Long-lived charged particles at FCC-hh and FCC-he

Sho IWAMOTO（岩本　祥）

2 Nov. 2017
Seminar @ Tohoku 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)

0. Collider Physics basic
1. LLCPs
2. Future colliders (FCC-hh and FCC-he)
3. LLCP searches at FCC-hh
4. LLCP searches at FCC-he

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SUSY searches at the LHC : Nothing found

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Israel Institute of Technology

c-tagging for new physics at the LHC

Sho IWAMOTO（岩本　祥）

25 Oct. 2017
Workshop on beyond standard model and the early universe
@ Tohoku University

Sho Iwamoto, Gabriel Lee, Yael Shadmi, Yaniv Weiss [1703.05748]

(and discussion with Jonathan Shlomi @ Weizmann/ATLAS)

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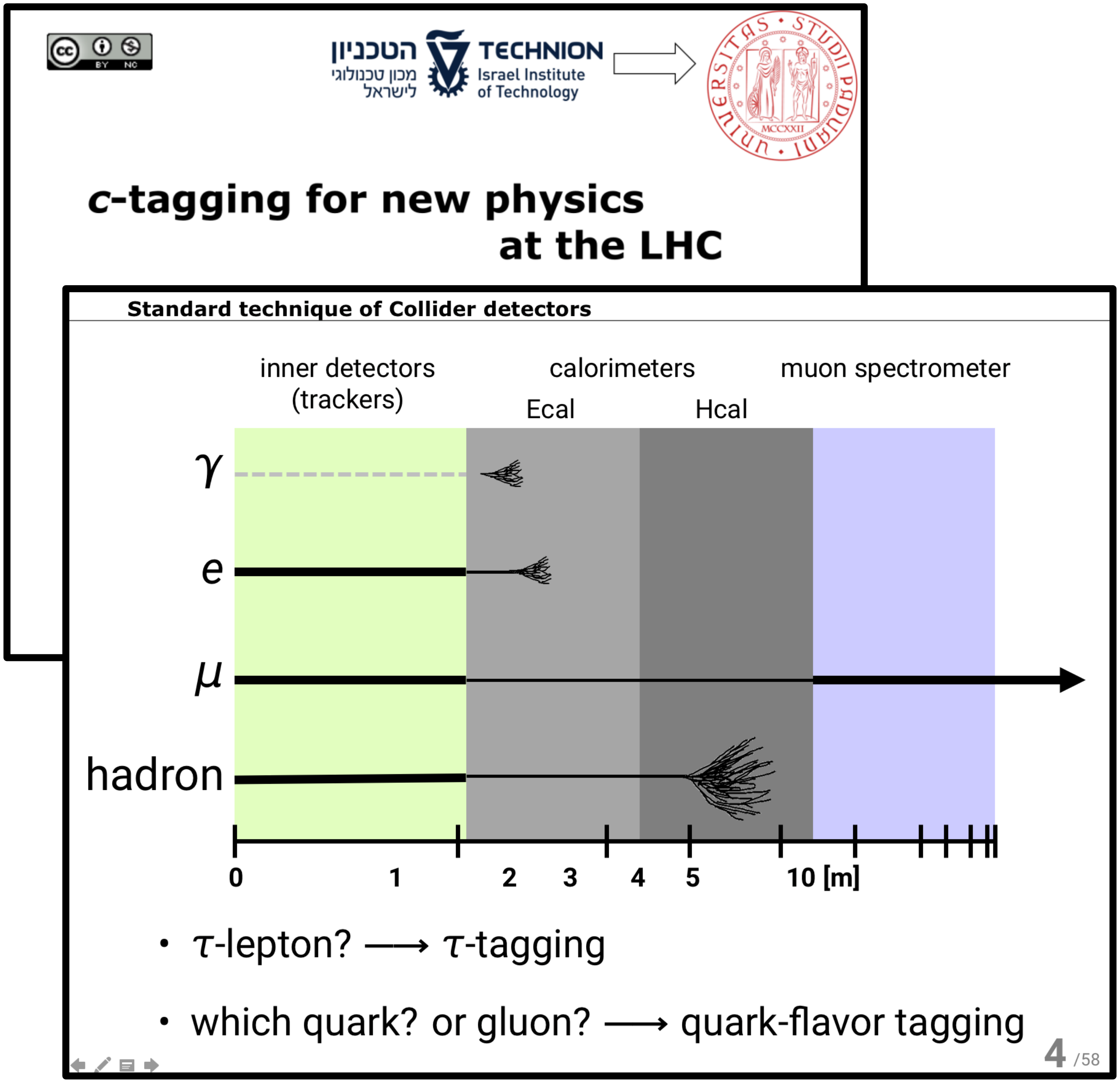

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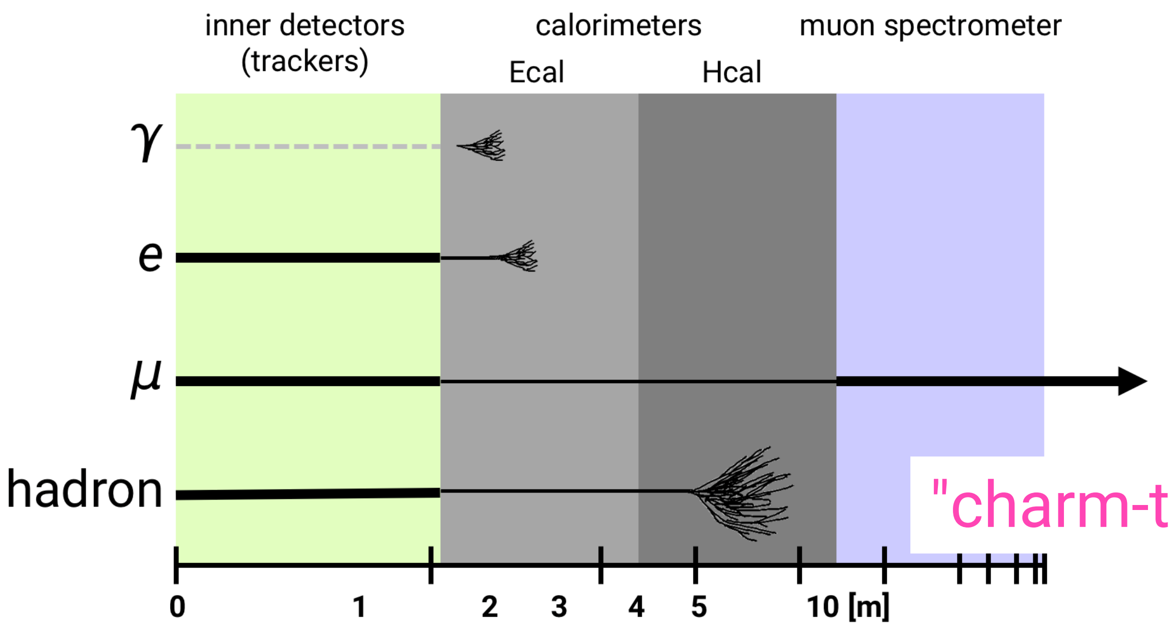
c-tagging for new physics at the LHC

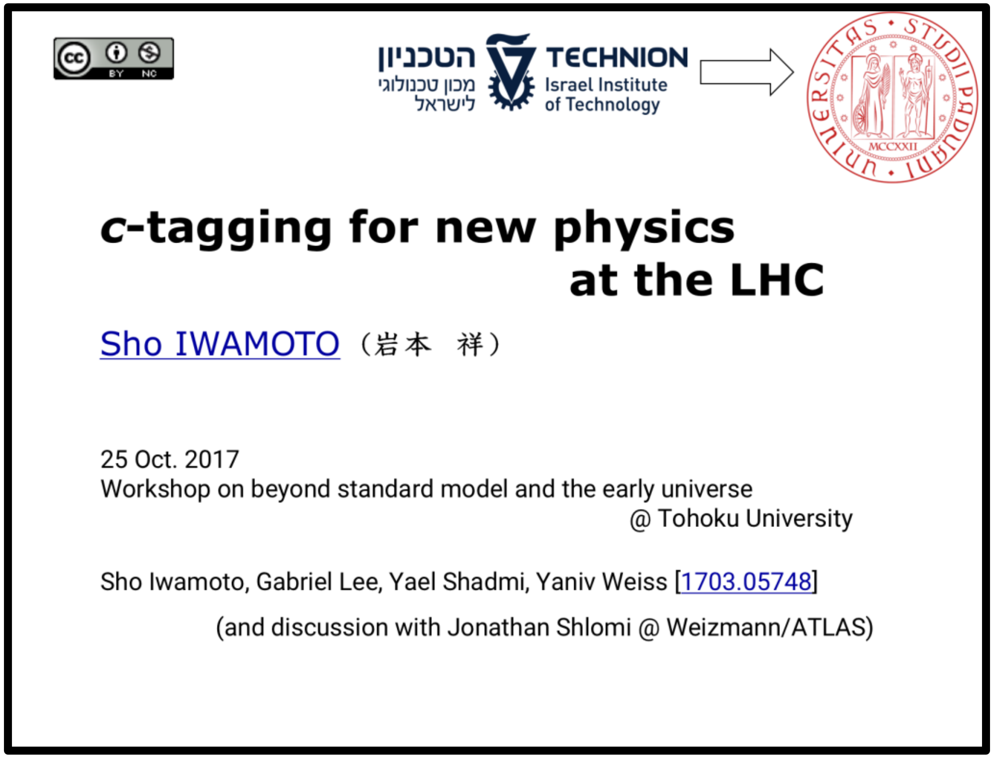
Standard technique of Collider detectors



"charm-tagging"

- τ-lepton? ⟶ τ-tagging
- which quark? or gluon? ⟶ quark-flavor tagging

4 /58



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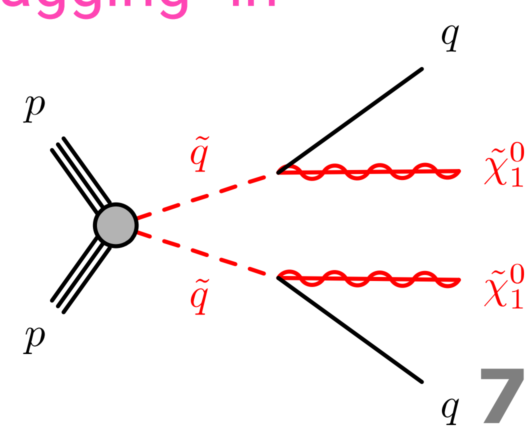
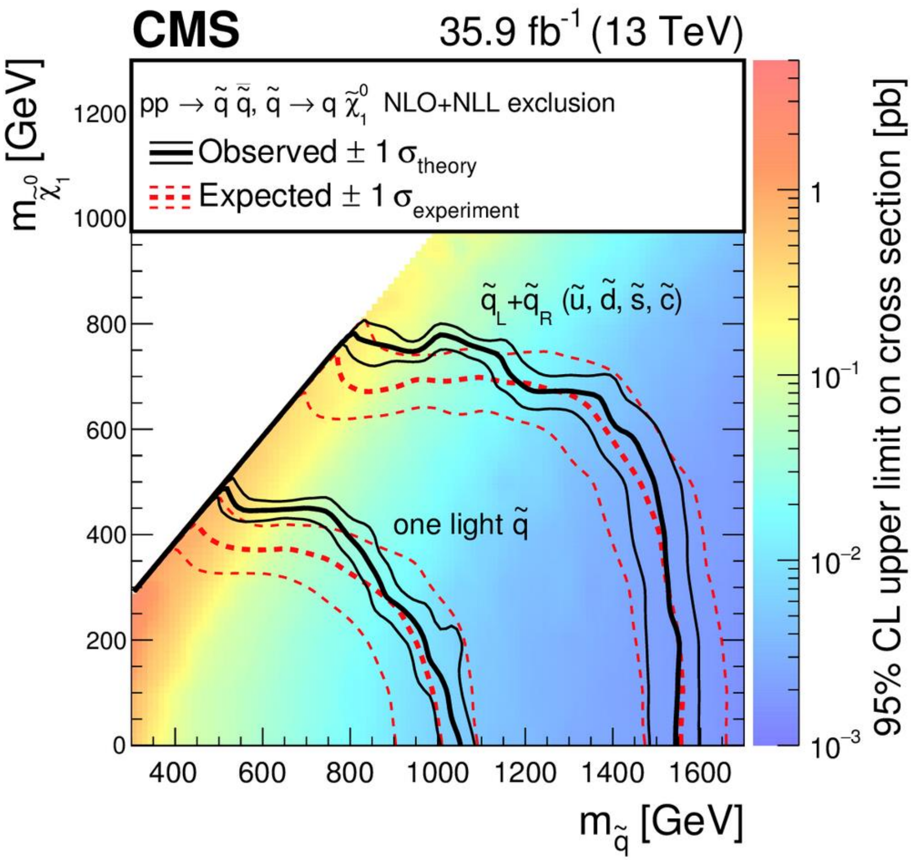
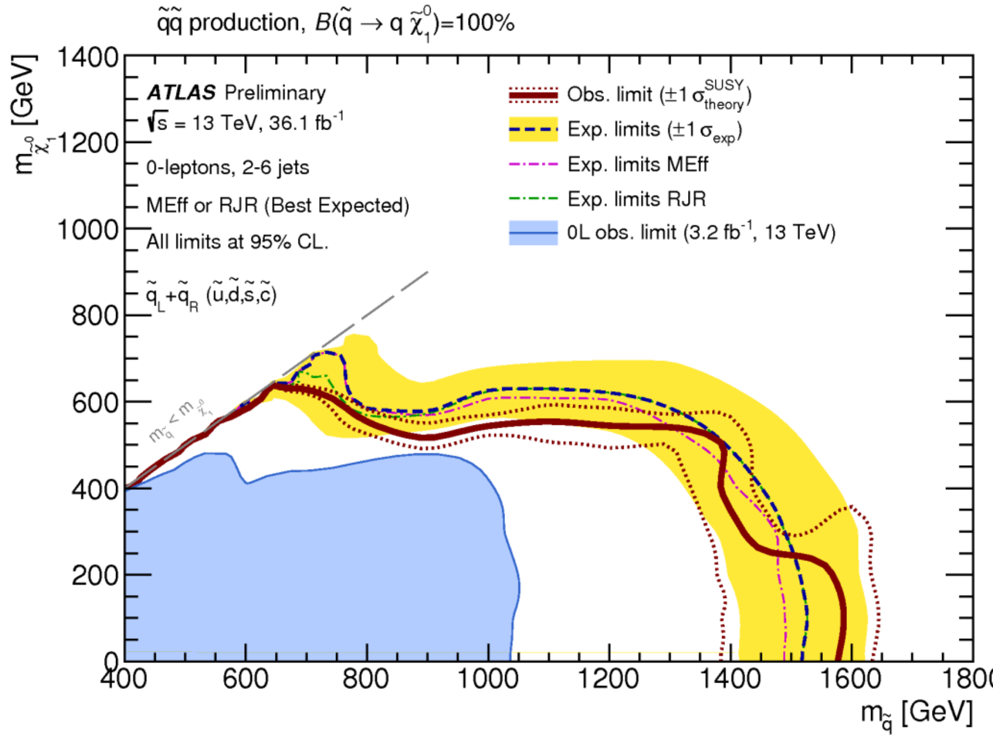
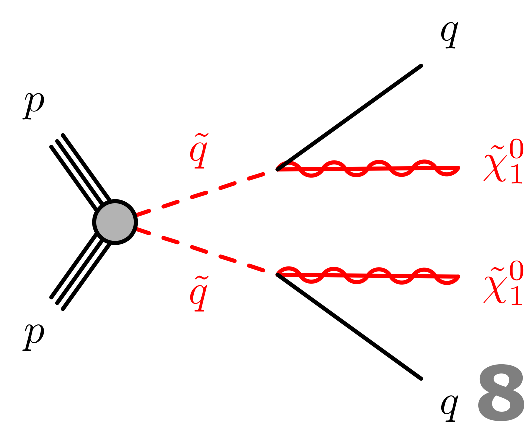
"charm-tagging" in

