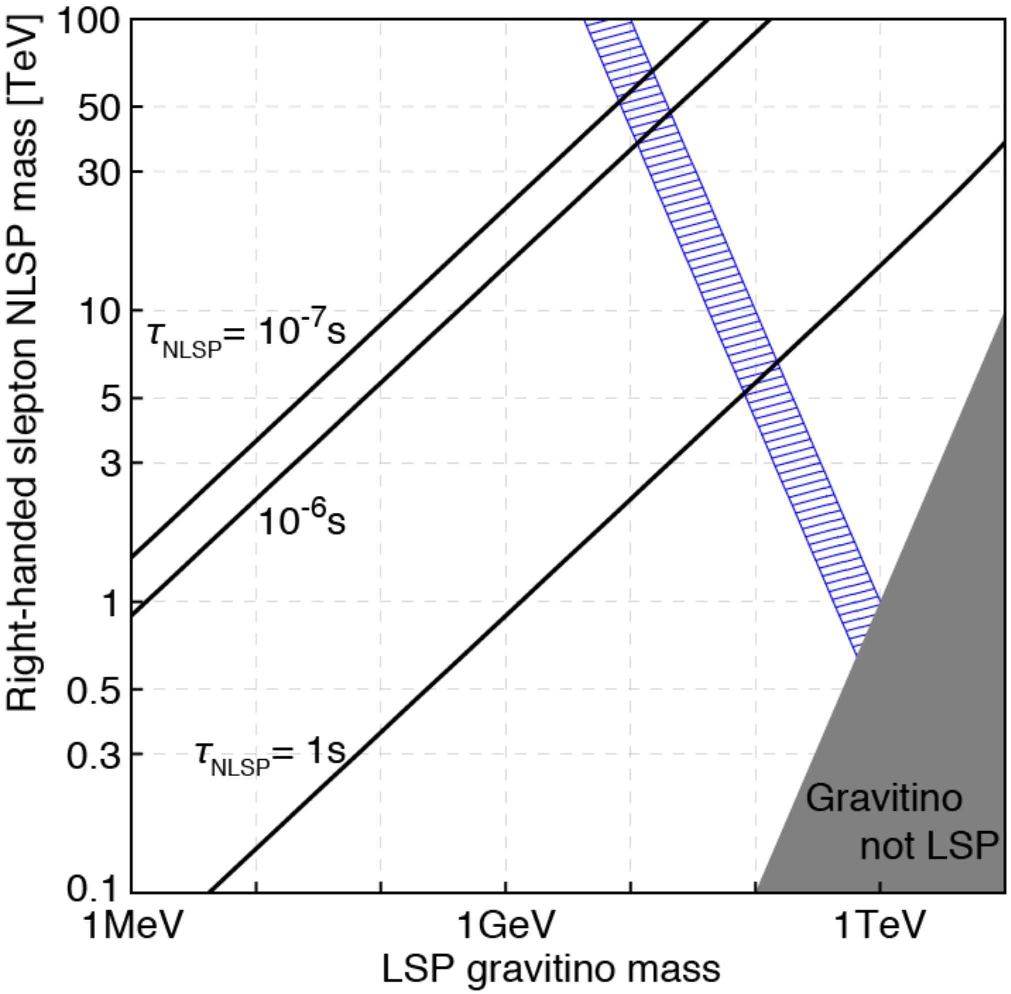
→ thermal relic with $(\Omega h^2)_{\tilde{l}} \gg 0.12$

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)

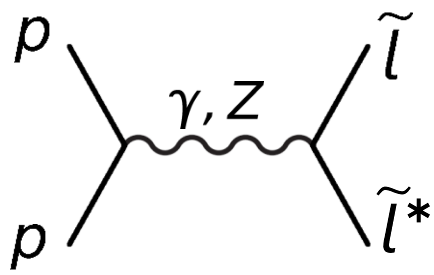
LLCP search target

(BBN/CMB constraints are relevant.)

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

■ 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)

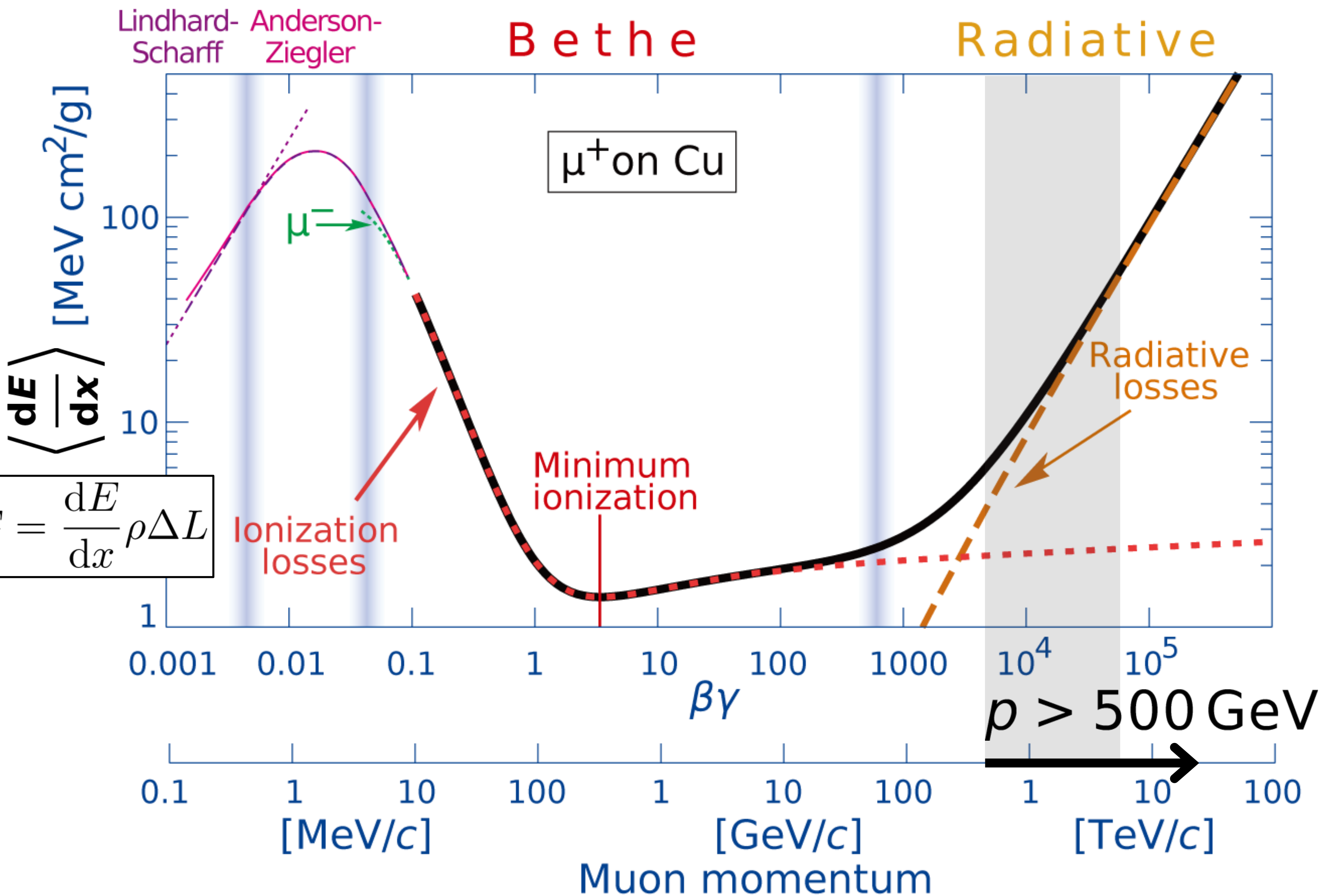


- ➢ same detection method.
  - "stable" $\tilde{l}$ → muon-like track but with a larger mass.
  - "in-flight decay" → disappearing track.

→ just an extrapolation of LHC analysis,

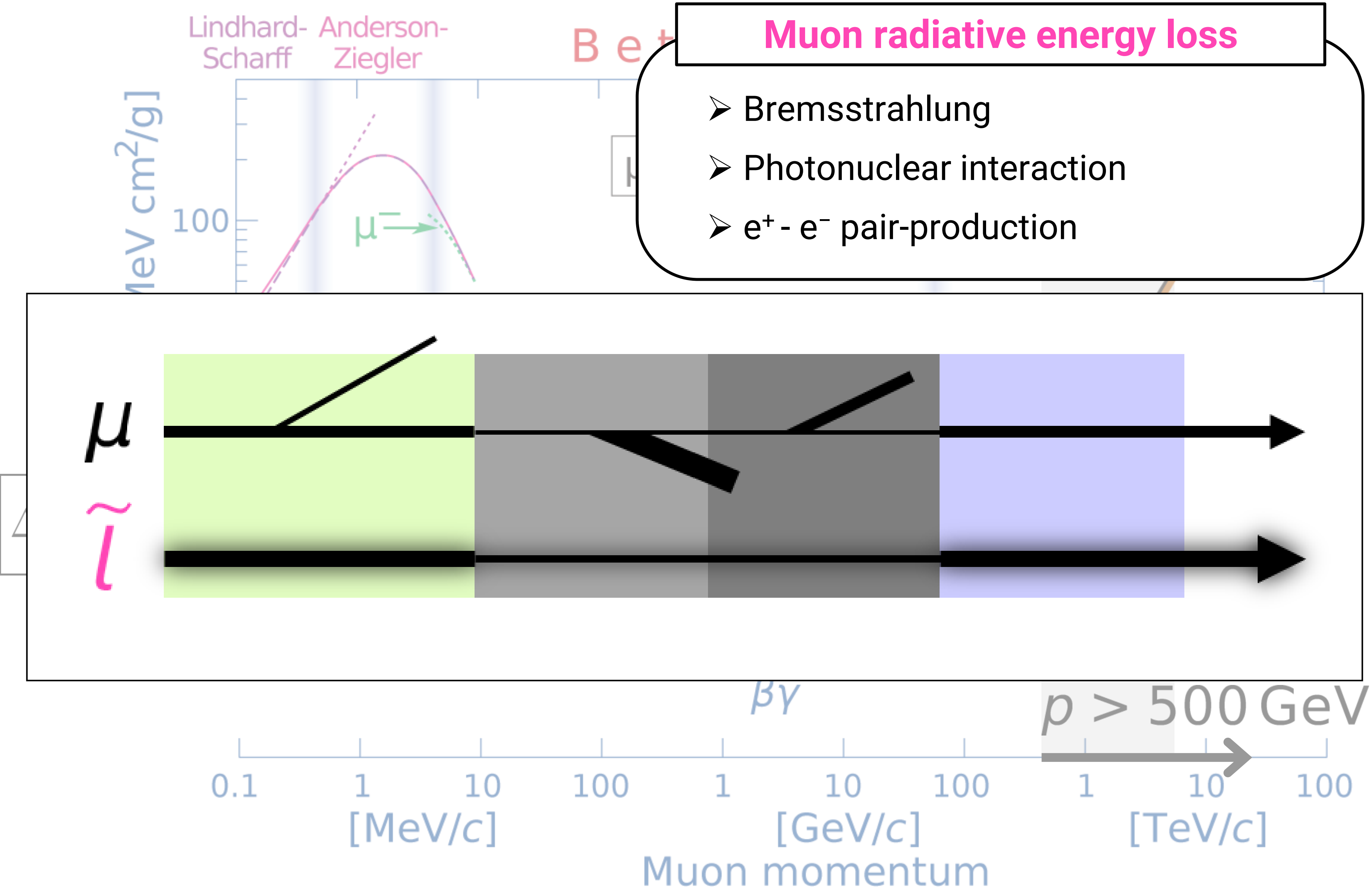
but **a new handle** to reduce "muon BKG" from SM:

"muon radiative energy loss."