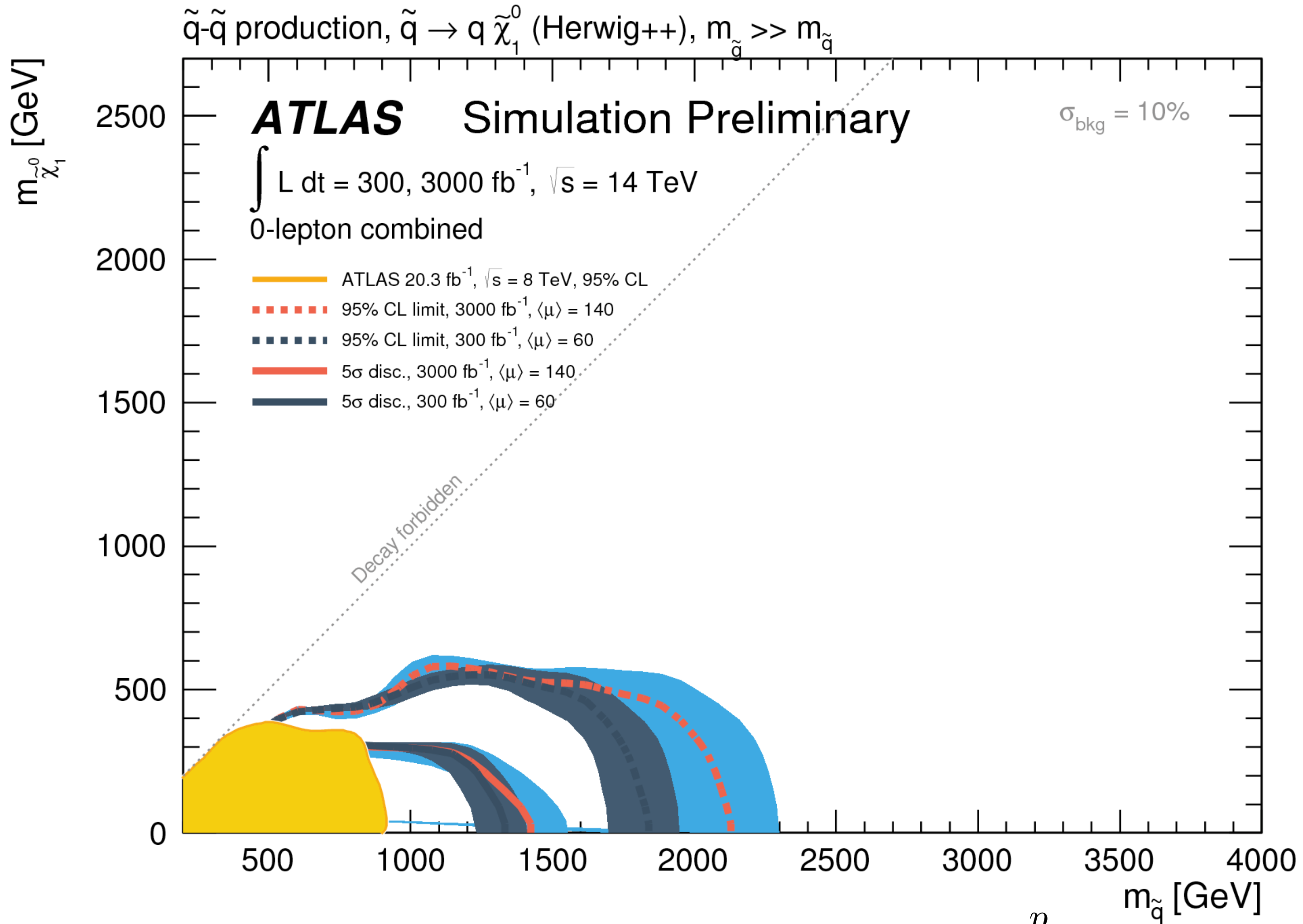


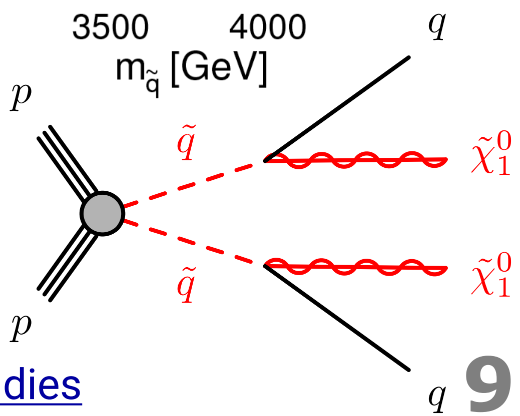




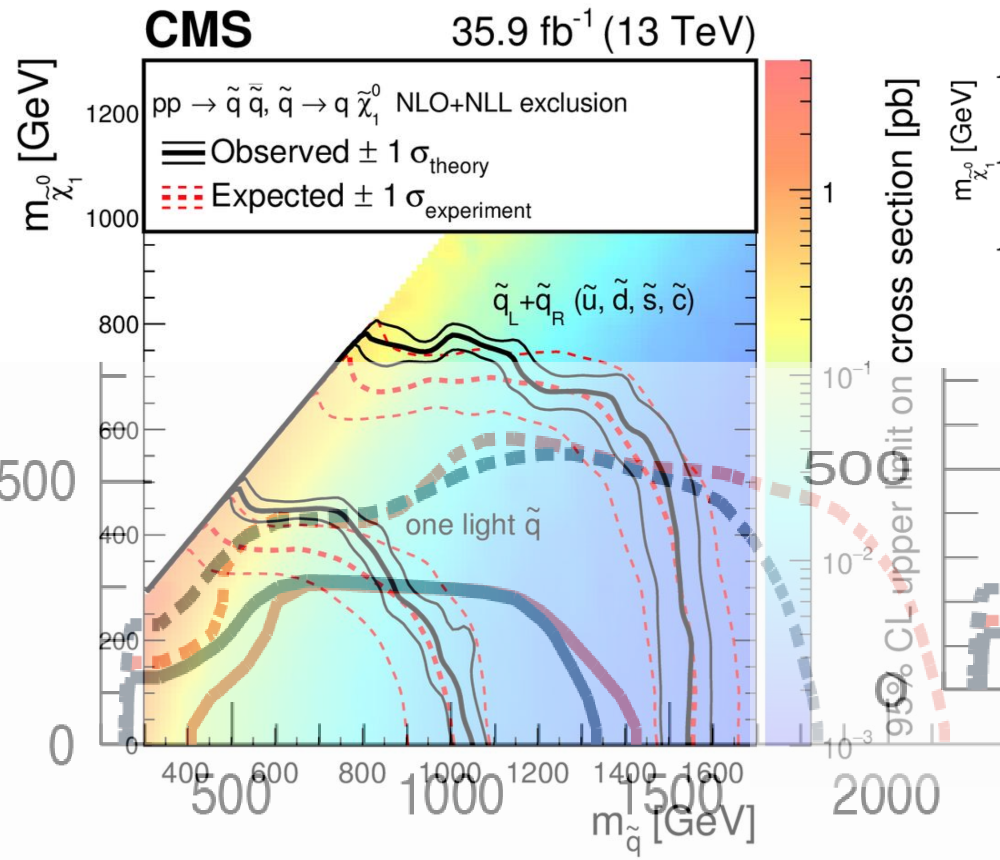
[1705.04650](1705.04650) / ATLAS-CONF-2017-022

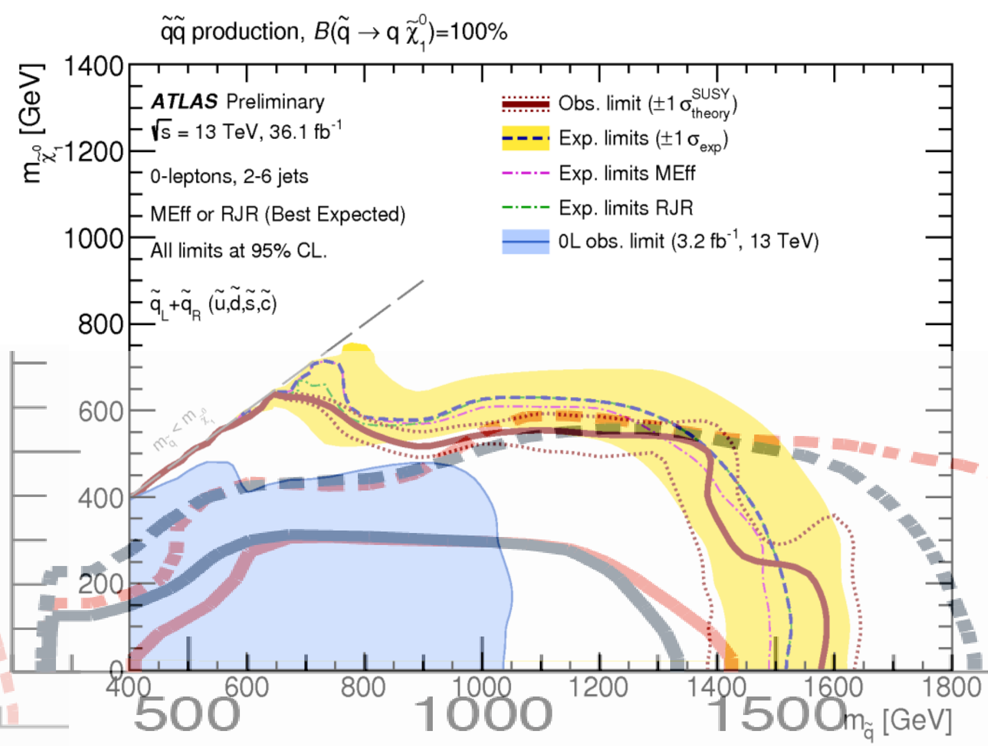






ATL-PHYS-PUB-2014-010
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies





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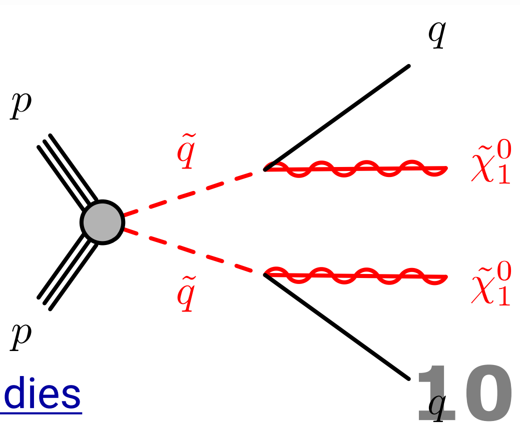

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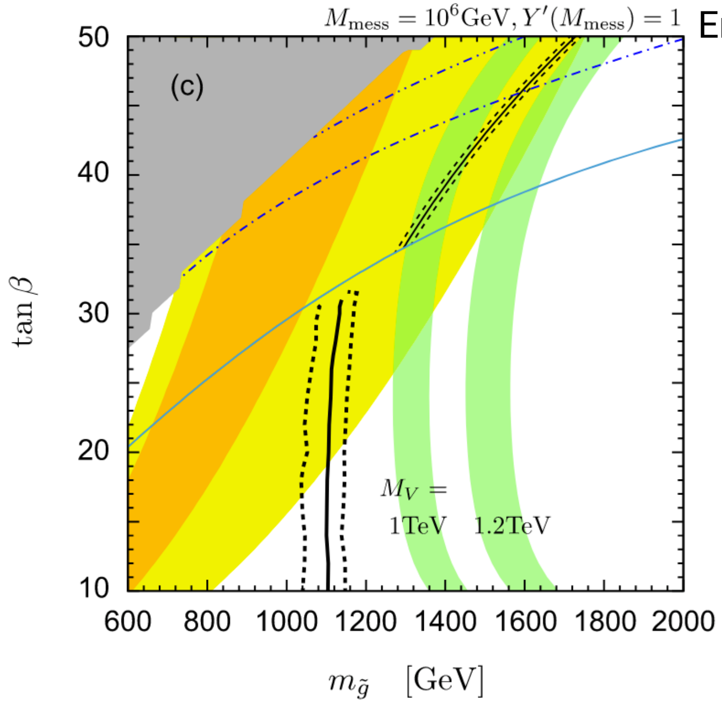
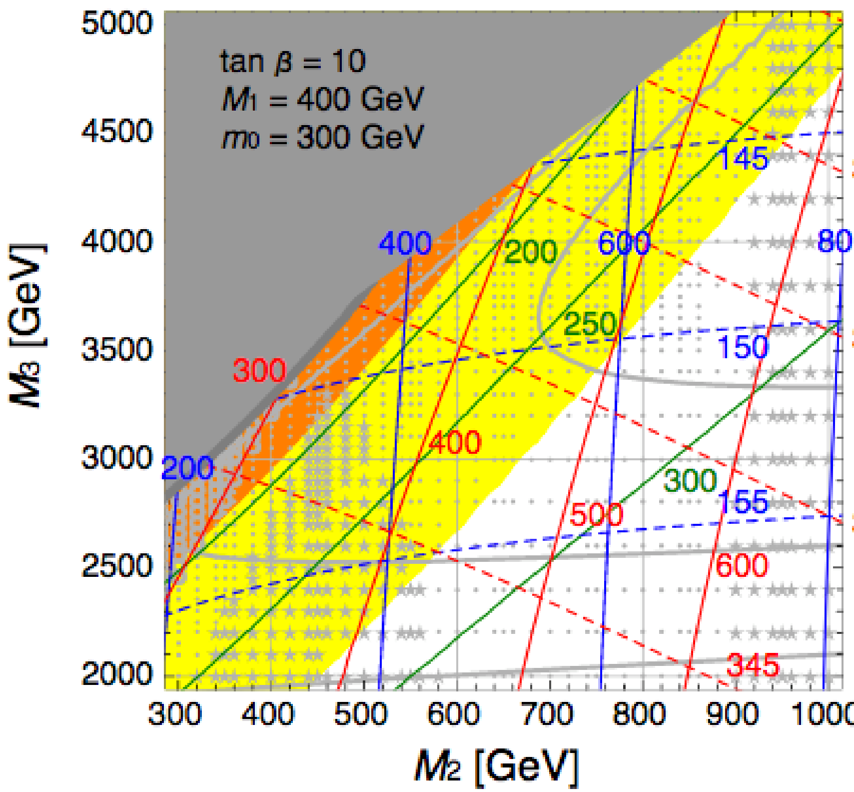
Muon g-2 anomaly?

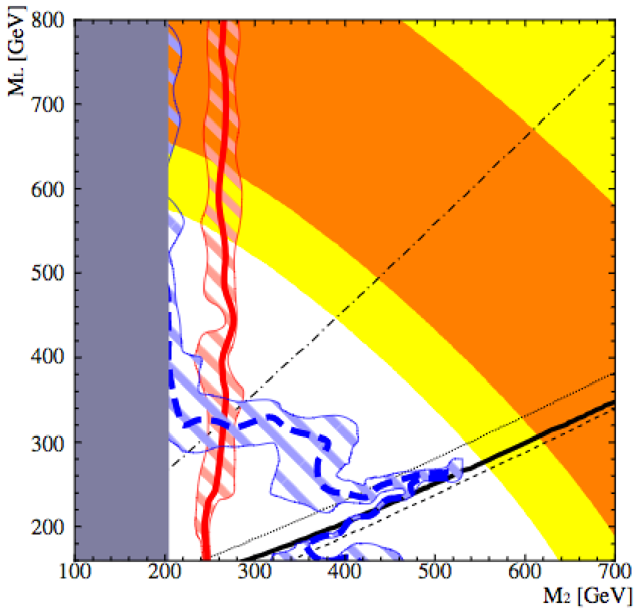


Endo, Hamaguchi, Ishikawa, SI, Yokozaki [1212.3935]



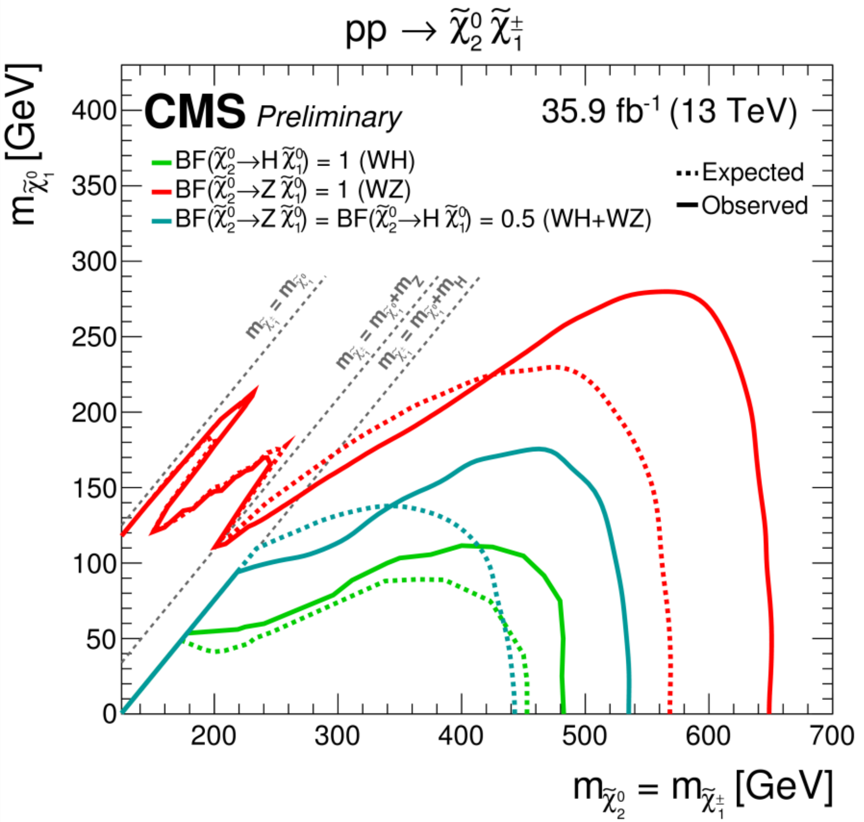
SI, Yanagida, Yokozaki [1407.4226]

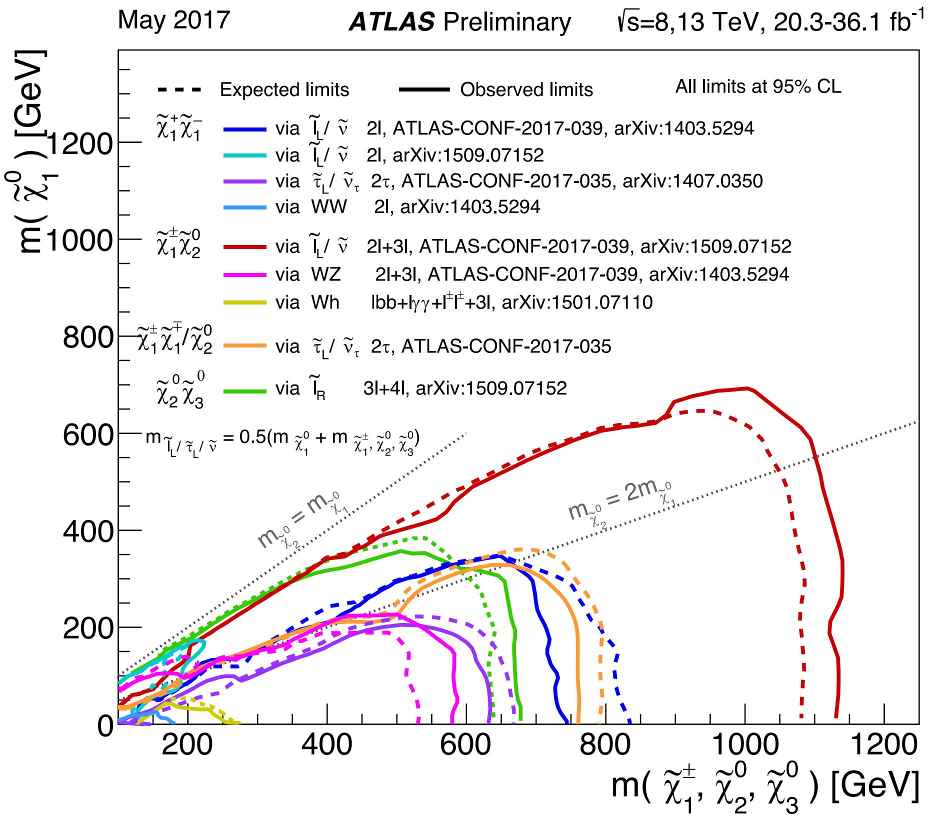
Bino(LSP) , **Wino**, L/R-slepton, and stau masses are shown.



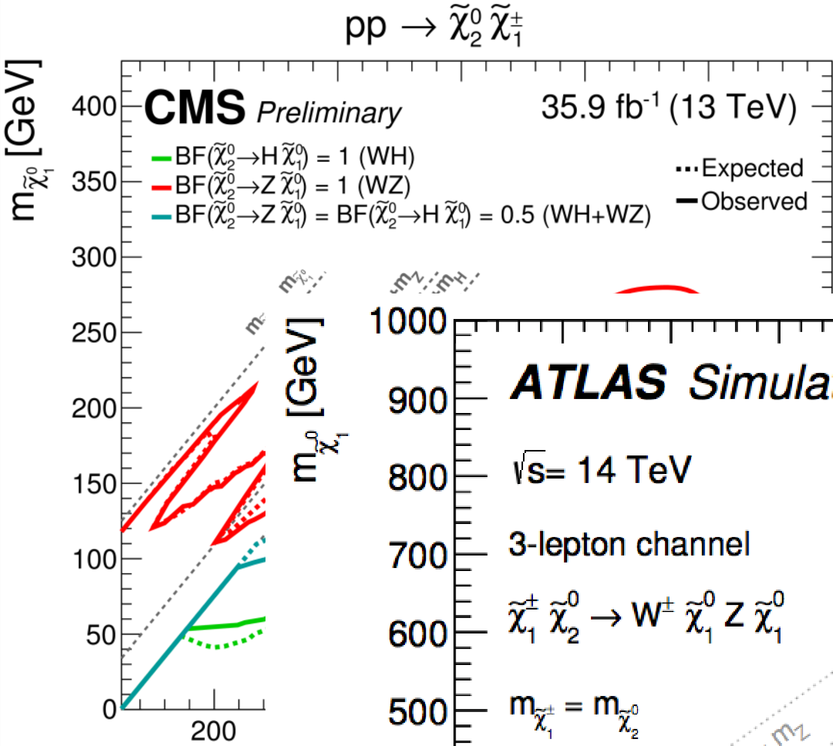
(c) $\mu = M_2/2$, $m_{\rm R} = 3\,{\rm TeV}$

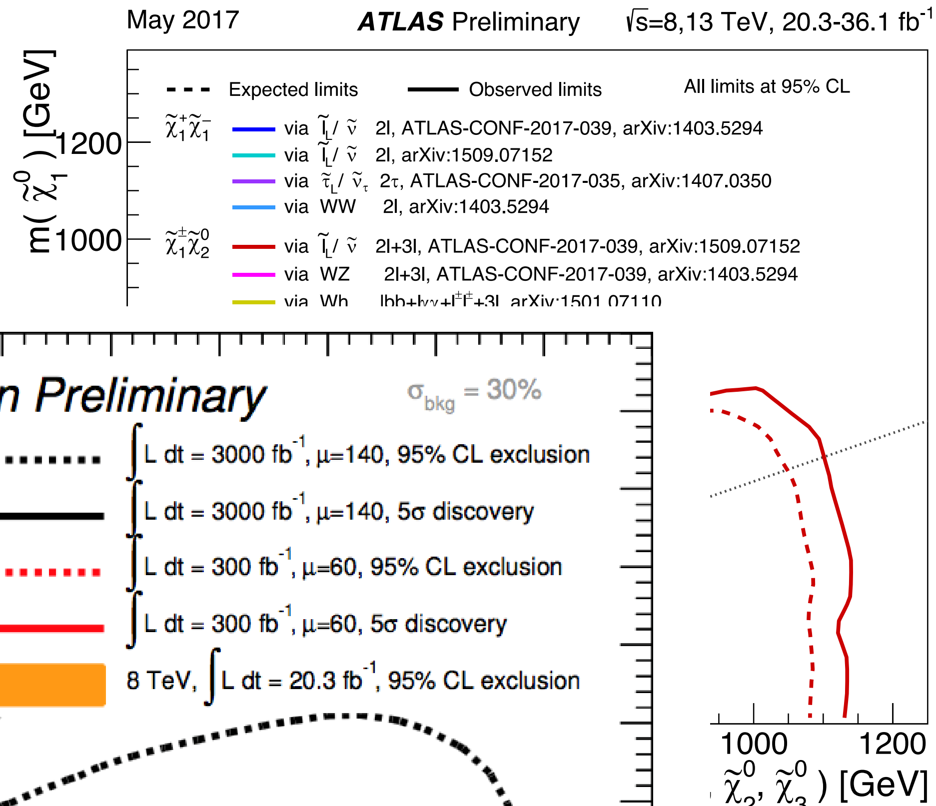
Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

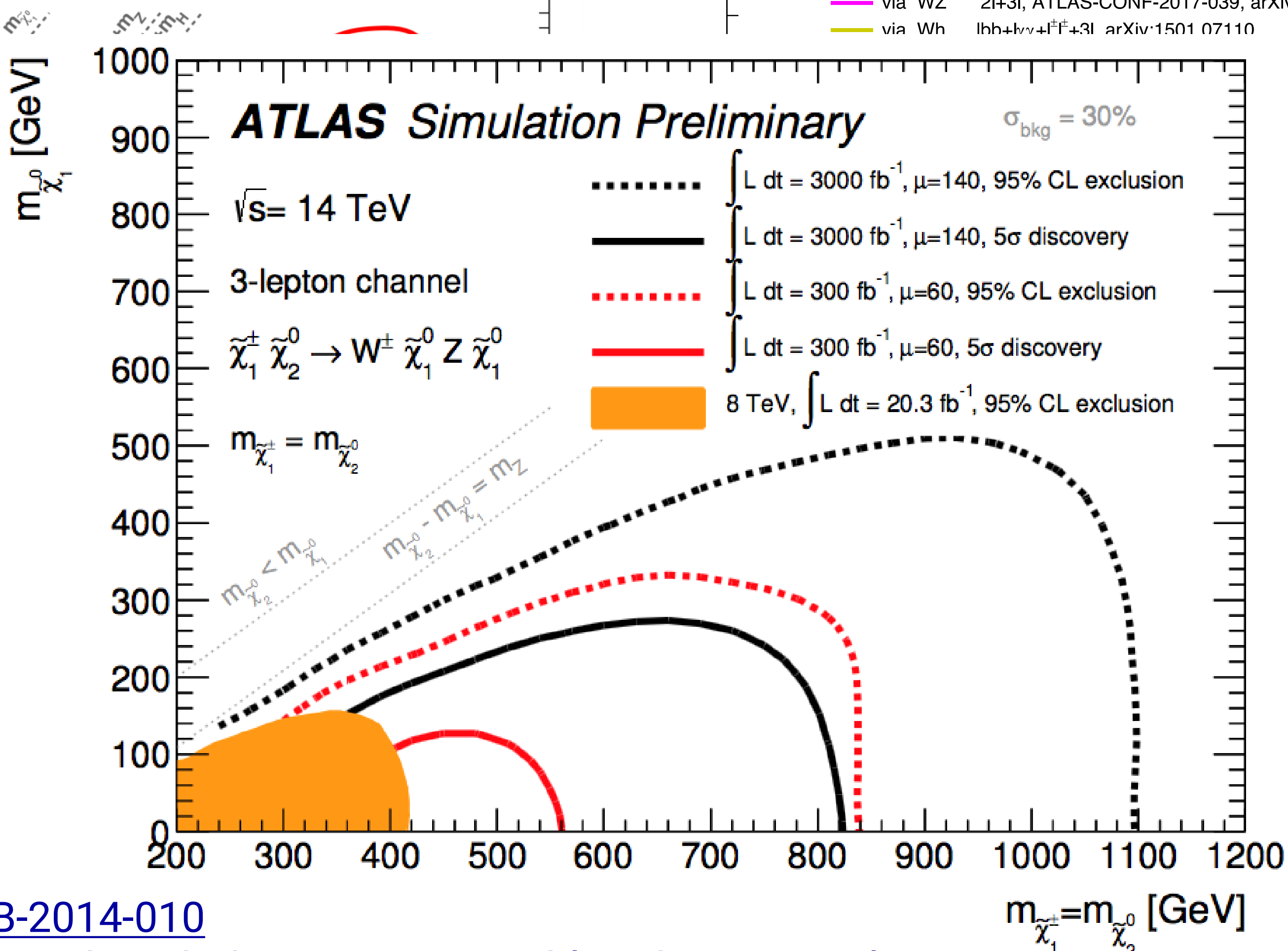




CMS Summary plot https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
ATLAS-CONF-2017-039