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

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



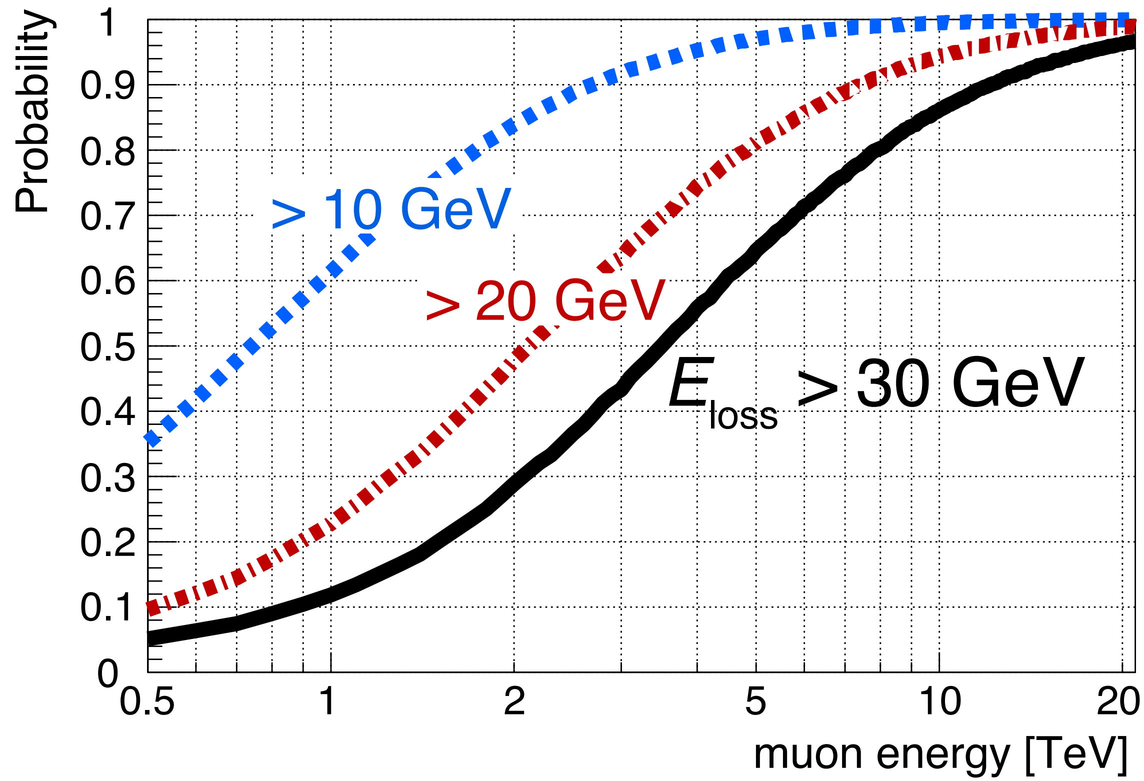
Muon radiative energy loss

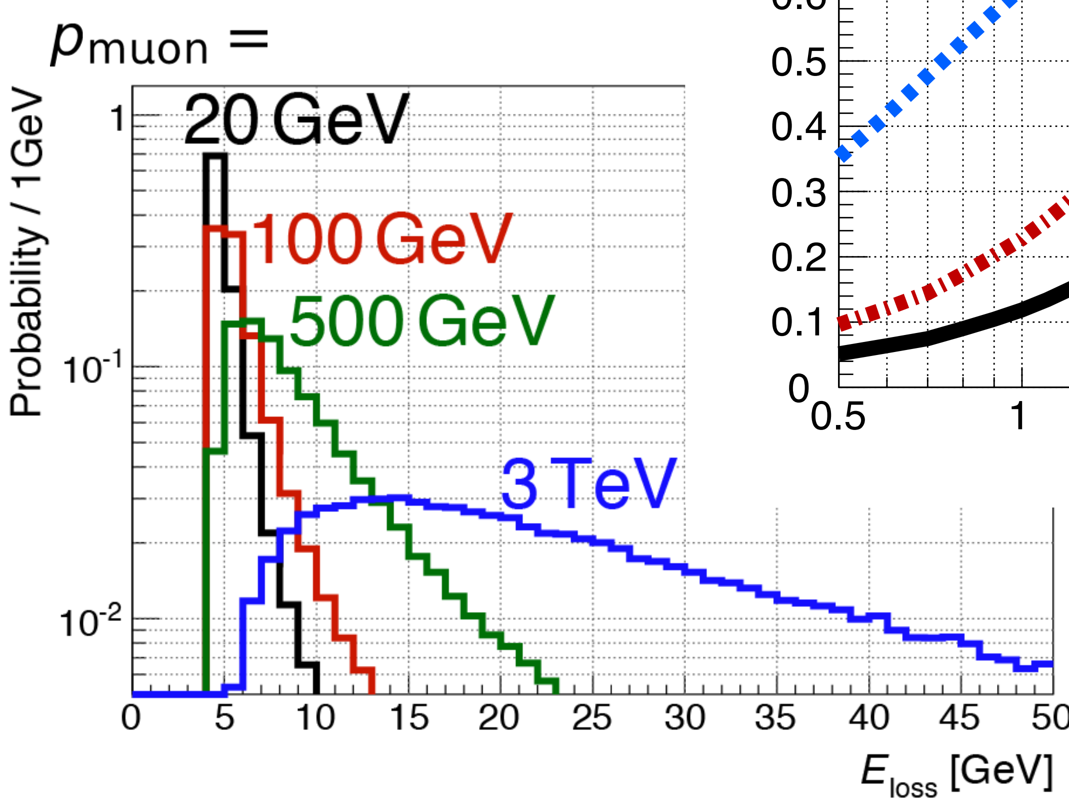
- Bremsstrahlung
- Photonuclear interaction
- e^+ - e^- pair-production

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.

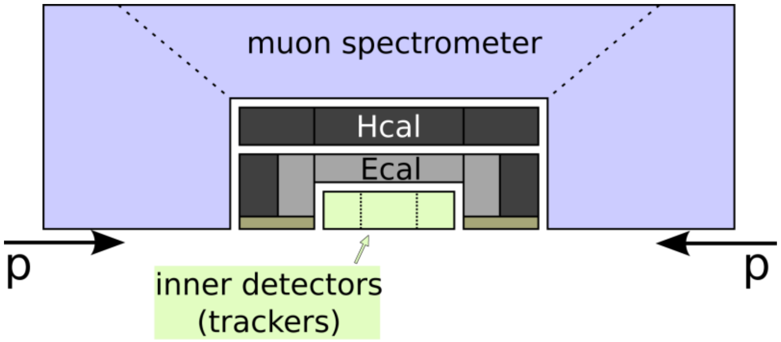




[Simulated with GEANT 4]

 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 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

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

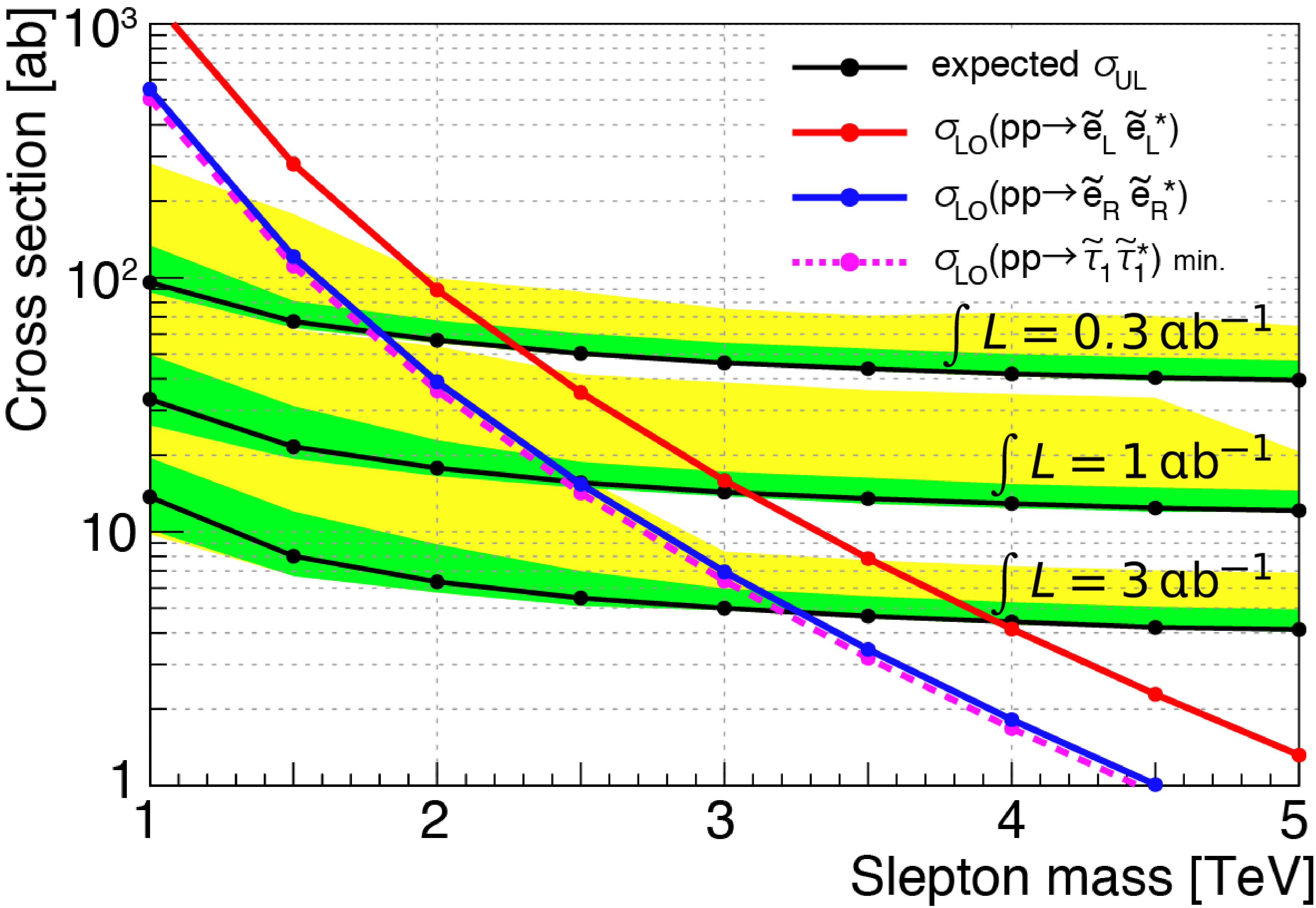
- $|\eta| < 2.4$
- $0.4 < \hat{\beta} < 0.95$ (from ToF)
- $E_{\mathrm{loss}} < 30\,\mathrm{GeV}$

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

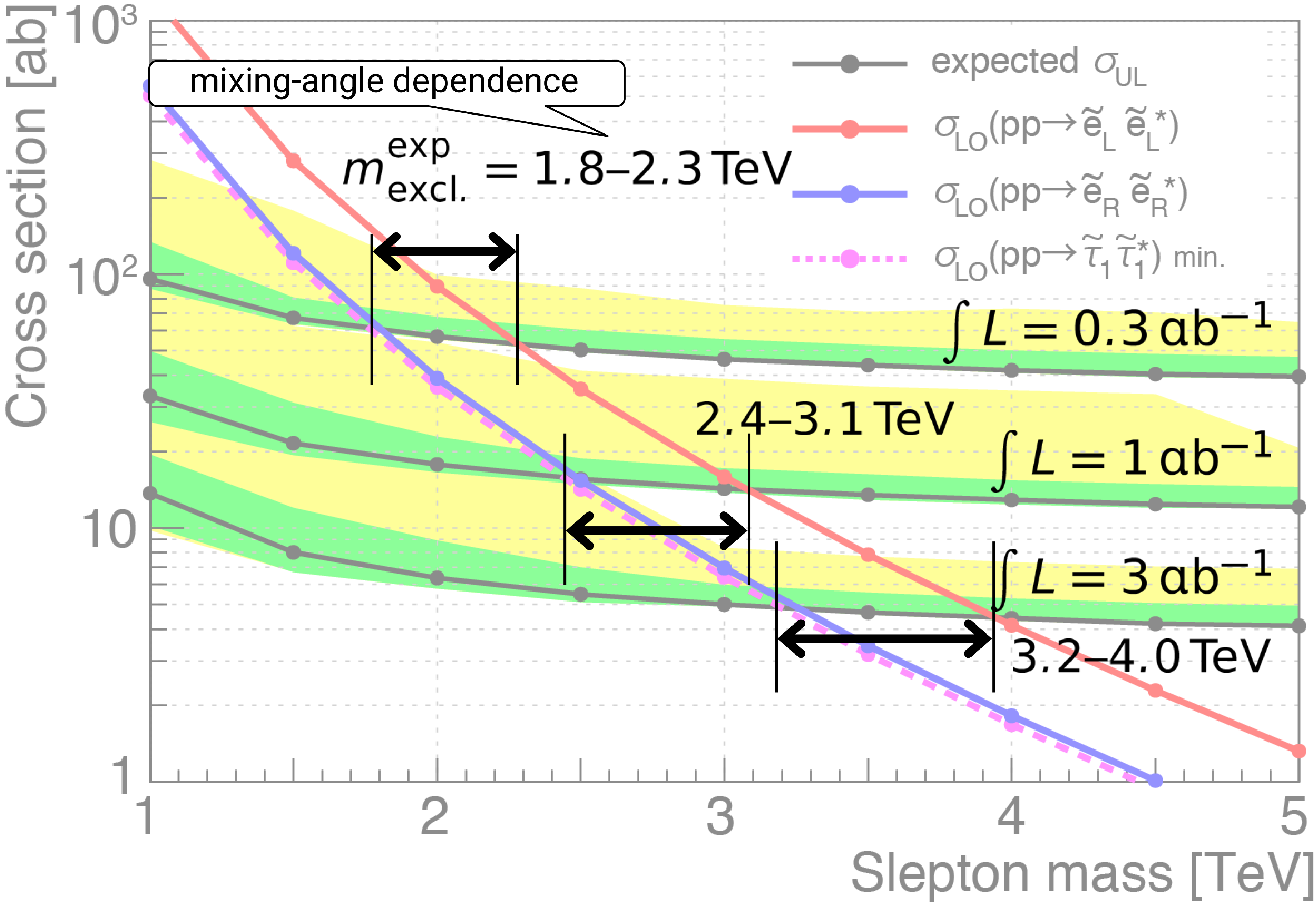
	1 TeV	3 TeV	BKG
$N_{\mathrm{LLCP}} = 0$	483	1.34	(a lot)
$N_{\mathrm{LLCP}} = 1$	378	4.46	2.78×10^5
$N_{\mathrm{LLCP}} = 2$	424	10.1	34.6

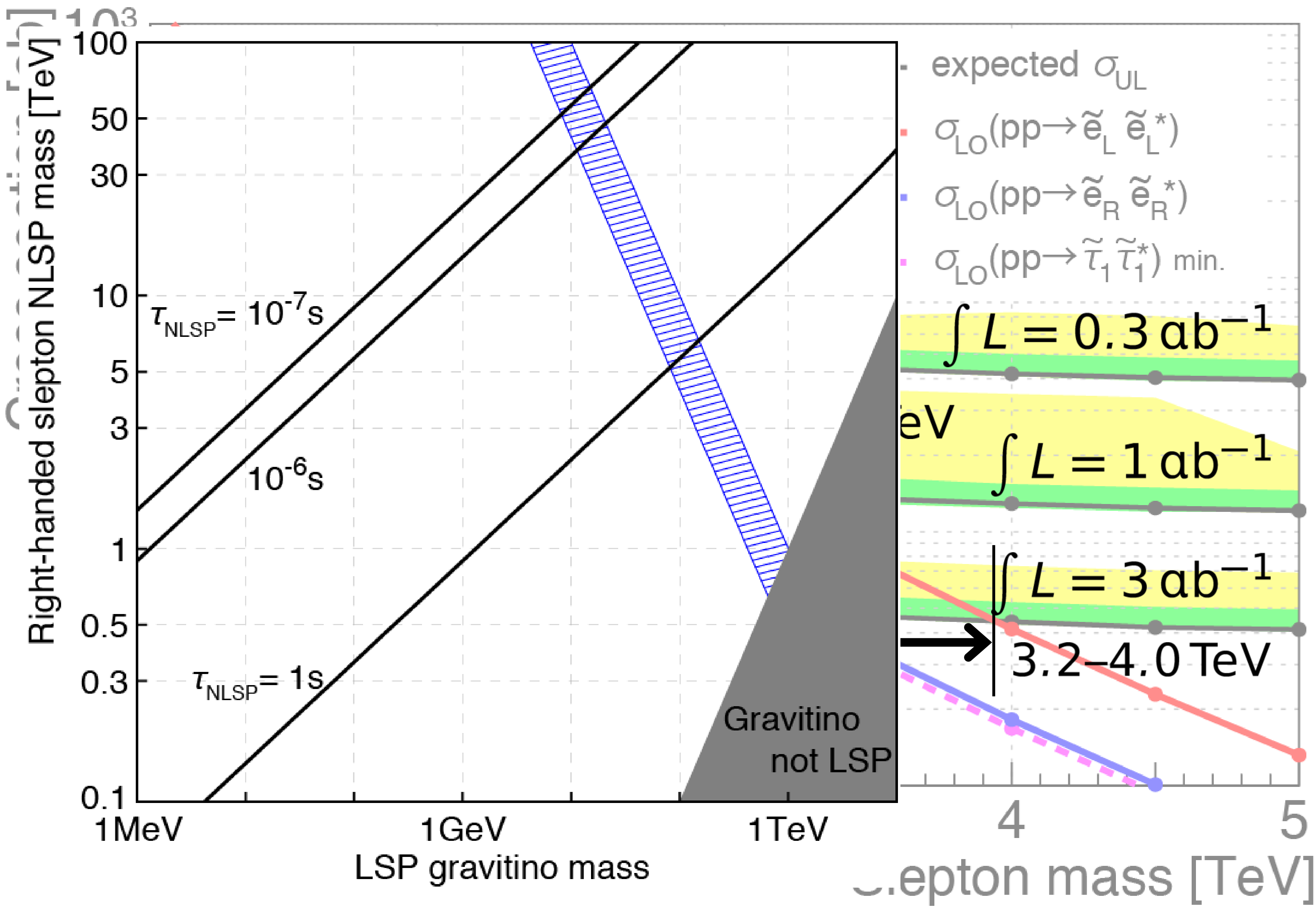
SR

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



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.
$\int L = 0.3\,\mathrm{ab}^{-1}$
$\int L = 1\,\mathrm{ab}^{-1}$
$\int L = 3\,\mathrm{ab}^{-1}$


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


Right-handed slepton NLSP mass [TeV]
100
50
30
10
5
3
1
0.5
0.3
0.1
τ_{NLSP}= 10^{-7}s
10^{-6}s
τ_{NLSP}= 1s
Gravitino not LSP
1MeV
1GeV
1TeV
LSP gravitino mass
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.
$\int L = 0.3\,\mathrm{ab}^{-1}$
$\int L = 1\,\mathrm{ab}^{-1}$
$\int L = 3\,\mathrm{ab}^{-1}$
3.2–4.0 TeV
4
5

3. LLCP @ FCC-he

Kechen Wang (DESY),
S.I. (Technion),
Monica D'Onofrio (U. Liverpool),
Georges Azuelos (U. Montreal, TRIUMF) [17??.?????]

(subgroup in BSM@ep collaboration)

- FCC-he main targets:
  - PDFs
  - strong coupling
- What's more?
  - Higgs & Electroweak physics
  - QCD (heavy quark PDFs)
  - low-x physics (non-linear QCD?)
- 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]

- Slepton LSP decaying
  - to ~keV gravitino
  - via tiny R-parity violation

["stable" / in-flight decay]

$$c\tau \sim 1.8\times10^{-5}\,\mathrm{m}\left(\frac{m_{\tilde{l}}}{100\,\mathrm{GeV}}\right)^{-5}\left(\frac{m_{\tilde{G}}}{1\,\mathrm{eV}}\right)^{2}, \quad 0.50\,\mathrm{m}\left(\frac{m_{\tilde{l}}}{100\,\mathrm{GeV}}\right)^{-1}\left(\frac{\lambda_{ijk}}{10^{-8}}\right)^{-2}.$$

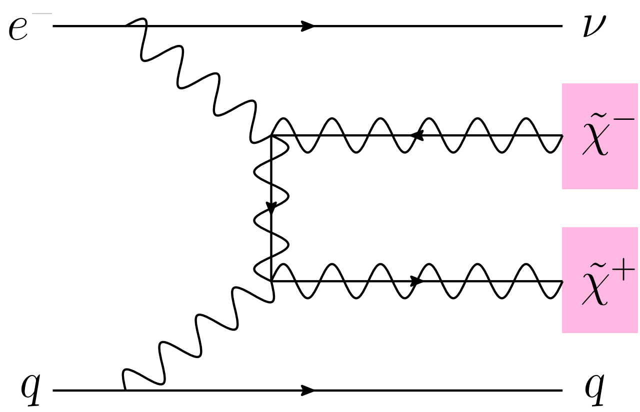
- Pure-Wino LSP / Pure-Higgsino LSP [in-flight decay]
  - long-lived because of small $\delta m = m_{\tilde{W}^\pm} - m_{\tilde{W}^0}$, $m_{\tilde{H}^\pm} - m_{\tilde{H}^0}$

$m_{\tilde{W}}$ [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

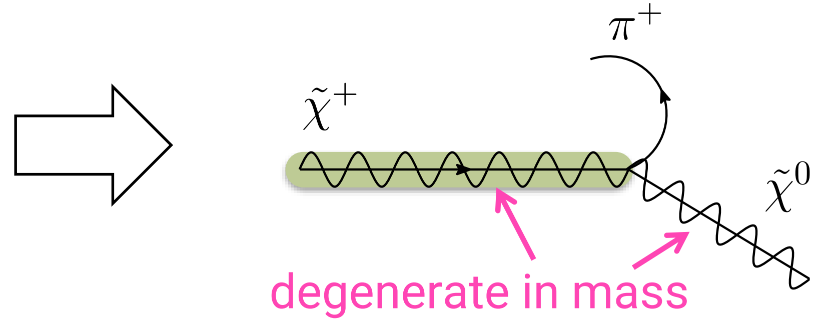
$m_{\tilde{H}}$ [GeV]	200	250	300	350	400	450	500	550	600	700	800	900
δm [MeV]	297	306	313	319	323	326	329	331	333	336	338	340
$c\tau$ [mm]	11	10	9.4	8.9	8.5	8.2	8.0	7.8	7.7	7.4	7.2	7.1

(Higgsino is more challenging because of smaller $c\tau$)

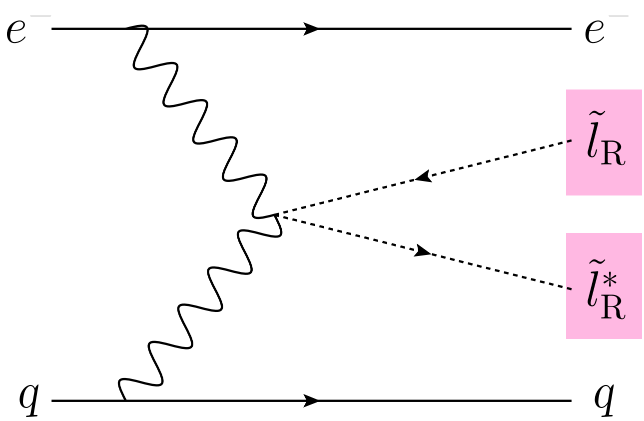
- Simplest models: 4-body production; $\sigma < 1$ fb ... (´・ω・`)
  - Pure-Wino / Pure-Higgsino LSP



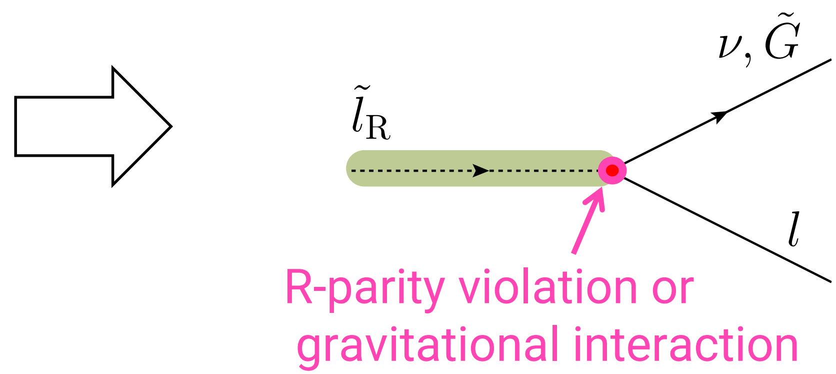
disappearing track



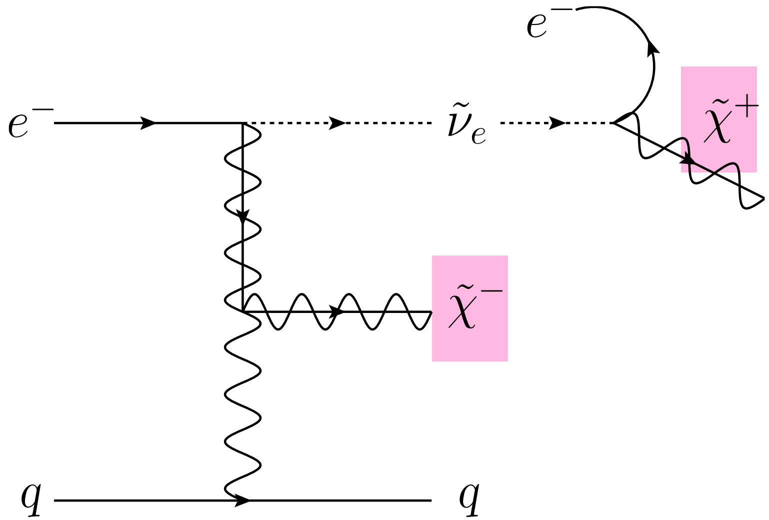
  - Slepton LSP



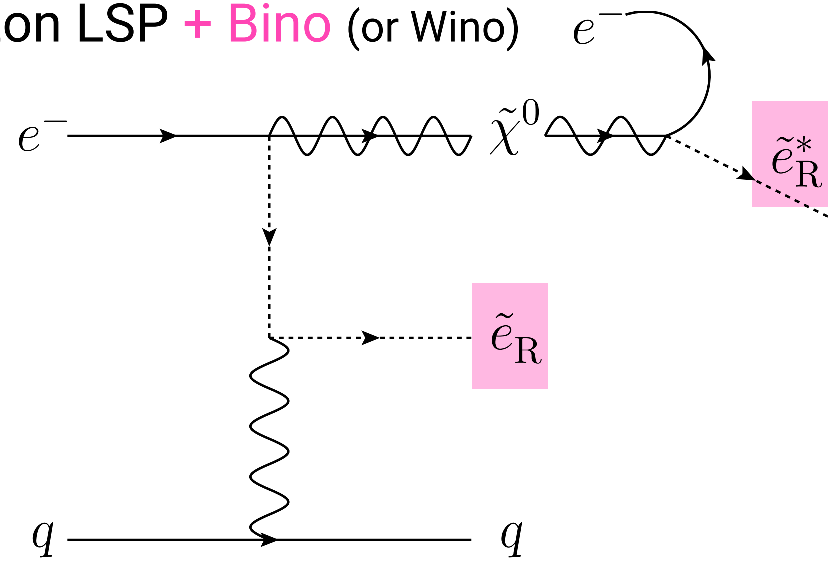
disappearing track (or "kink")