CMS Summar … SUS

ATLAS-CONF-

ATL-PHYS-PUB-2014-010

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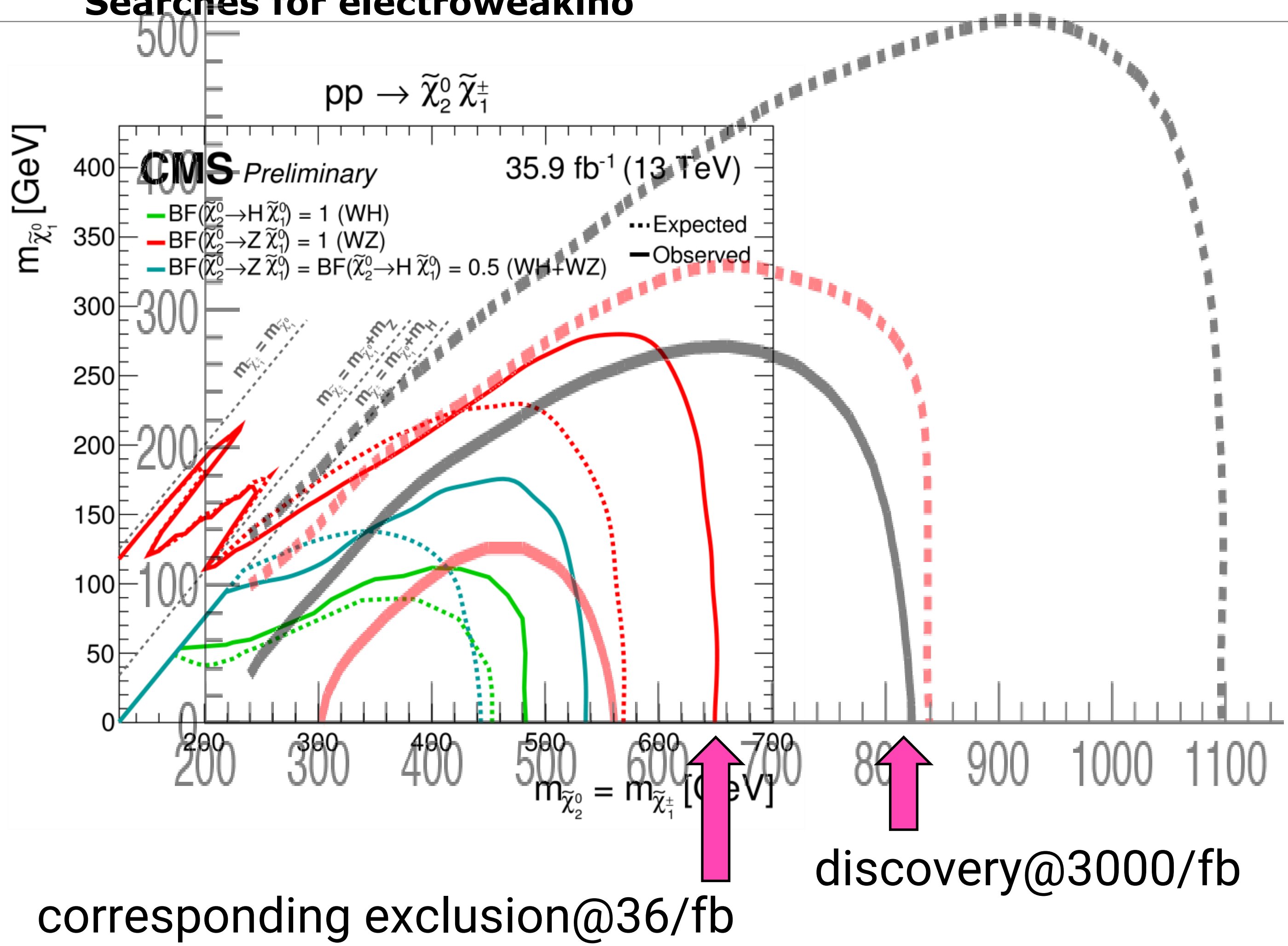

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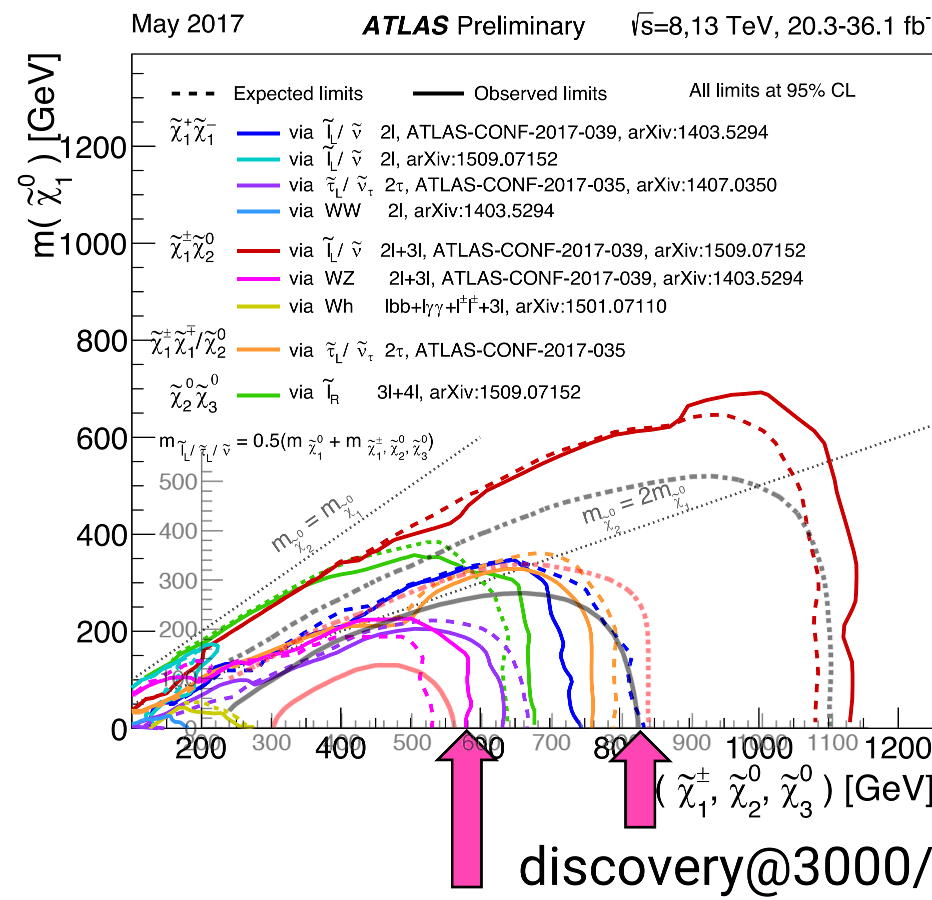

discovery@3000/fb

corresponding exclusion@36/fb

ATLAS-CONF-2017-039

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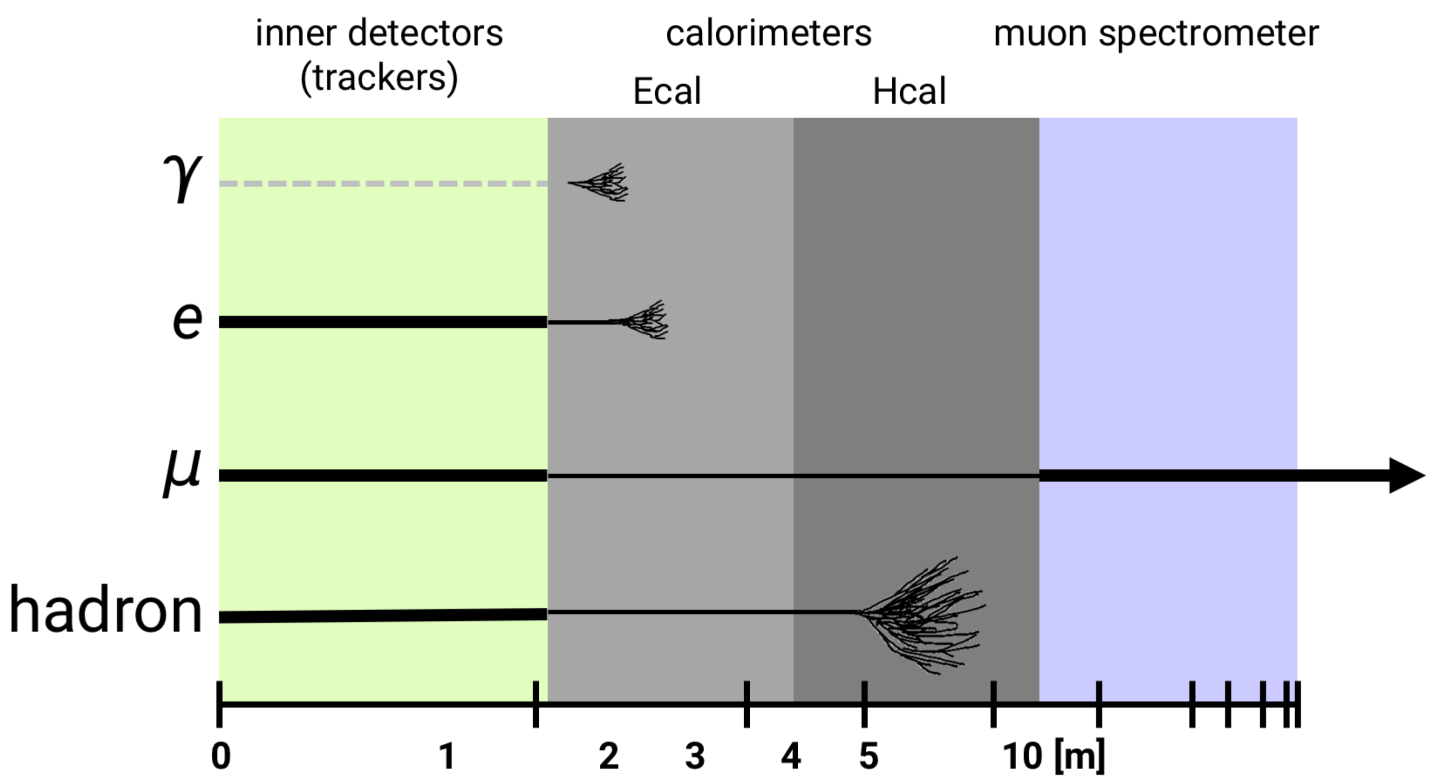
0. Collider Physics basic

- What do "discovery" and "exclusion" mean?
-

Standard technique of Collider detectors



- τ-lepton? $\longrightarrow$ τ-tagging
- which quark? or gluon? $\longrightarrow$ quark-flavor tagging

0. Collider Physics basic

- What do "discovery" and "exclusion" mean?
- How do they distinguish "e" and "μ"?

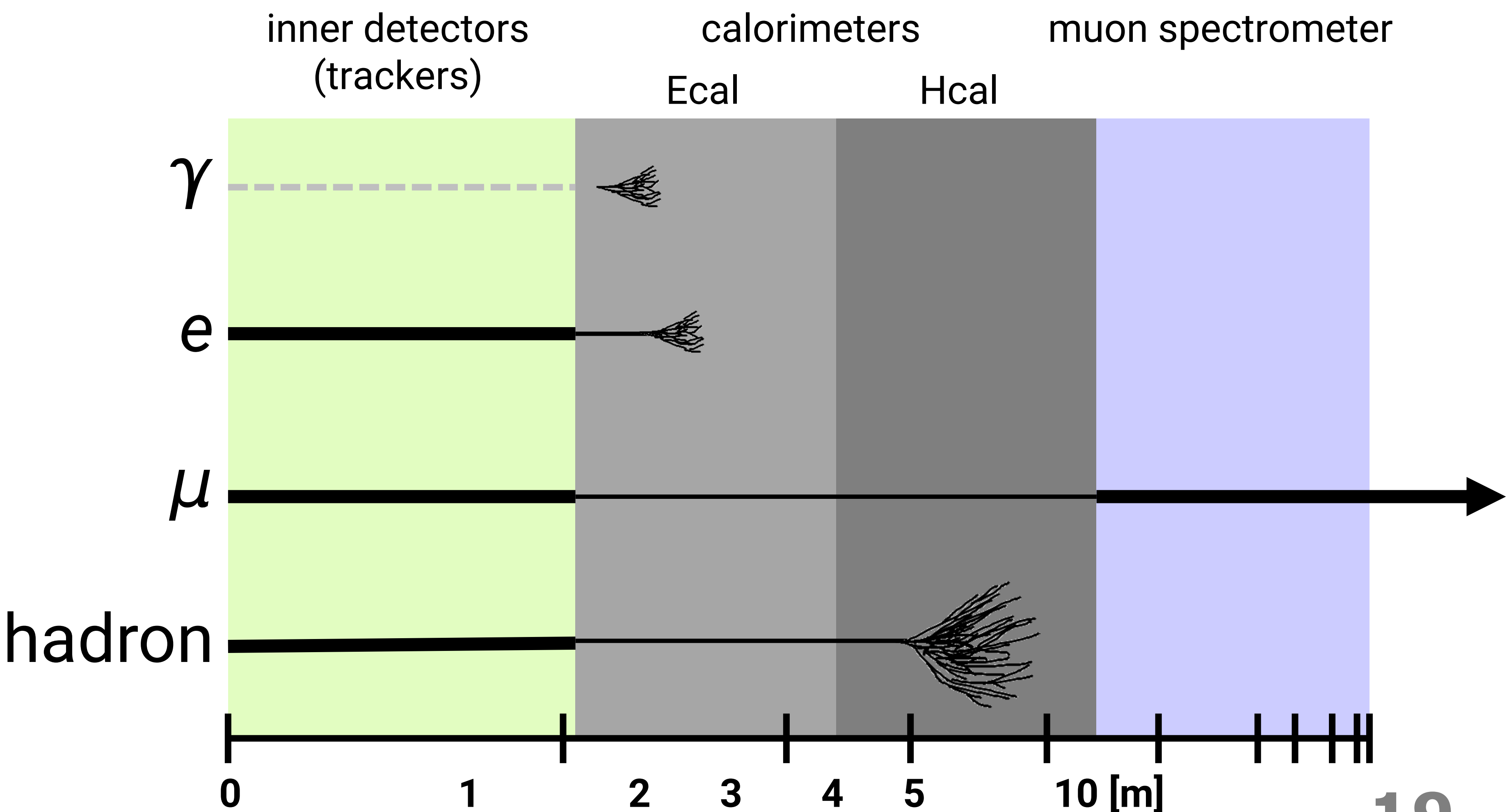
0. Collider Physics basic

- What do "discovery" and "exclusion" mean?

→ **blackboard**

0. Collider Physics basic

- How do they distinguish "*e*" and "*μ*"?



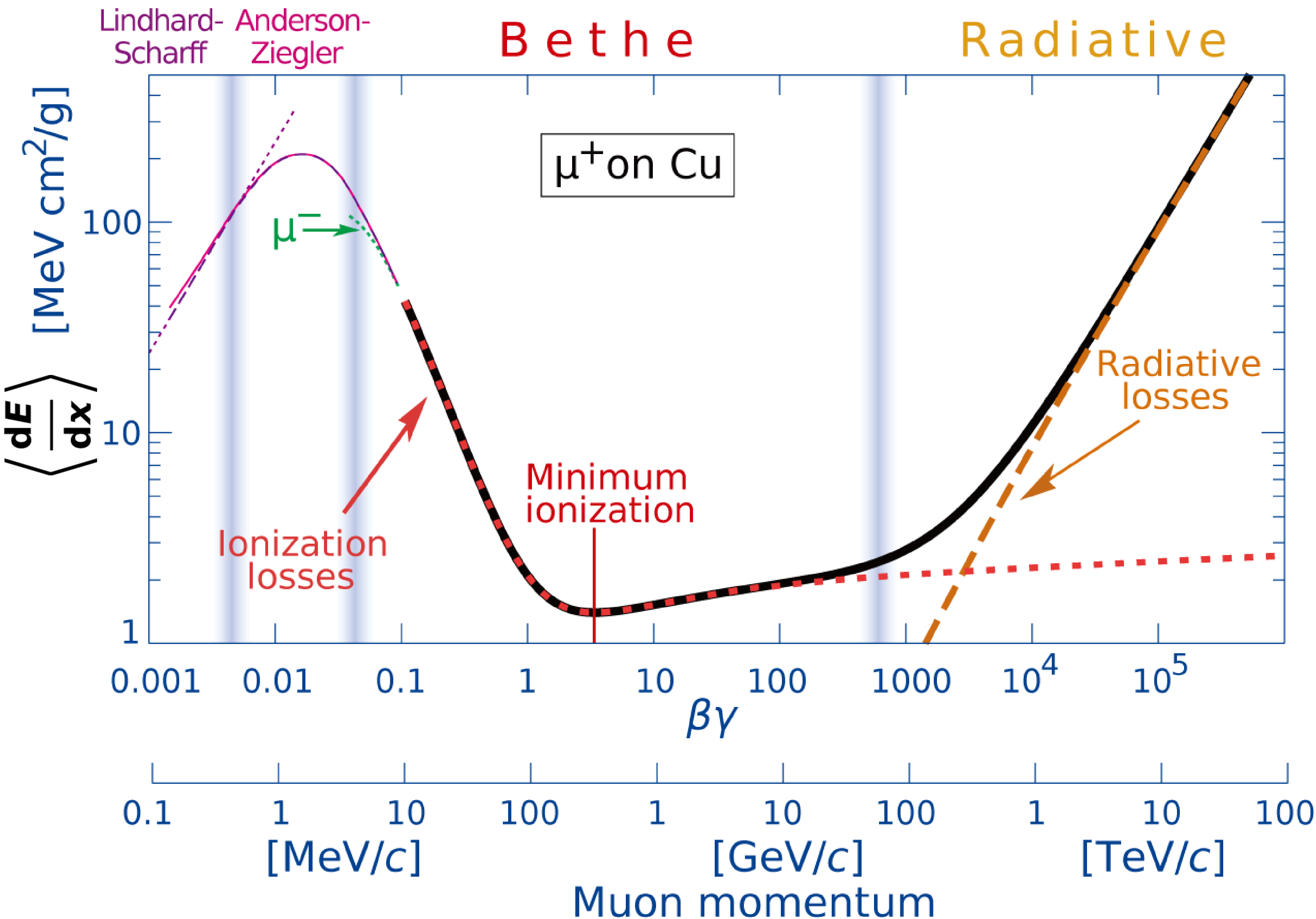


Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

1. **LLCPs**
2. **Future colliders (FCC-hh and FCC-he)**
3. **LLCP searches at FCC-hh**
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(subgroup in BSM@ep collaboration)

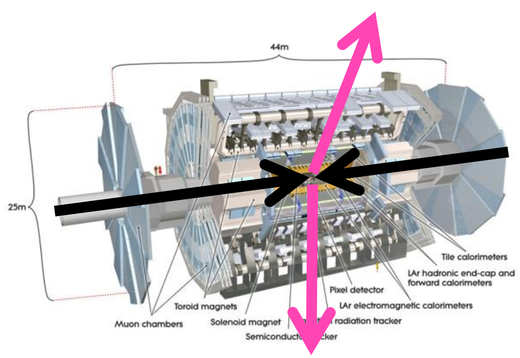
- Particle property

  $m > O(100)$GeV

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

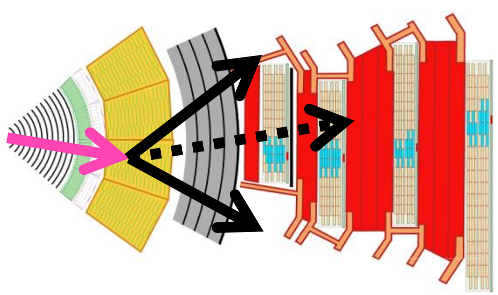
×

- Lifetime
  - "stable"



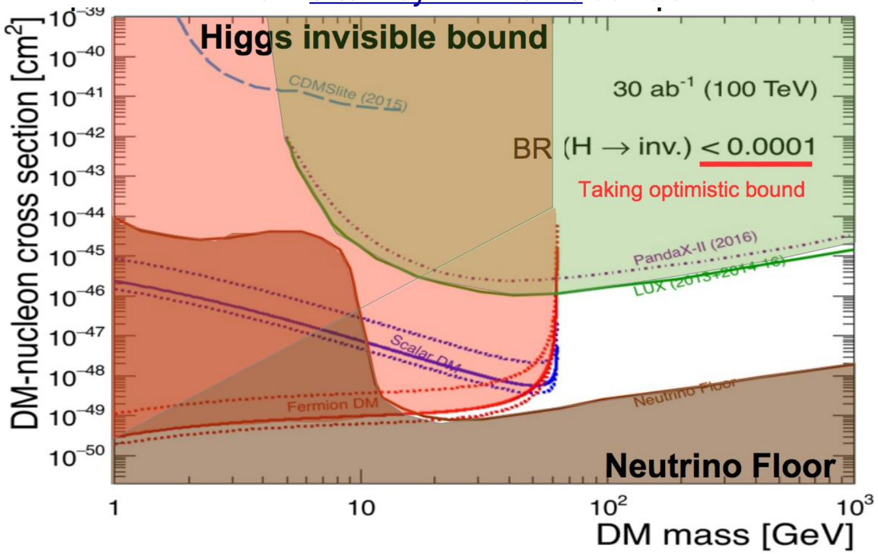
$c\tau \gtrsim 1\,\mathrm{m}$

  - "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

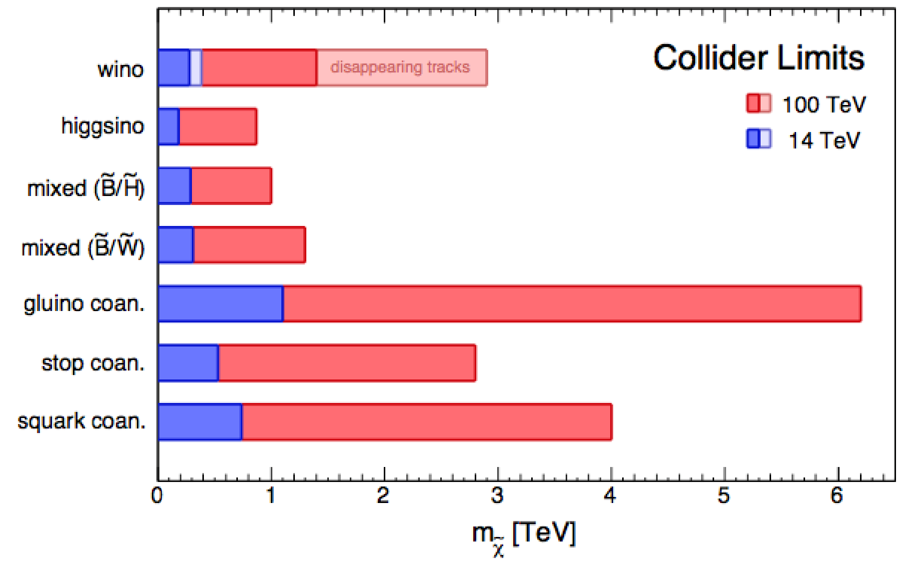
non-standard DM/cosmology with LLCP
→ next slides

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

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



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

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

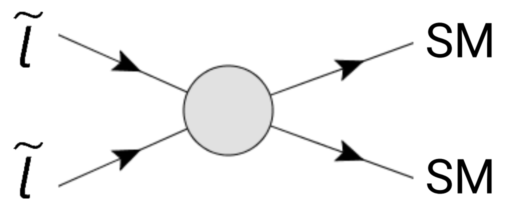
■ Li problem

- 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]



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

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

frozen-out

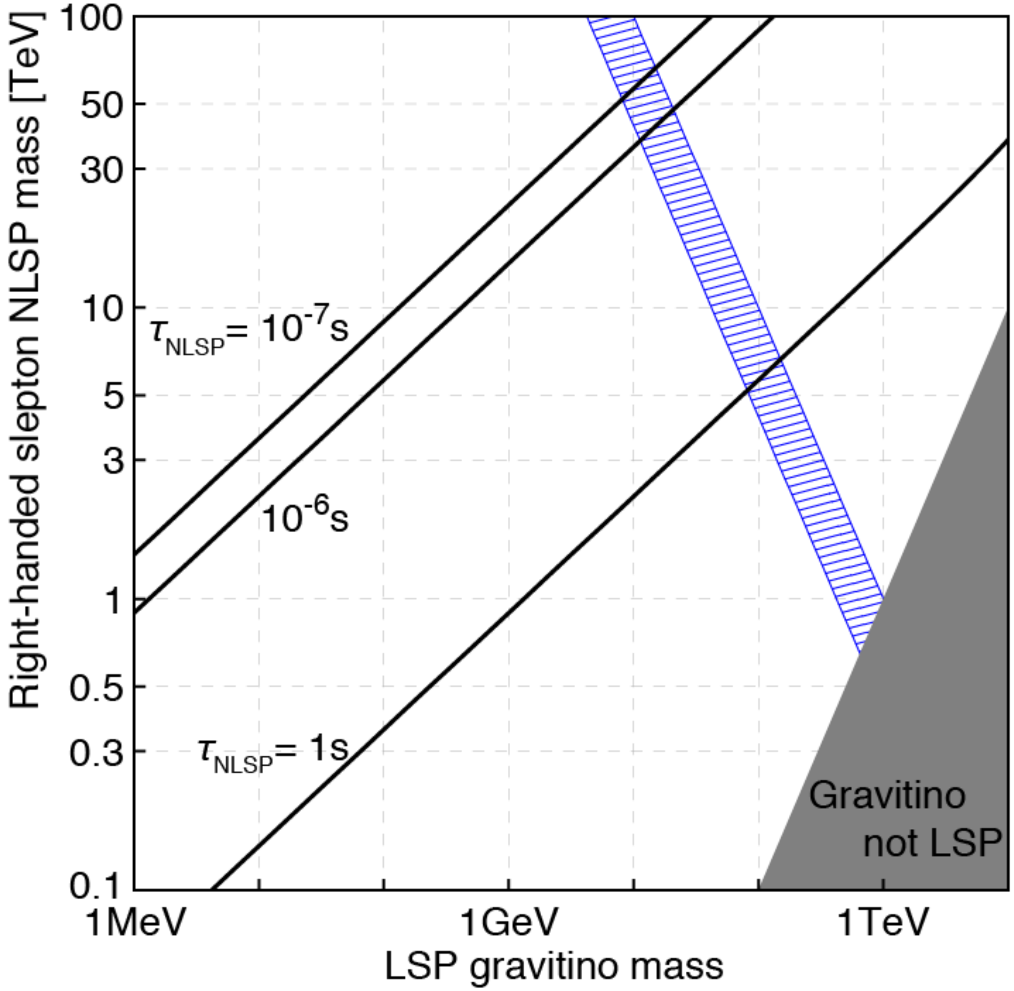
→ thermal relic with $(\Omega h^2)_{\tilde{l}} \gg 0.12$

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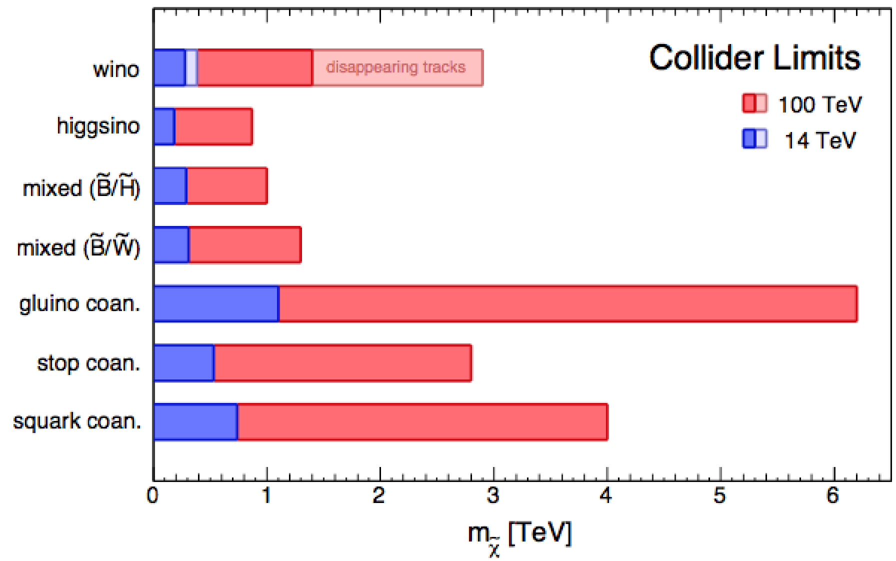

"Physics at the FCC-hh" Report [1606.00947]