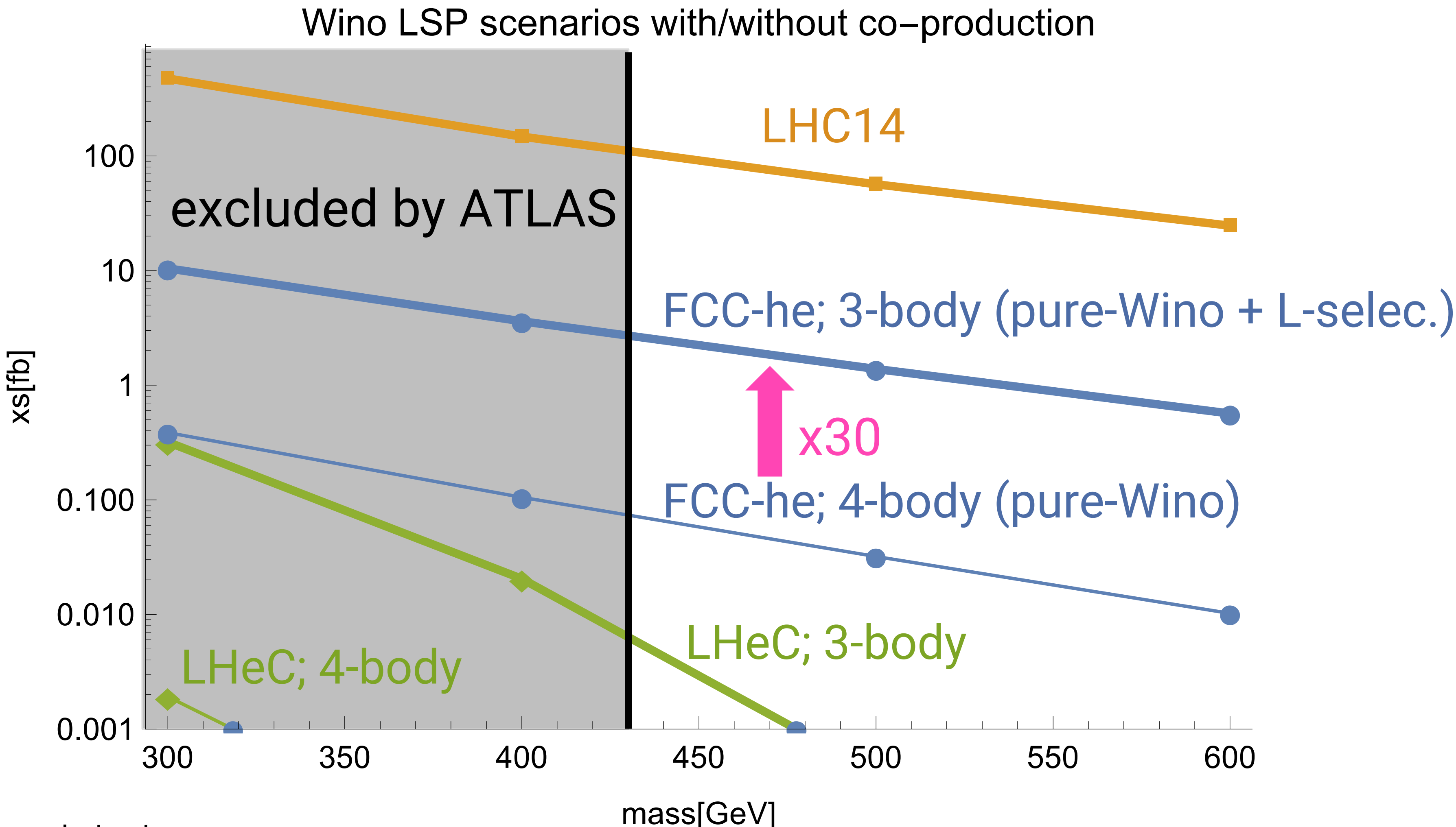
- Introducing co-LSP allows **3-body** production
  - Pure-Wino ~~/ Pure-Higgsino LSP~~ + left-handed selectron



  - Slepton LSP + Bino (or Wino)



- Nominal production cross section (without acceptances / efficiencies)

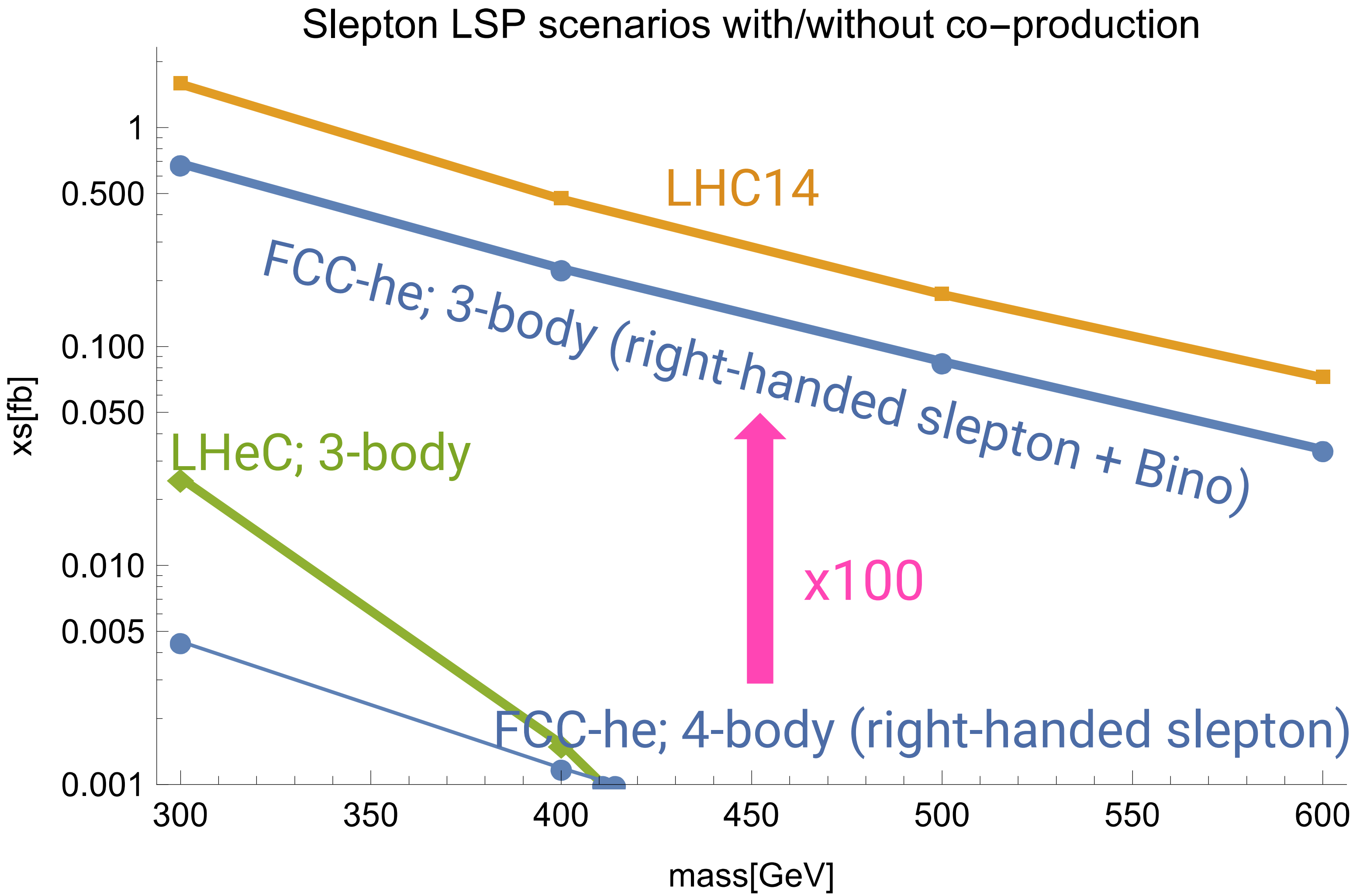


With no polarization.

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 $m_{\tilde{\chi}_1^0} = m_{\tilde{e}} + 1\,\mathrm{GeV}$

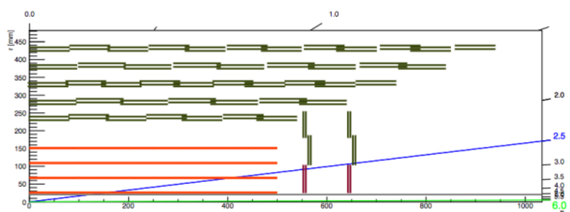
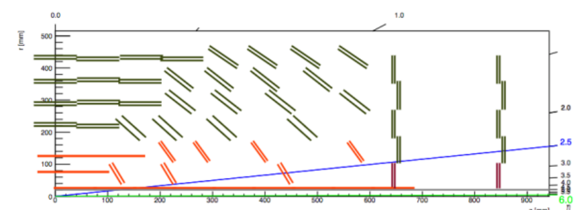
- SUSY scenarios with LLCP:
  - Pure-Wino LSP
  - Slepton LSP (with a lighter gravitino / tiny RpV)

  } **4-body production**; HL-LHC will be better.

  - Pure-Higgsino LSP → too small lifetime; not promising.
- Add another sparticle: **3-body production; much more events**
  - Pure-Wino LSP + left-handed slepton
  - Slepton LSP + Bino (or Wino)

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

❖ Analysis with the proposed detector layout is ongoing.

❖ Any "theoretical" motivation?

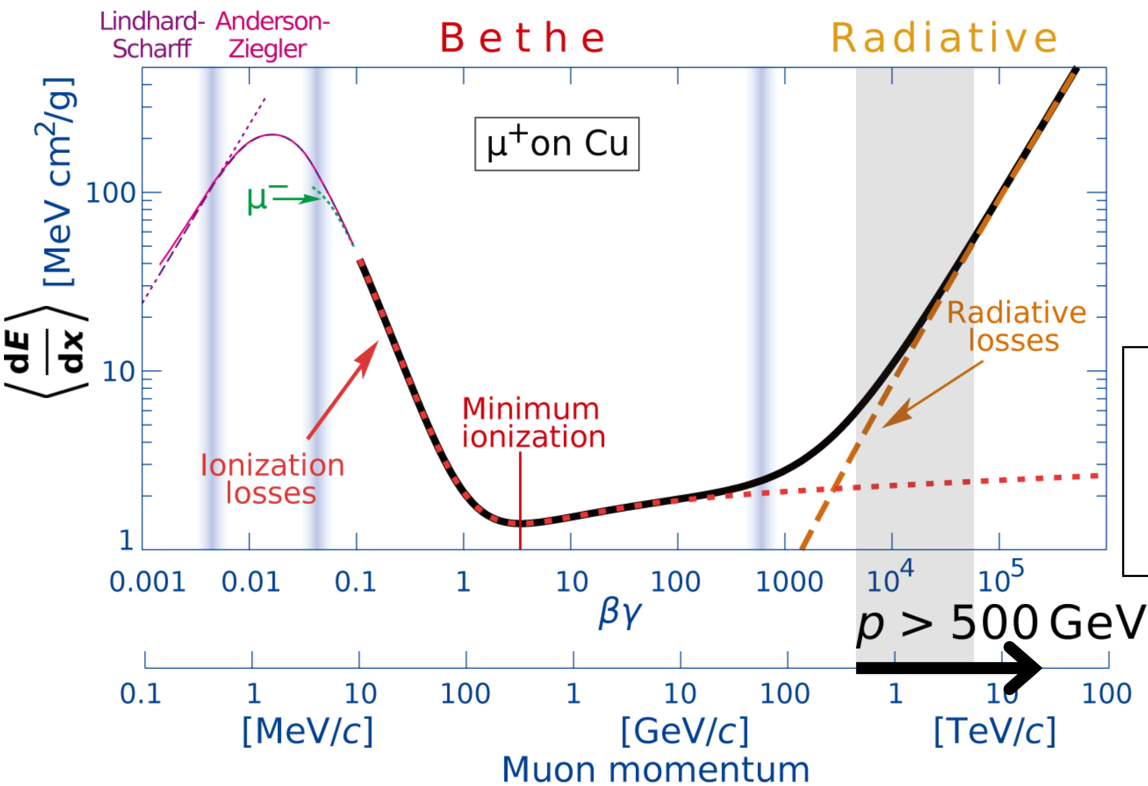
❖ Any other ideas to improve the sensitivity?

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

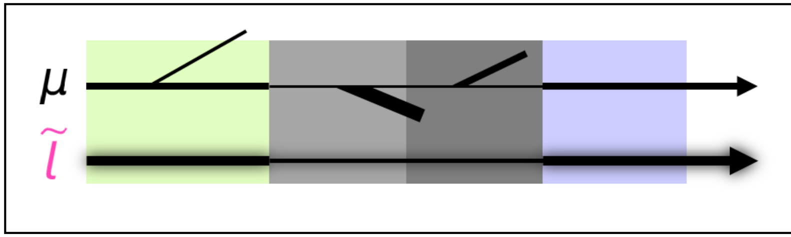
	0.3ab^{-1}	1ab^{-1}	3ab^{-1}
Exclusion	1.8−2.3	2.4−3.1	3.2−4.0
Discovery	1.6−2.2	2.3−3.0	3.1−4.0

in TeV

- **“Muon radiative energy loss”**

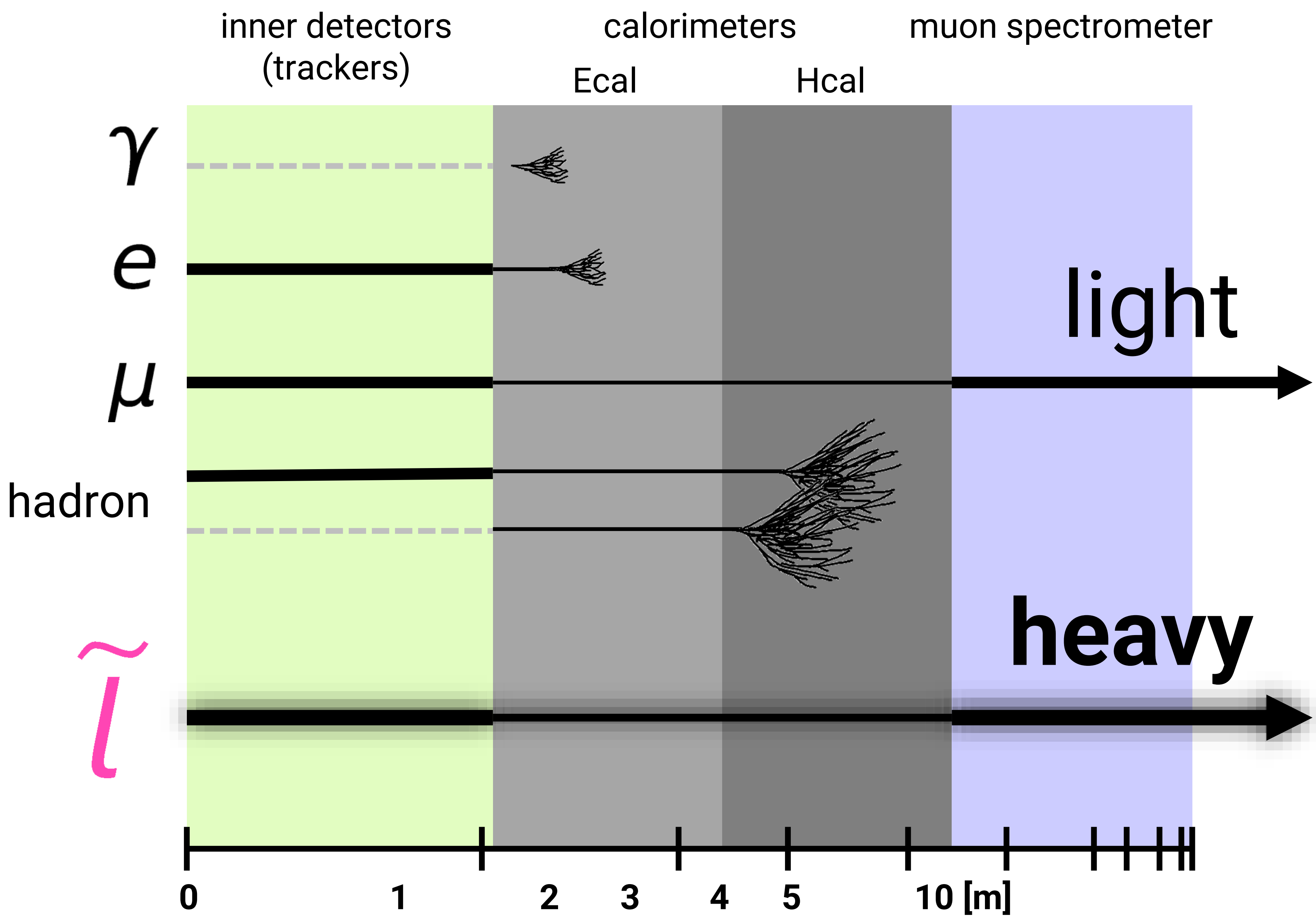


- Bremsstrahlung
- Photonuclear interaction
- e^+-e^- pair-production



→ **34%** of BKG reduction

Velocity measurement


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

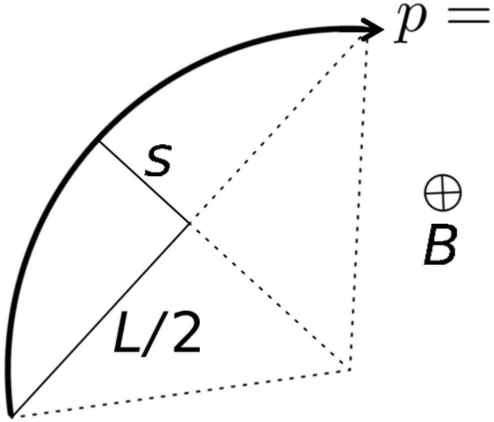
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

momentum & velocity

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

➢ momentum

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



➢ velocity

- TOF [time-of-flight]

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

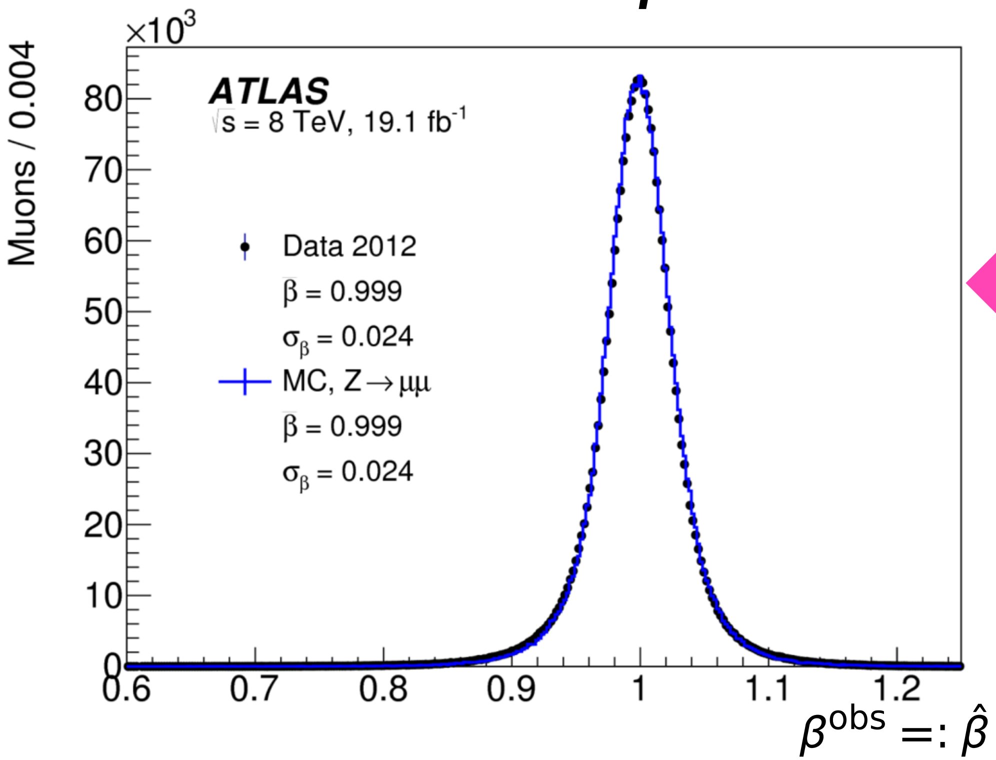
- d*E*/d*x* [ionization energy loss]

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

momentum & velocity

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

ATLAS muon data: **Δ*β* = 2.4%**



➢ velocity

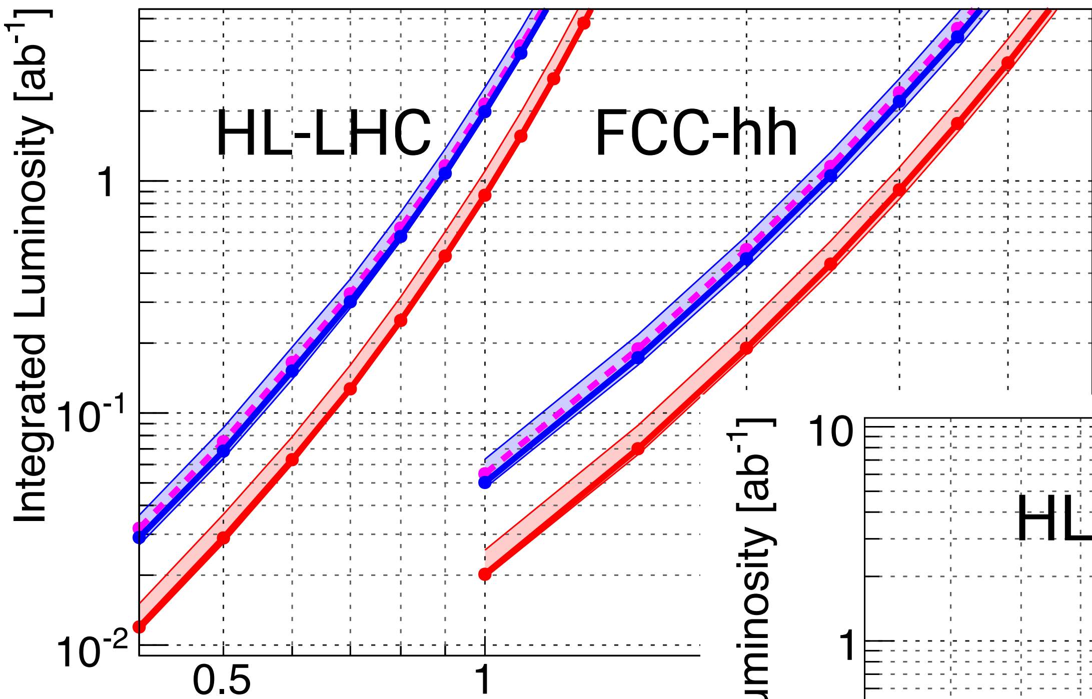
- TOF [time-of-flight]

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

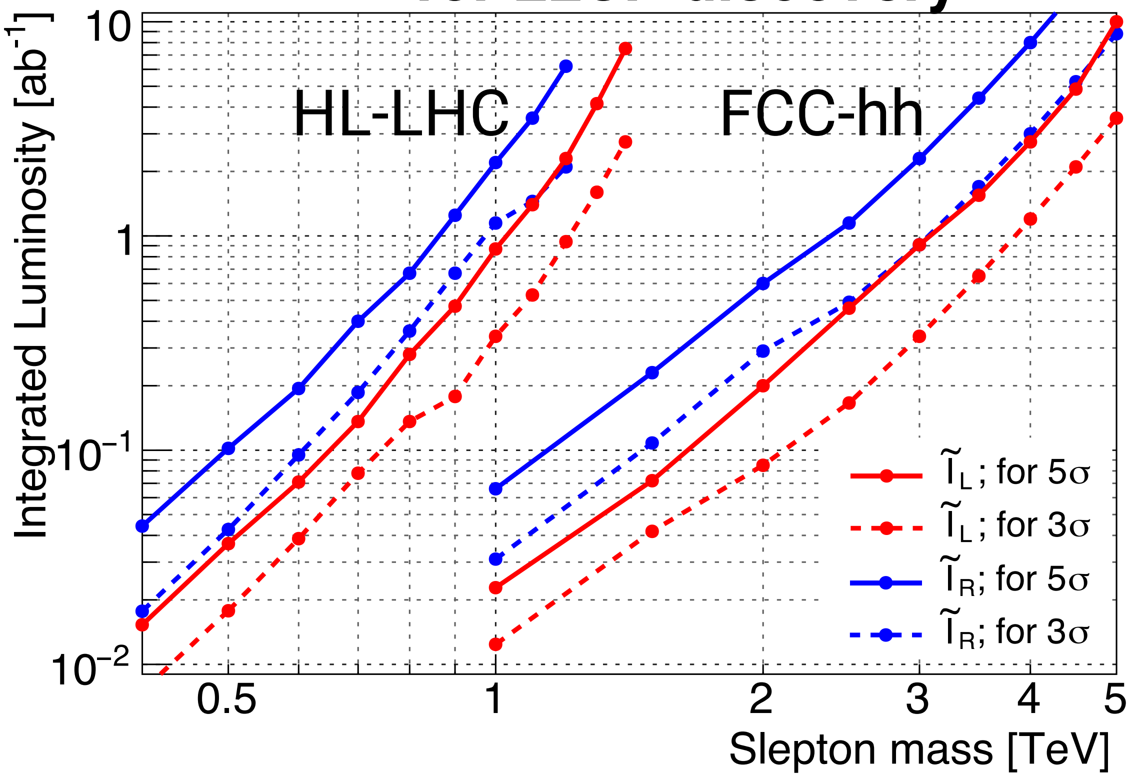
- d*E*/d*x* [ionization energy loss]