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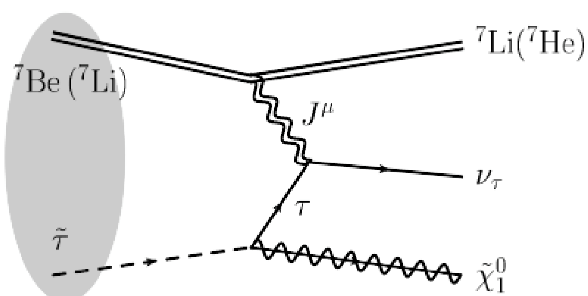

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  - co-annihilation
    - $(\tilde{B}\text{-}\tilde{\tau}) \lesssim 700$ GeV
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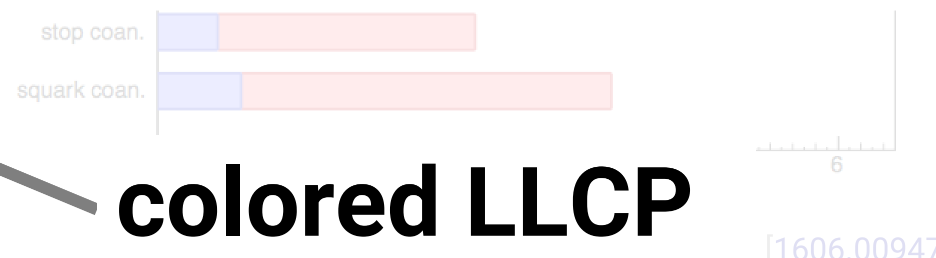
    Harigaya, Kaneta, Matsumoto [1403.0715], Ellis, Olive, Zheng [1404.5571] etc.
  - super-WIMP scenario → $\tilde{l} >$ O(1) TeV (as we see soon.)

non-colored LLCP

... covered in this talk

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



colored LLCP

(→ hadronize: “R-hadron”)

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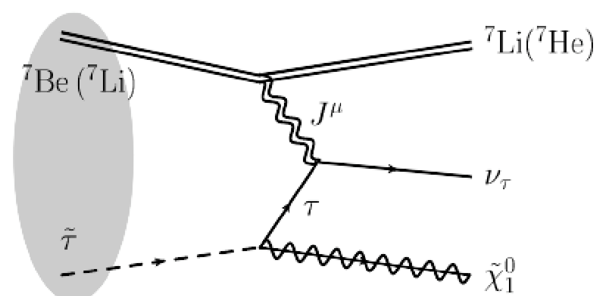

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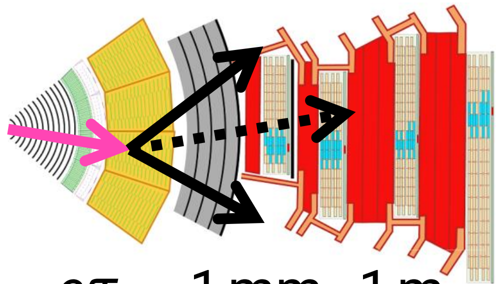


$c\tau \sim 1\,\mathrm{mm}$–$1\,\mathrm{m}$

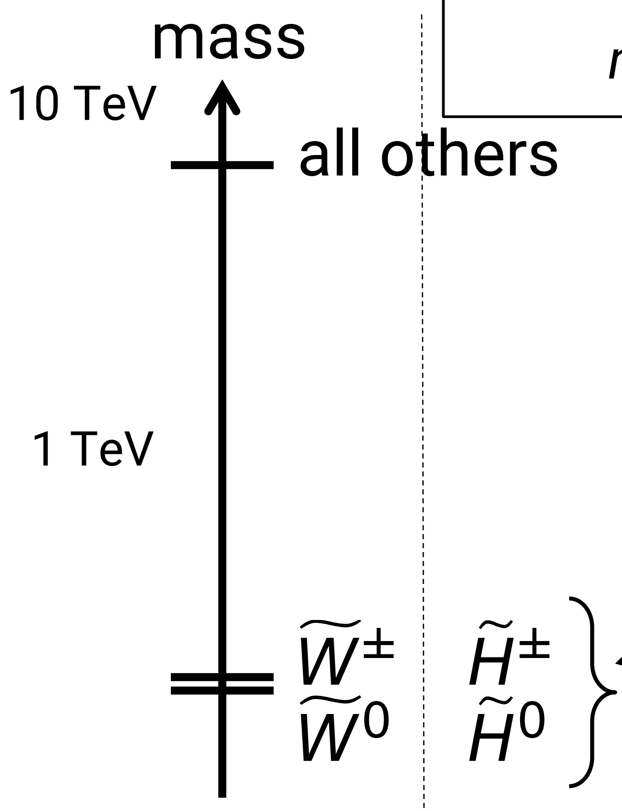
- **Simple MSSM models**
  - Pure-Wino dark matter
  - Pure-Higgsino dark matter

⇩

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

($\delta m > 0$)

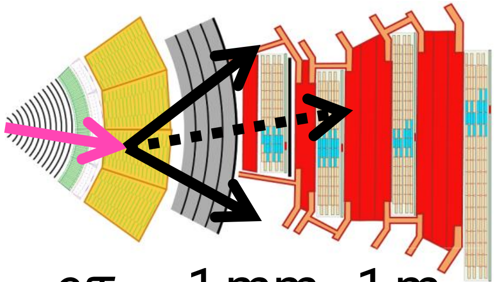
$$\delta m = m_{\tilde{W}^{\pm}} - m_{\tilde{W}^{0}},\quad m_{\tilde{H}^{\pm}} - m_{\tilde{H}^{0}}$$



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)

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



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

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

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

⇓

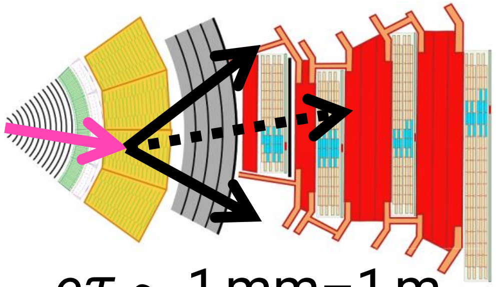
$\tilde{\chi}^\pm$ long-lived because of small δm

($\delta m > 0$)

$m_{\tilde{W}}$ [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



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

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  - Pure-Wino dark matter **60mm**
  - Pure-Higgsino dark matter **7mm**

⇩

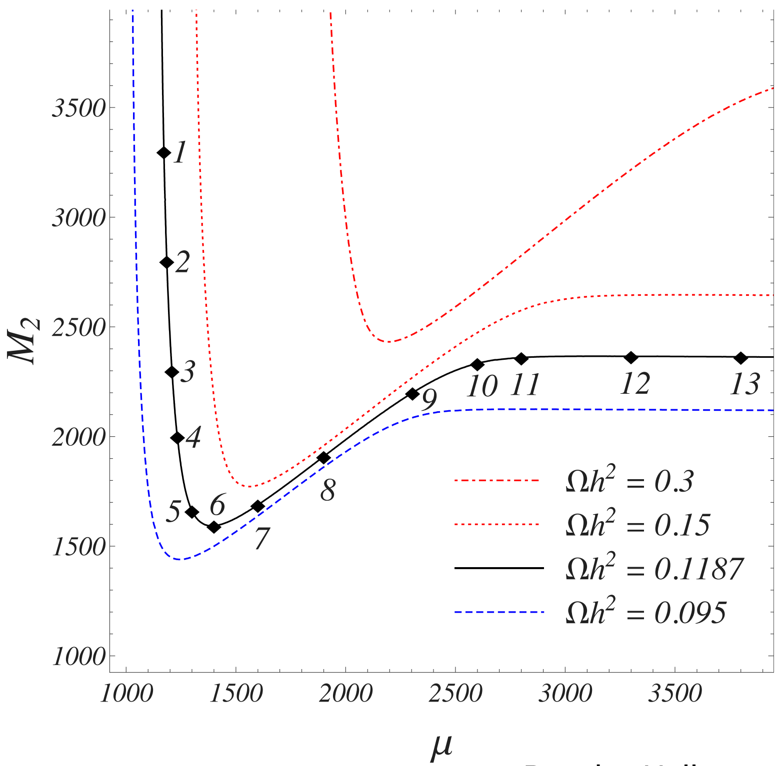
$\tilde{\chi}^{\pm}$ long-lived because of small δm

($\delta m > 0$)

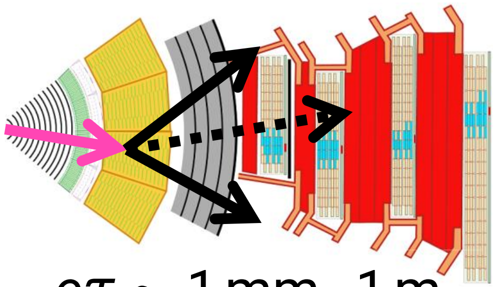
(but DM underabundant for "observable" region)

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

$m_{A^0} = 500\,\mathrm{GeV},\ m_{\mathrm{sfermion}} = 9\,\mathrm{TeV},\ \tan\beta = 15$



Beneke, Hellmann, Ruiz-Femenia [1411.6930]



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

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

⇩

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

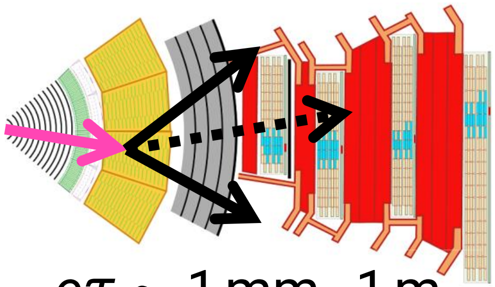
($\delta m > 0$)

(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
because of tiny couplings.



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with $\tilde{l}$ -LSP

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

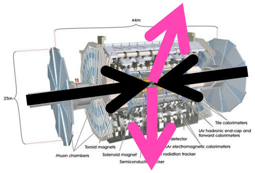
$$c\tau \sim 1.8\times 10^{-5}\,\mathrm{m}\left(\frac{m_{\tilde{l}}}{100\,\mathrm{GeV}}\right)^{-5}\left(\frac{m_{\tilde{G}}}{1\,\mathrm{eV}}\right)^{2}$$

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".

■ Dark Mattter



➢ co-annihilation

$\tilde{\tau}$-LLCP

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

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

$\tilde{l}$-LLCP

■ Li problem

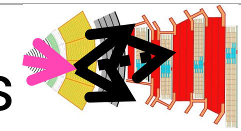
➢ MSSM $\tilde{\tau}$ with

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

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

$\tilde{\tau}$-LLCP

■ Simple MSSM models



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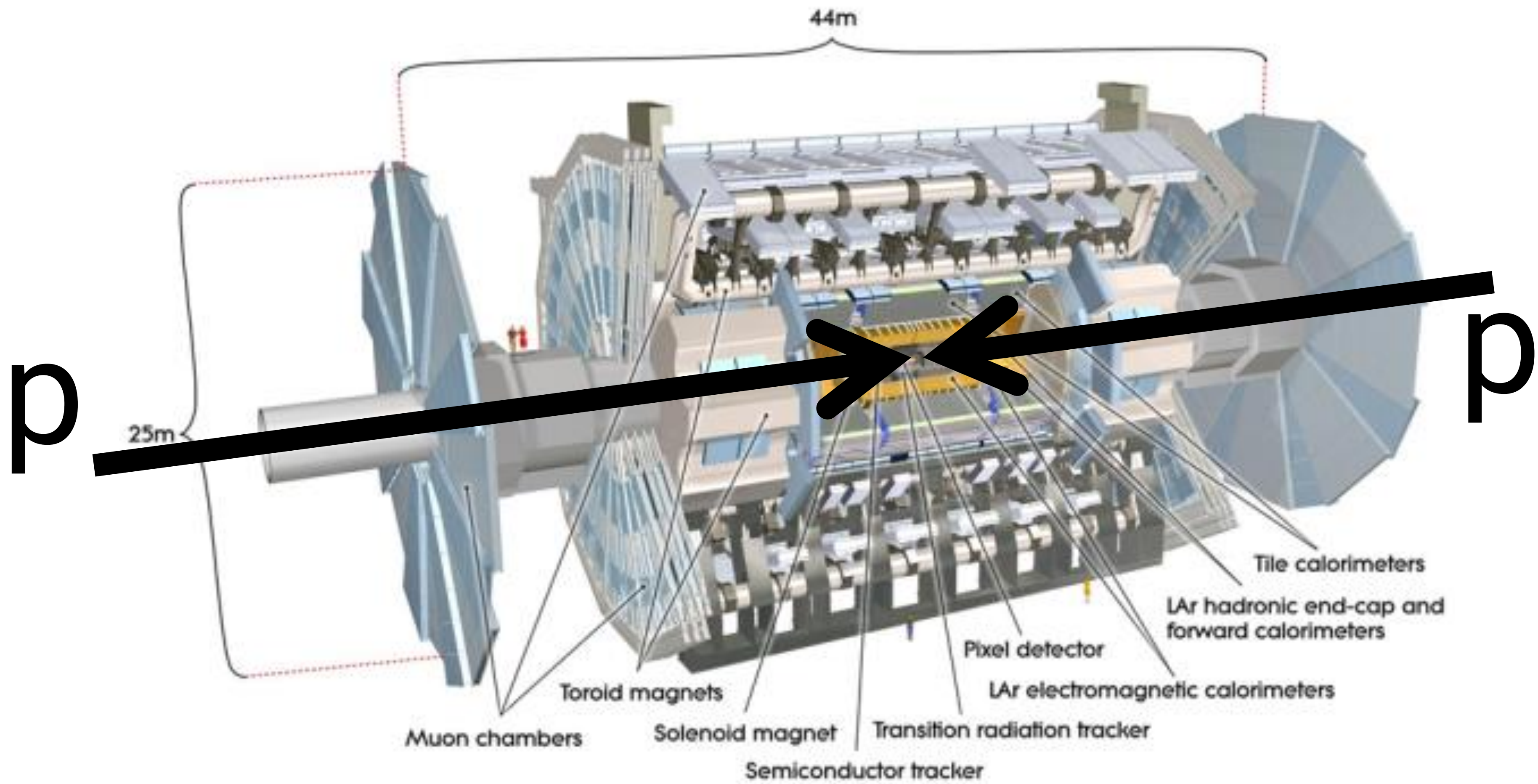
(subgroup in BSM@ep collaboration)