Exclusion & Discovery Reach

for LLCP exclusion



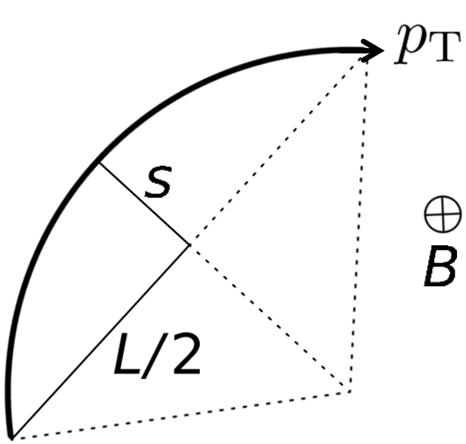
for LLCP discovery



Momentum resolution

Momentum resolution for very-large pT

ATLAS [1404.4562]; see also [1201.4704]



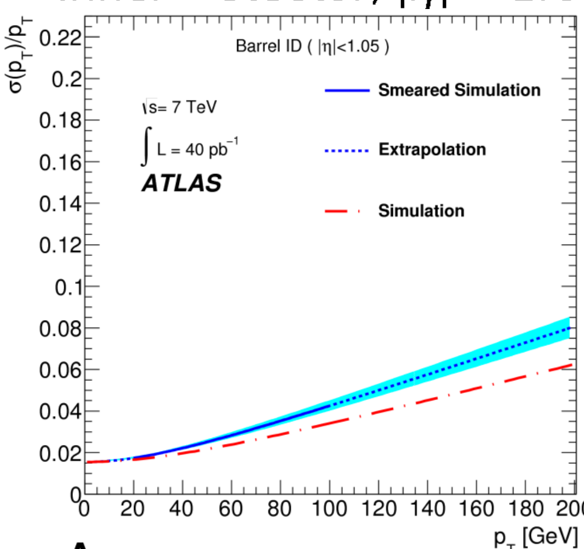
$$p_\mathrm{T} = \frac{L^2}{8s}|q|B \Longrightarrow \Delta p_\mathrm{T} = \frac{L^2|q|B}{8}\frac{\Delta s}{s^2} = \frac{8\Delta s}{L^2|q|B}\cdot p_\mathrm{T}^2$$

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

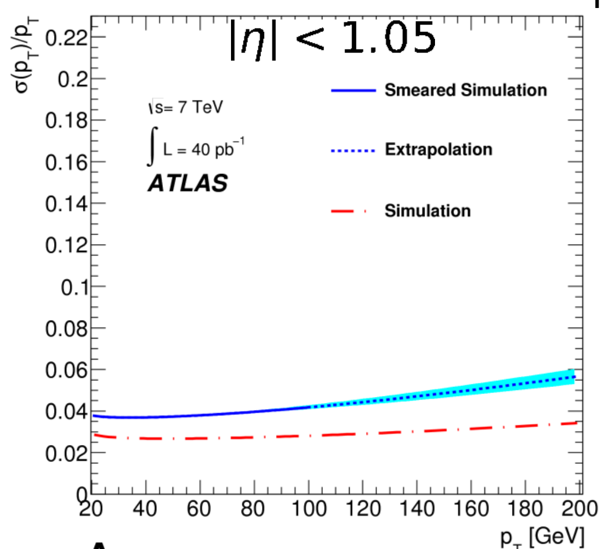
ATLAS 7 TeV results on muon momentum resolution

Inner Detector, $|\eta| < 1.05$

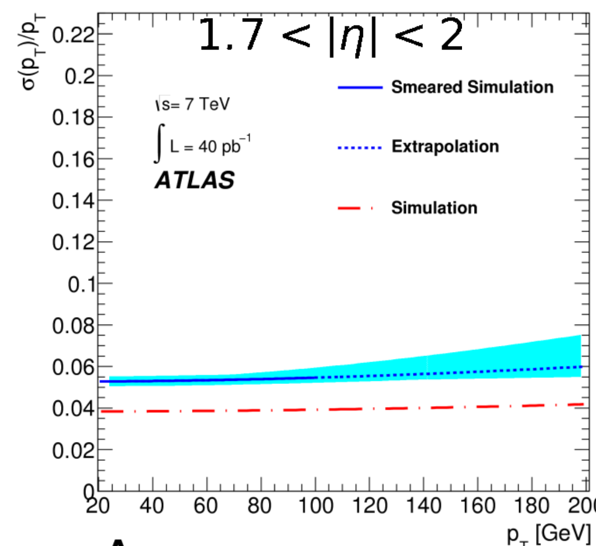
Muon spectrometer



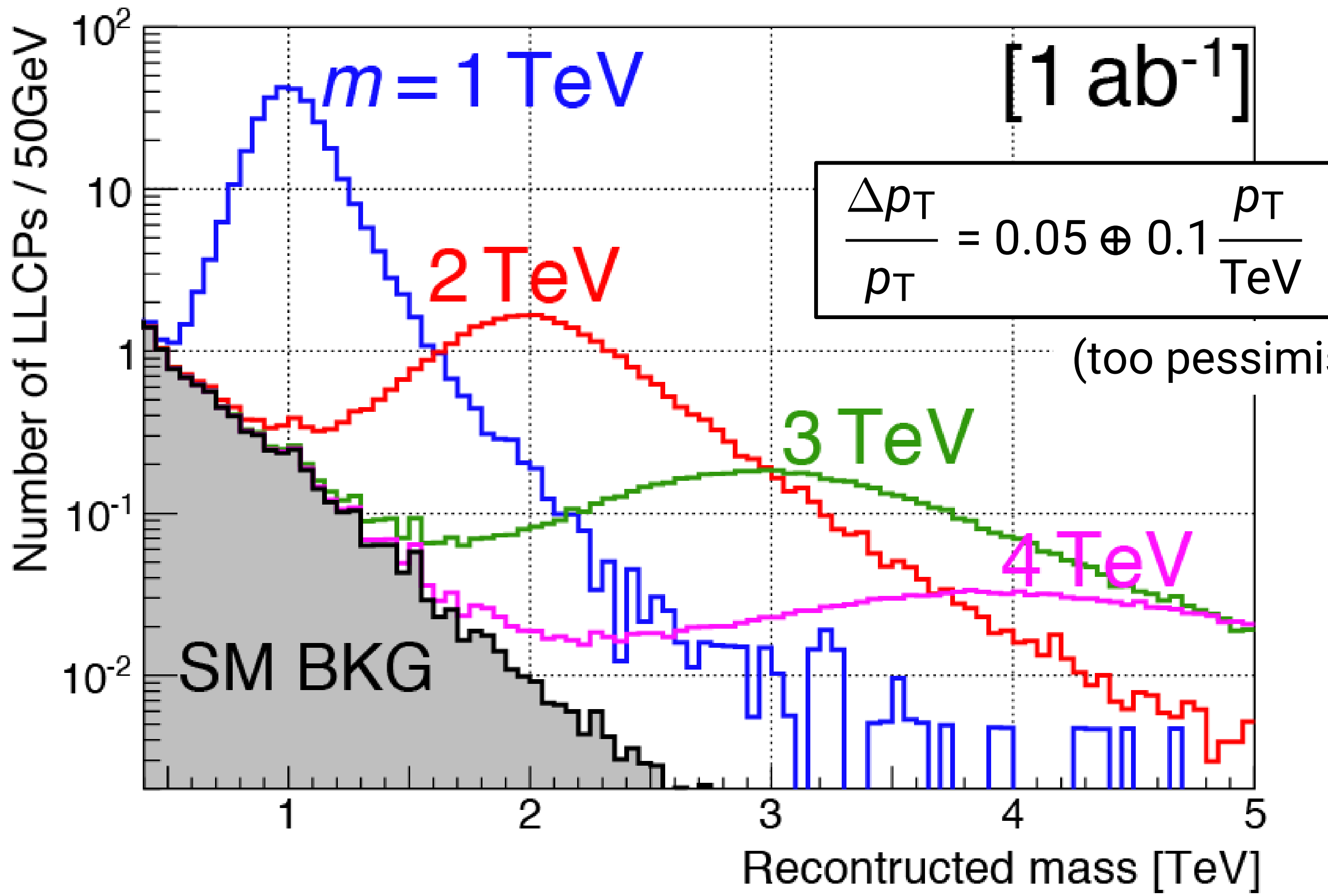
$$\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}} \sim 0.38 p_\mathrm{T}/\mathrm{TeV}$$



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



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



(too pessimistic?)

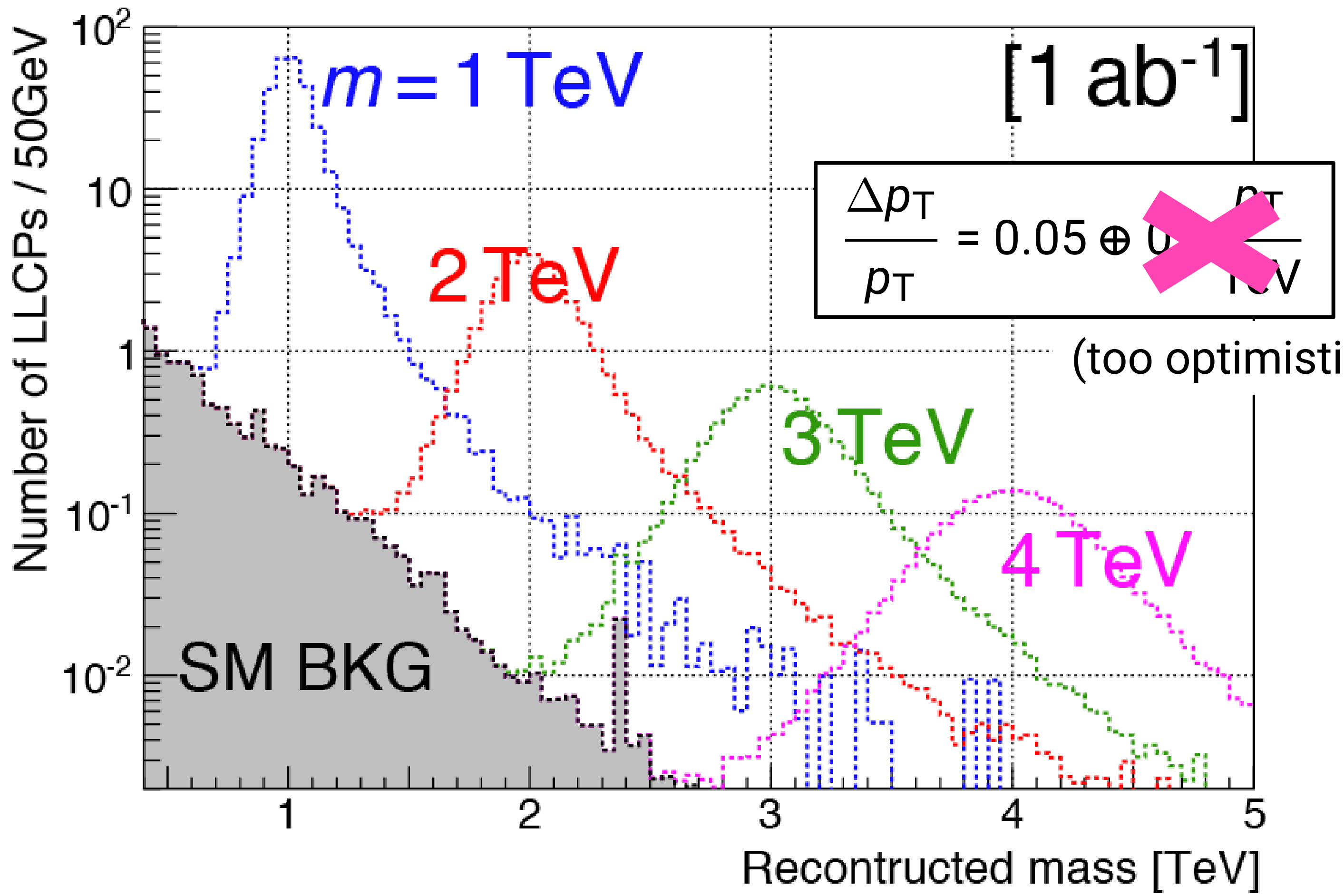
$$\left(= \frac{p}{\beta\gamma} = \frac{p_T \cosh \eta}{\beta\gamma} \right)$$

FCC-hh trk. goal: 10–20% @ 10 TeV (Michele Selvaggi's talk)

cf. ATLAS 7 TeV commissioning:

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

Feng, SI, Shadmi, Tarem [1505.02996]



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

FCC-hh trk. goal: 10–20% @ 10 TeV (Michele Selvaggi's talk)

cf. ATLAS 7 TeV commissioning:

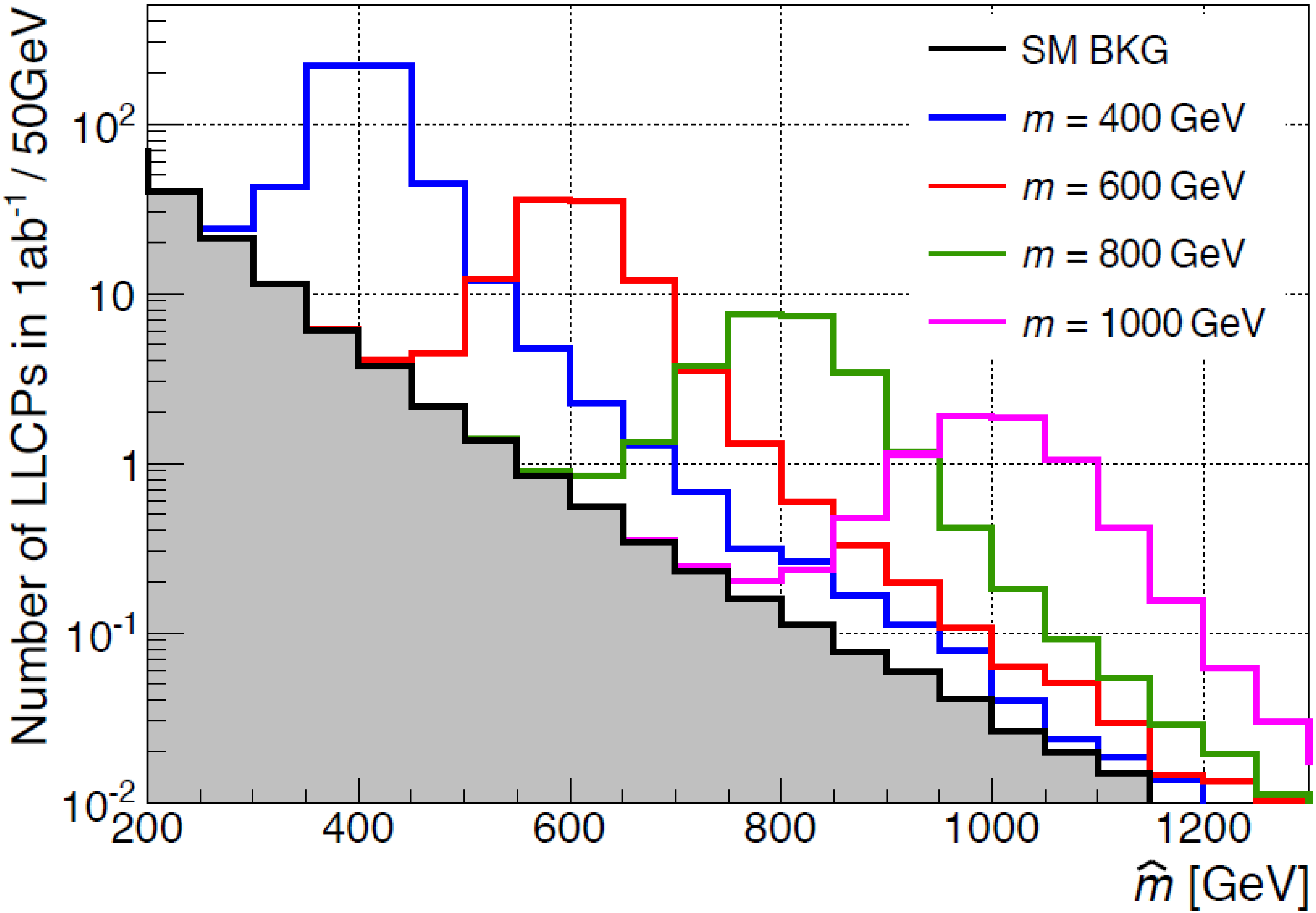
(ID-barrel, MS-barrel, MS-extbarrel) = (38%, 14%, 6%) @ 1 TeV

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

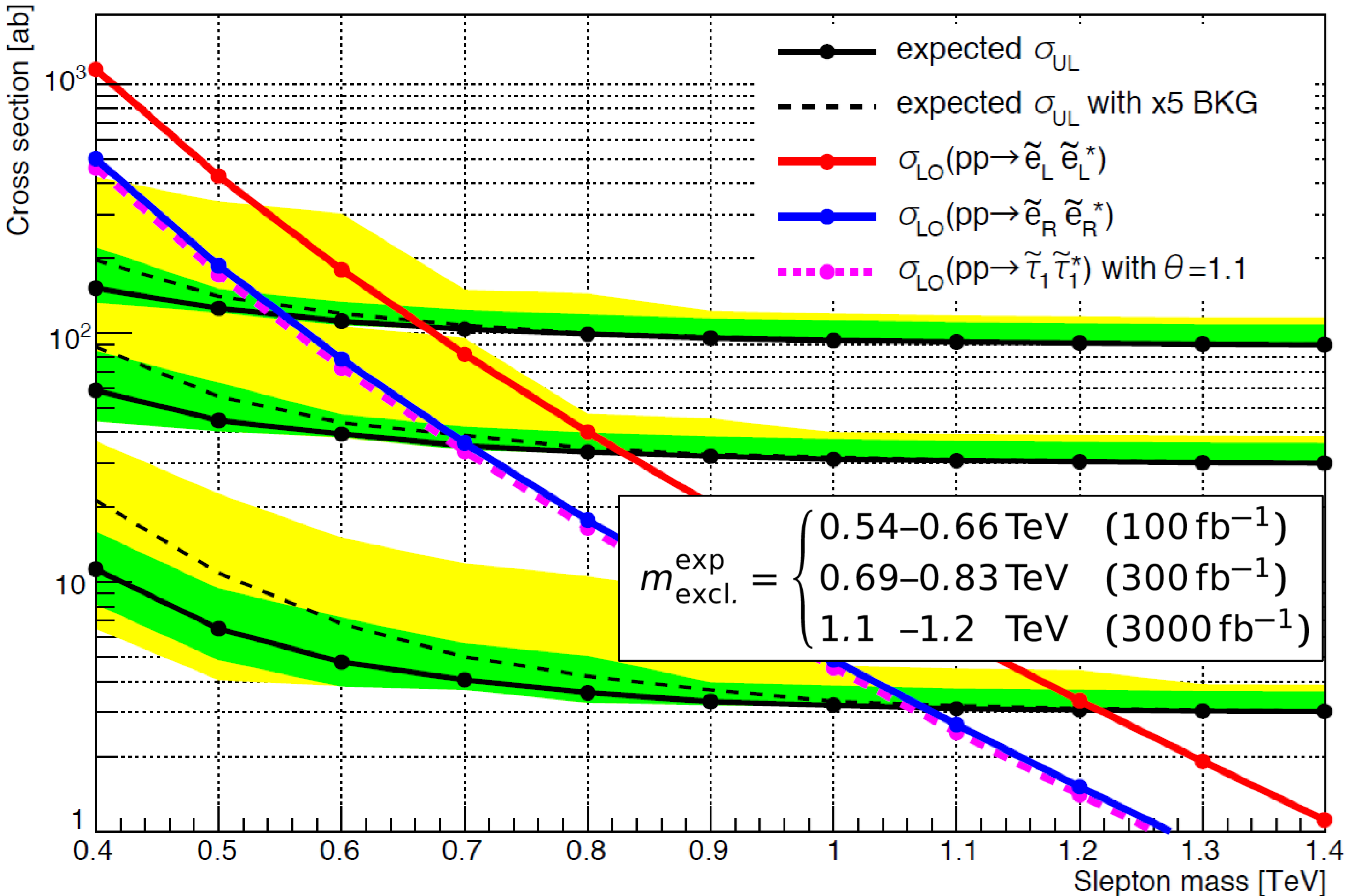
- $\tilde{l}$-selection flow

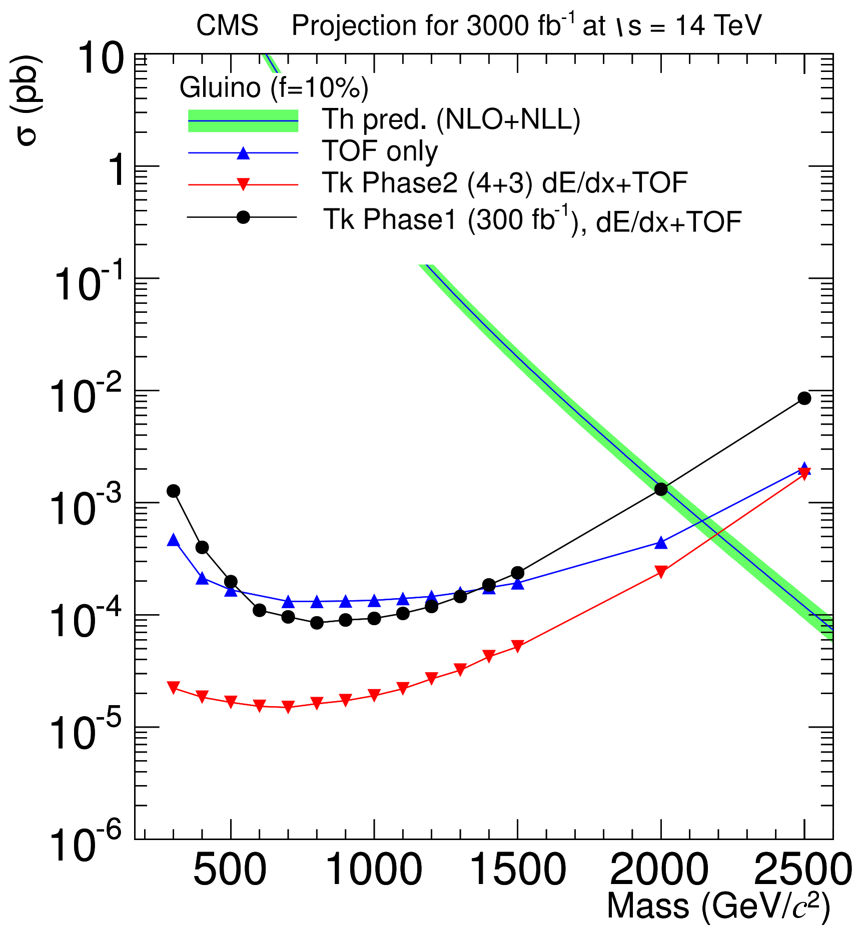
  reconstructed "muon" w.
  - $p_T > \mathbf{100}\,\mathrm{GeV}$
  - $|\eta| < 2.4$
  - $0.3 < \hat{\beta} < 0.95$
  - ~~$E_{\mathrm{loss}} < 30\,\mathrm{GeV}$~~
- Event selection
  - two $\tilde{l}$-candidates

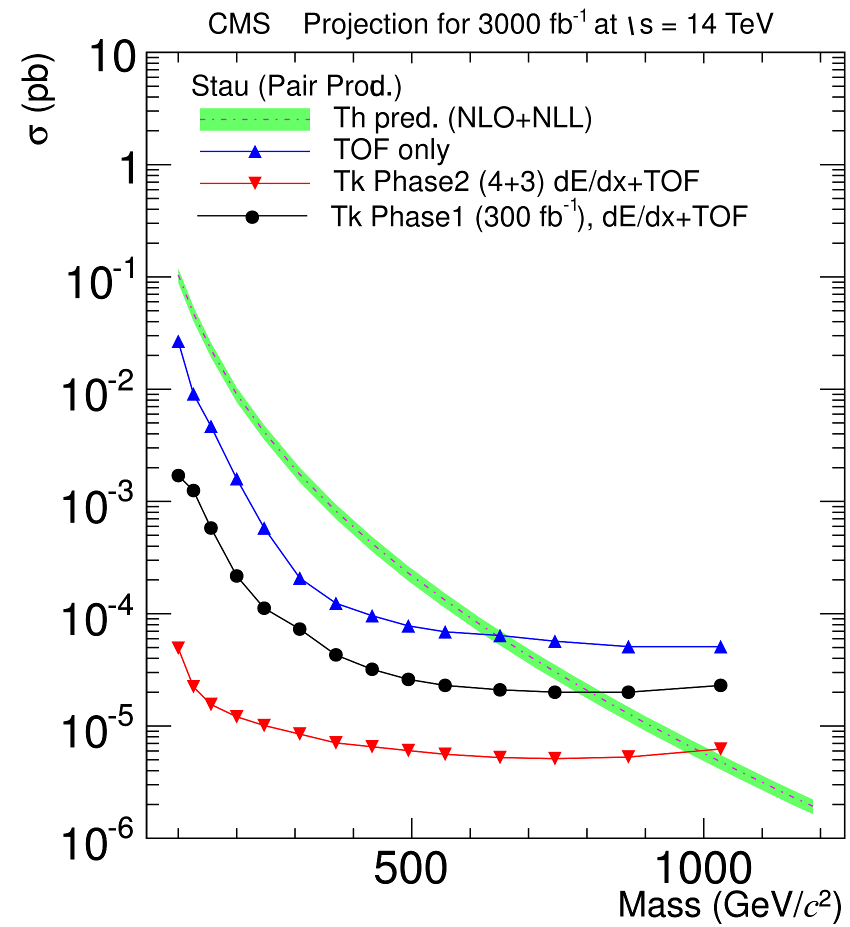

SM BKG
m = 400 GeV
m = 600 GeV
m = 800 GeV
m = 1000 GeV
Number of LLCPs in 1ab-1 / 50GeV
10^2
10
1
10^-1
10^-2
200
400
600
800
1000
1200
m̂ [GeV]