- (1) “stable” non-colored LLCPs



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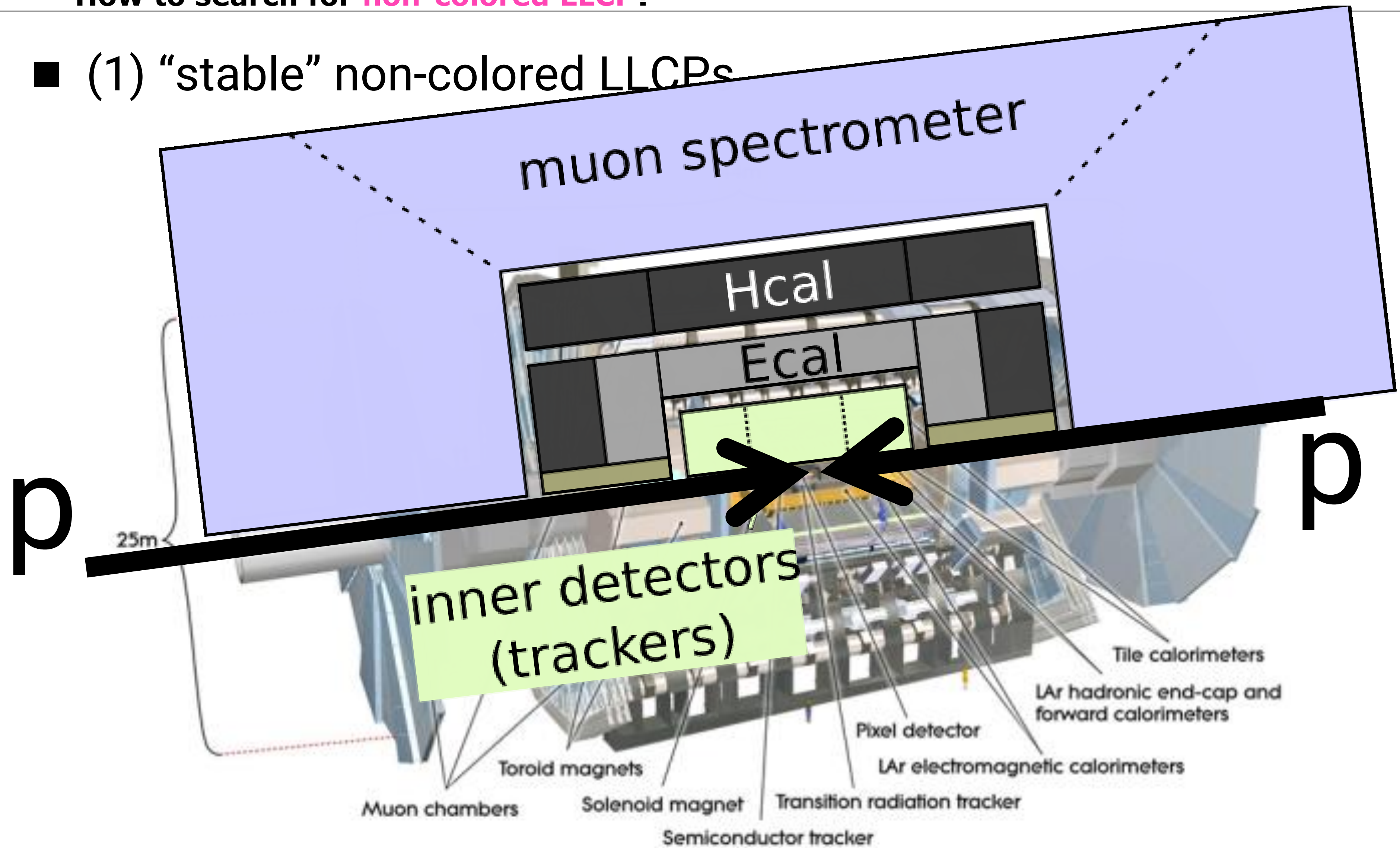

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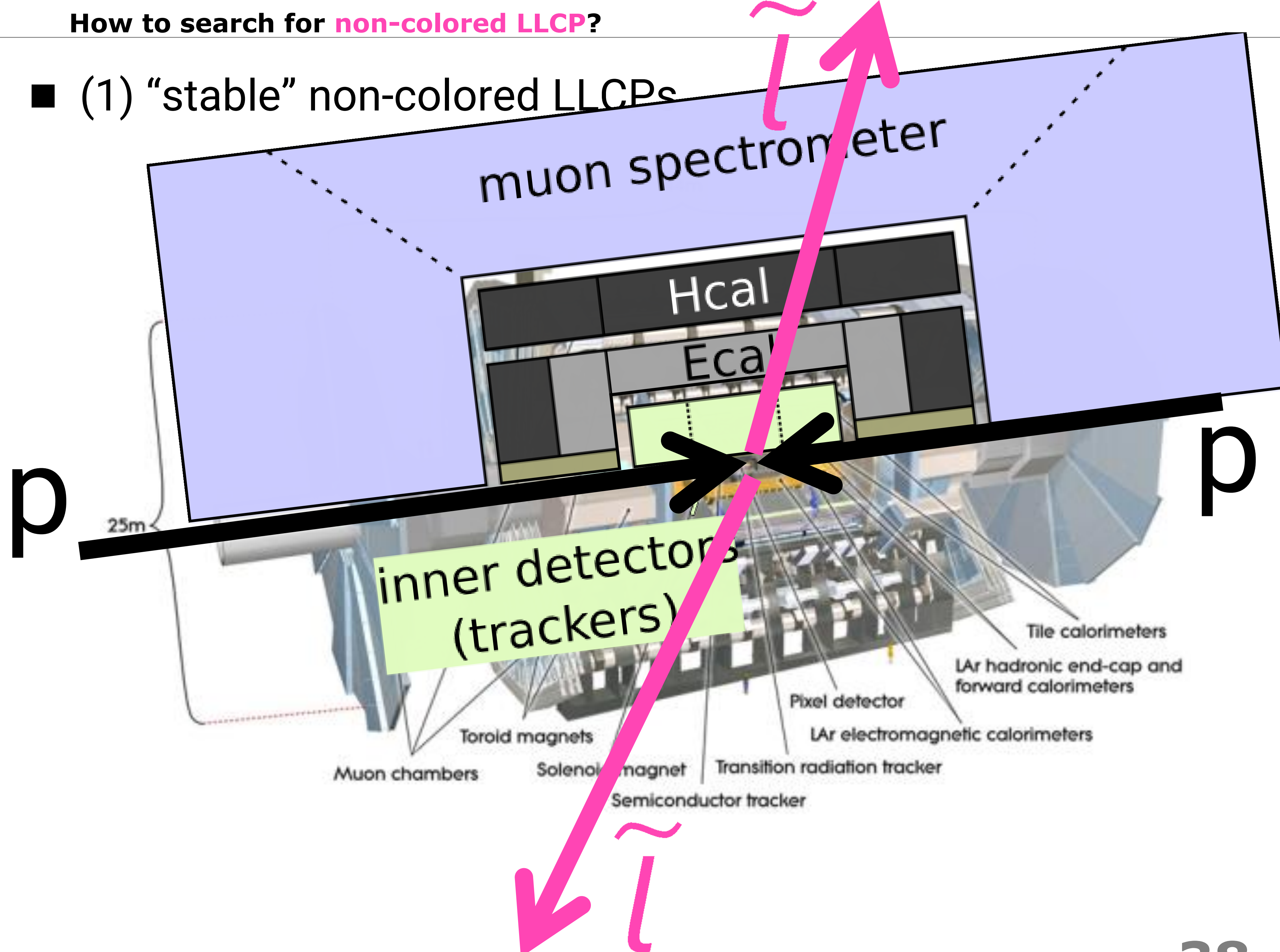
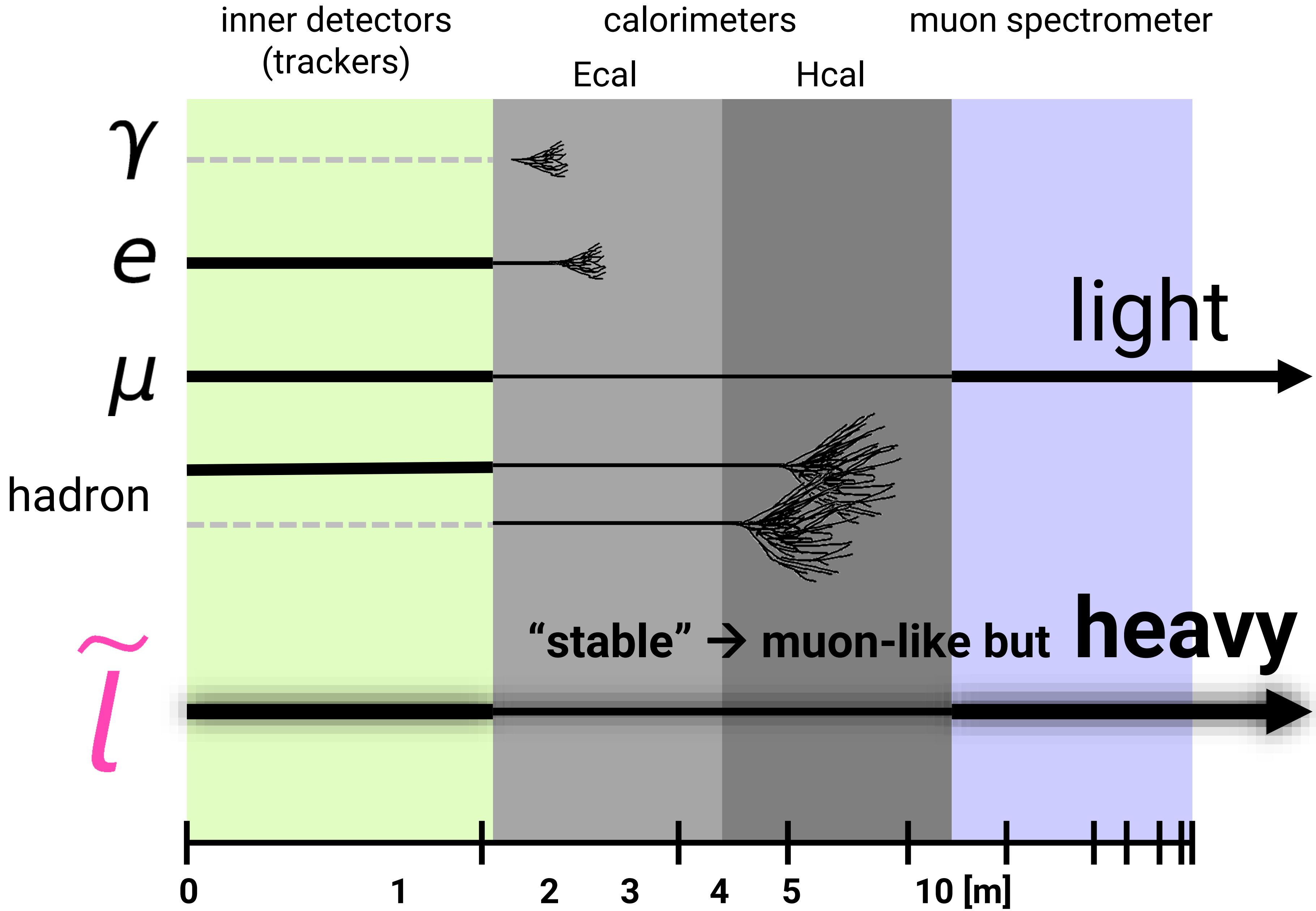




inner detectors
(trackers)
calorimeters
muon spectrometer
Ecal
Hcal
γ
e
μ
hadron
light
“stable” → muon-like but heavy
0
1
2
3
4
5
10 [m]

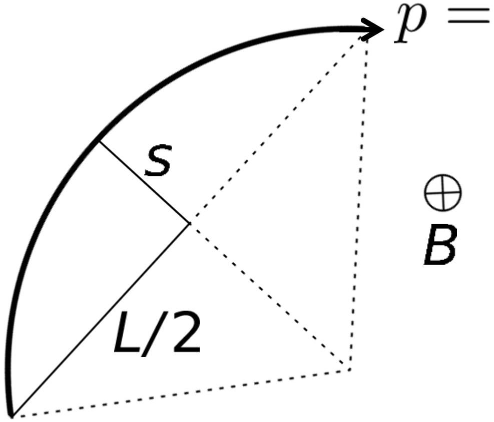
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

momentum & velocity

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

➢ momentum

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



➢ velocity

- TOF [time-of-flight]

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

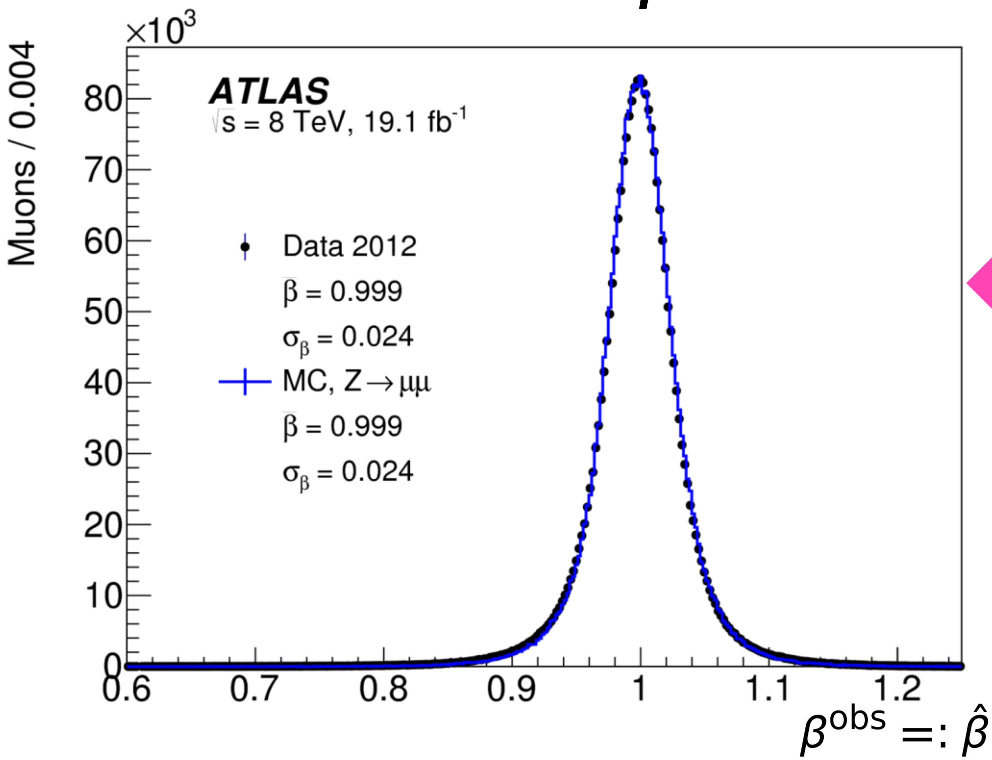
- d*E*/d*x* [ionization energy loss]