14 TeV LHC expectation

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



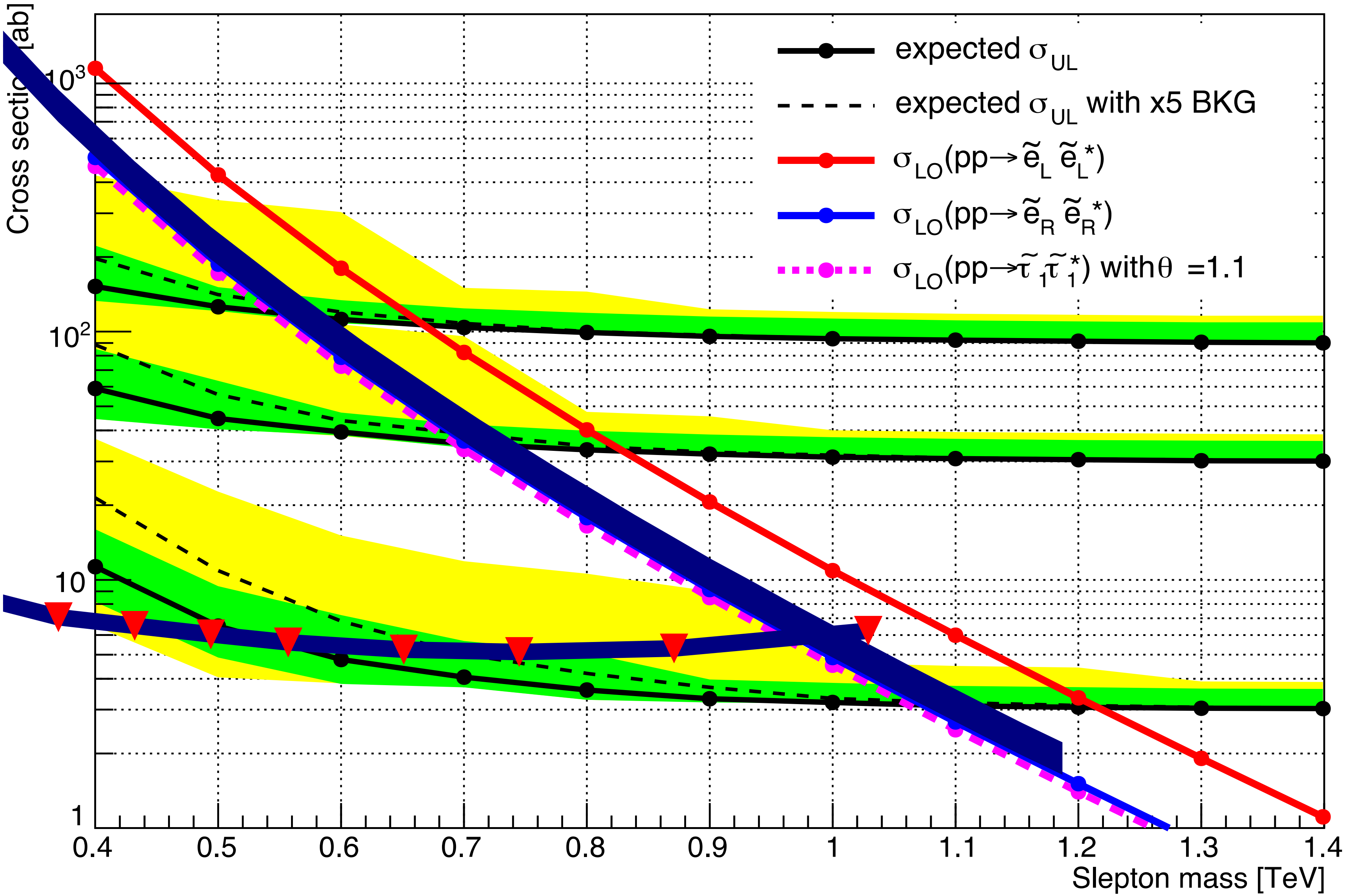


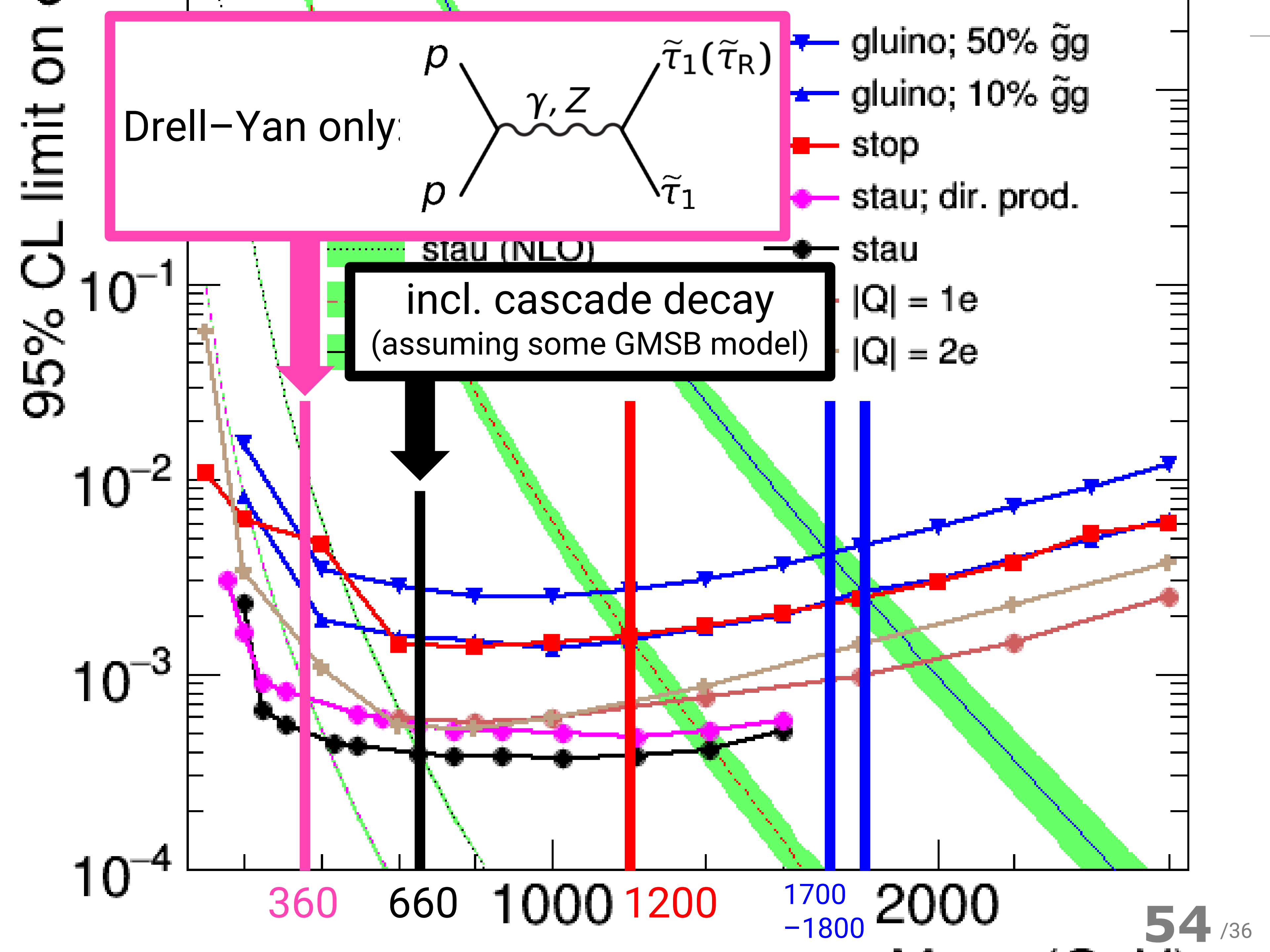


	current	HL-LHC
gluino:	1.7 TeV	→ 2.2 TeV?
stop:	1.2 TeV	→ 1.7 TeV?
stau (GMSB):	660 GeV	→ 1.2 TeV?
stau (DY):	360 GeV	→ 1.0 TeV?

(or discovery?)

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




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

Why β>0.4? (slepton dE/dx)

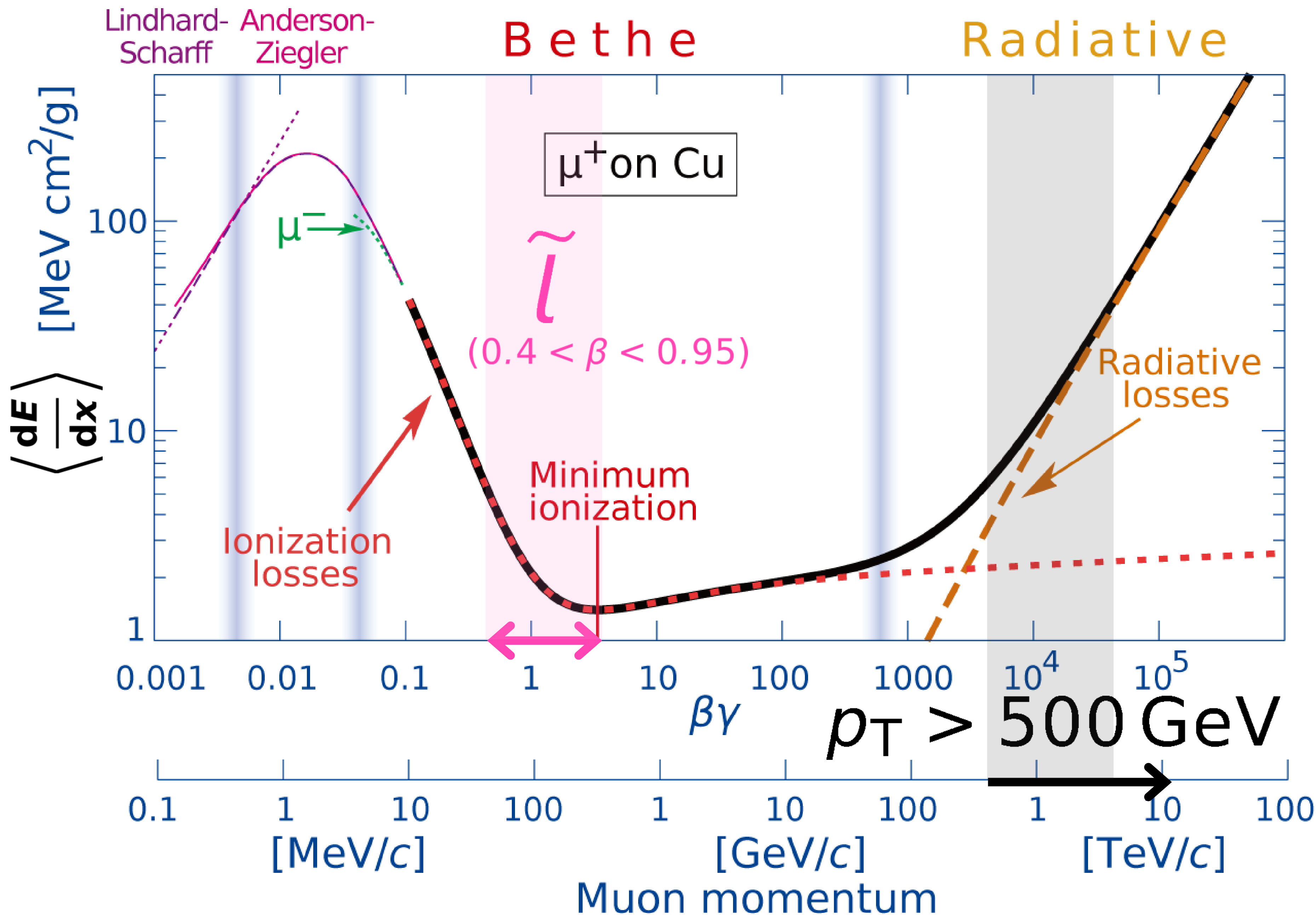


Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]