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

momentum & velocity

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

ATLAS muon data: **Δ*β* = 2.4%**



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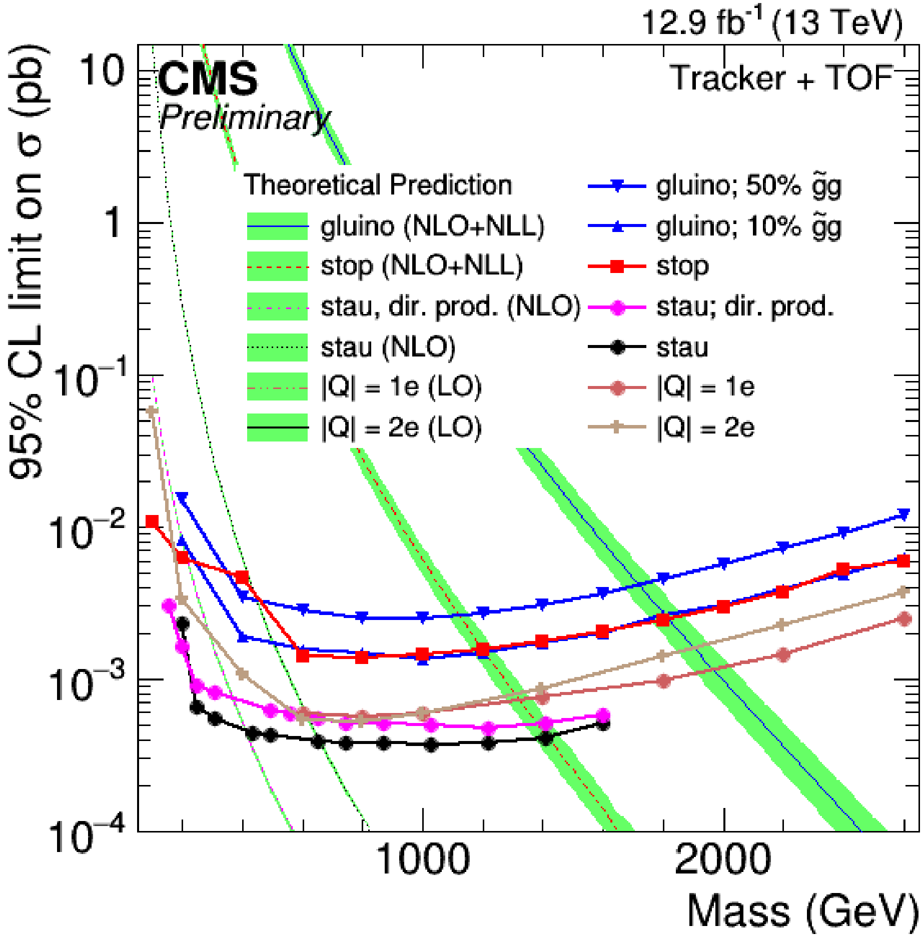
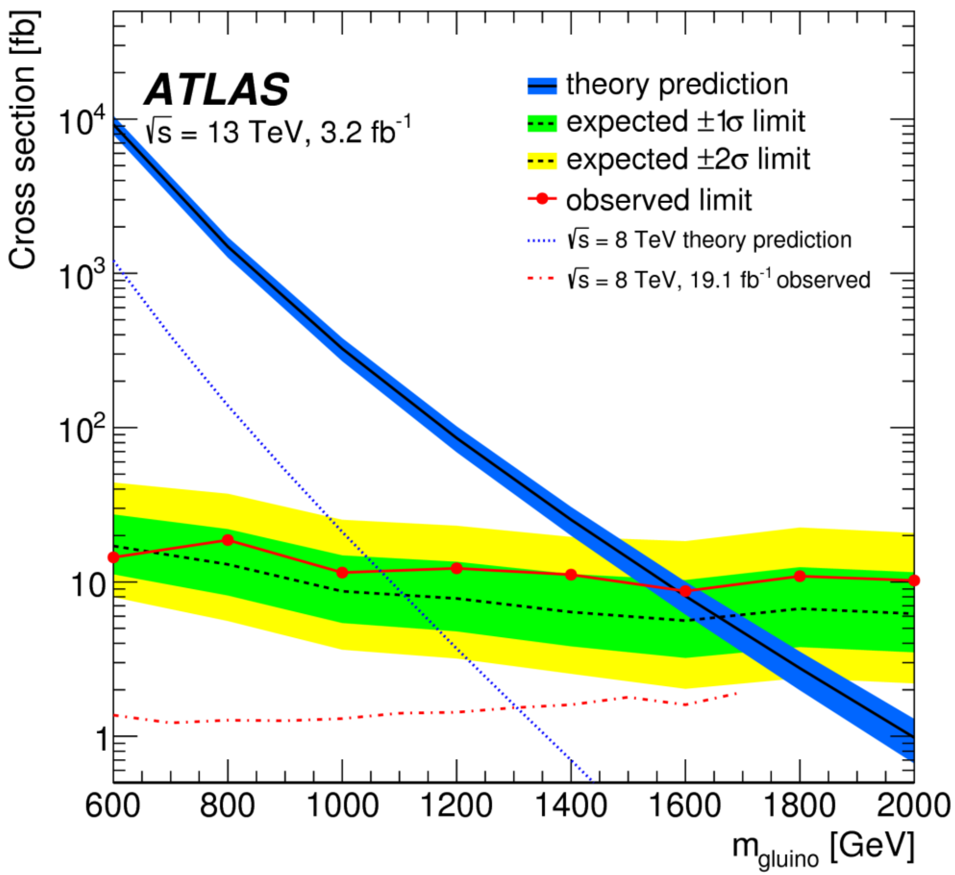
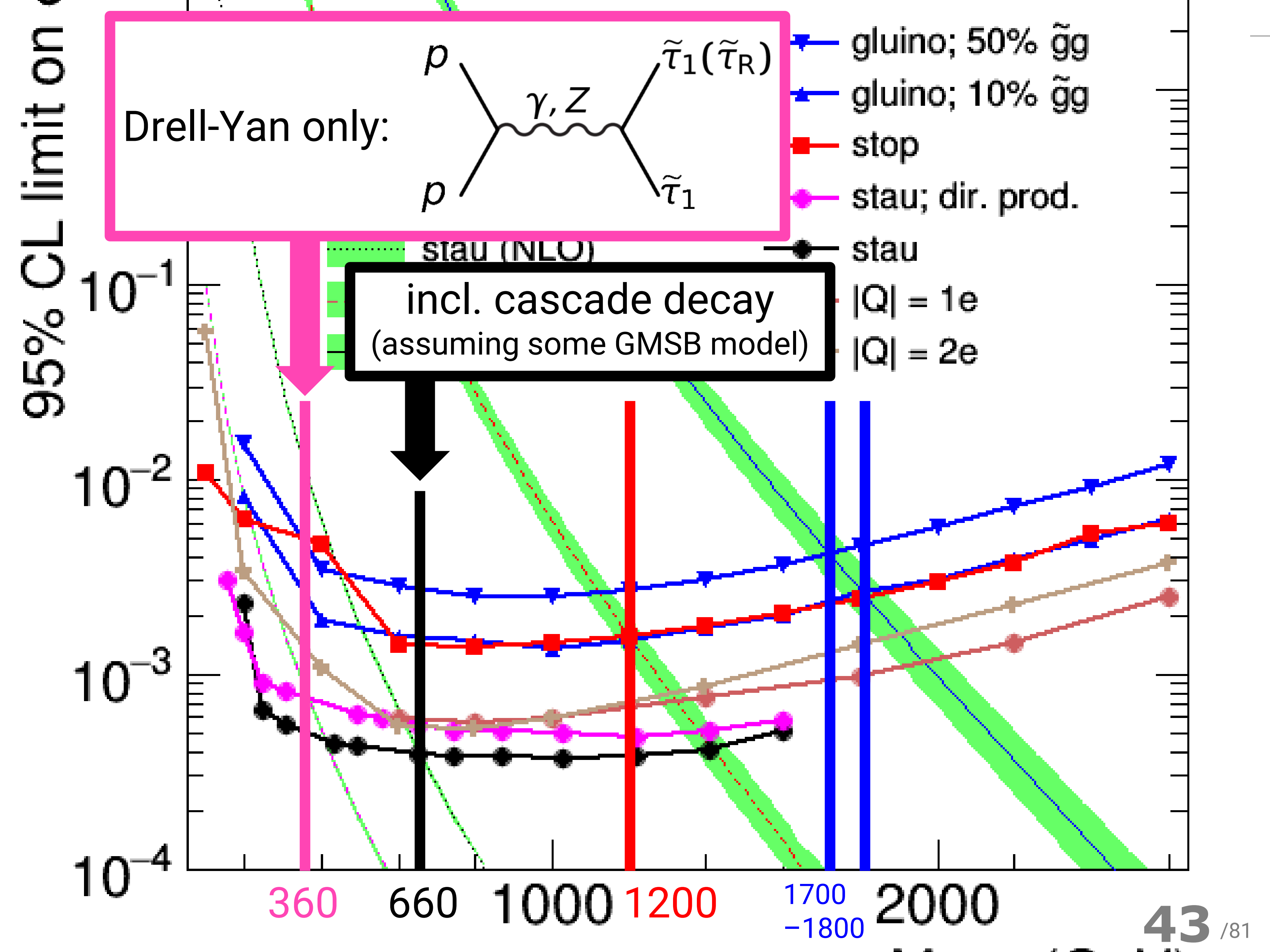
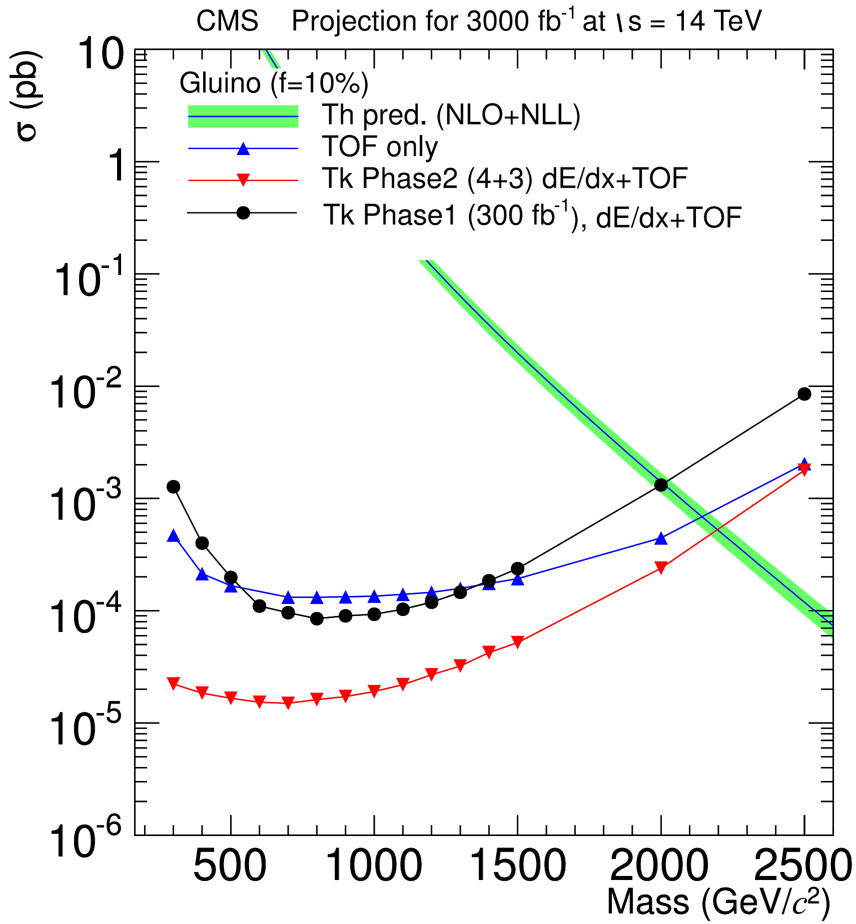
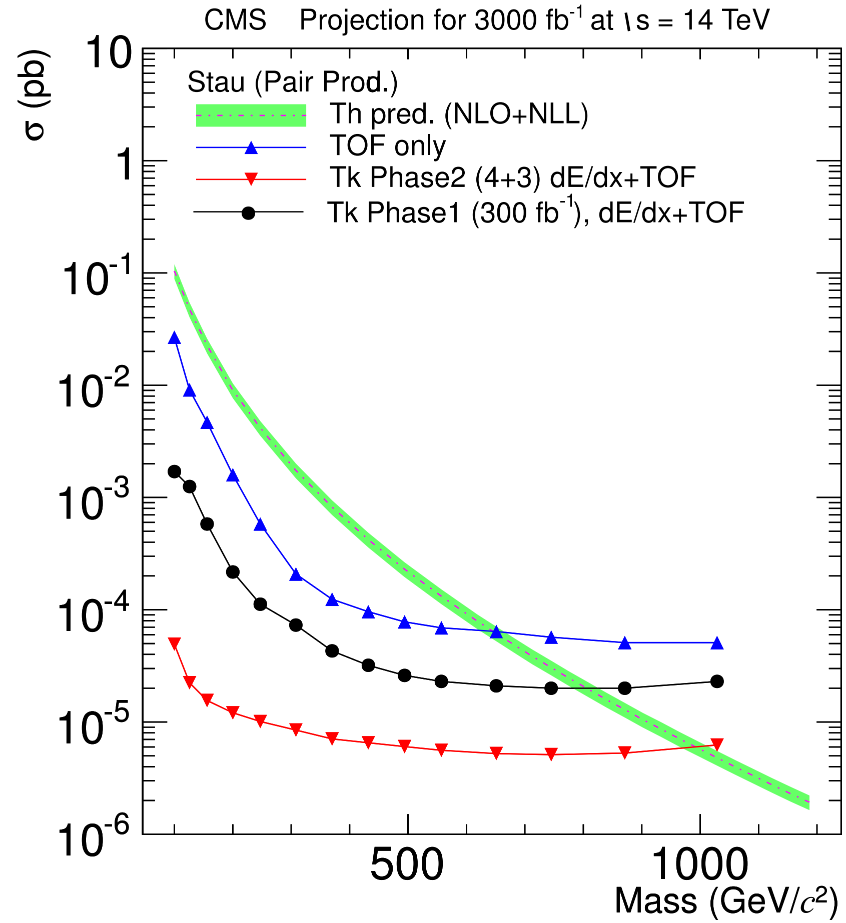

12.9 fb-1 (13 TeV)
CMS
Preliminary
Tracker + TOF
95% CL limit on σ (pb)
Theoretical Prediction
gluino (NLO+NLL)
stop (NLO+NLL)
stau, dir. prod. (NLO)
stau (NLO)
|Q| = 1e (LO)
|Q| = 2e (LO)
gluino; 50% g̃g
gluino; 10% g̃g
stop
stau; dir. prod.
stau
|Q| = 1e
|Q| = 2e
Mass (GeV)


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]


95% CL limit on
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
|Q| = 1e
|Q| = 2e
stau (NLO)
incl. cascade decay
(assuming some GMSB model)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
360
660
1000
1200
1700
−1800
2000

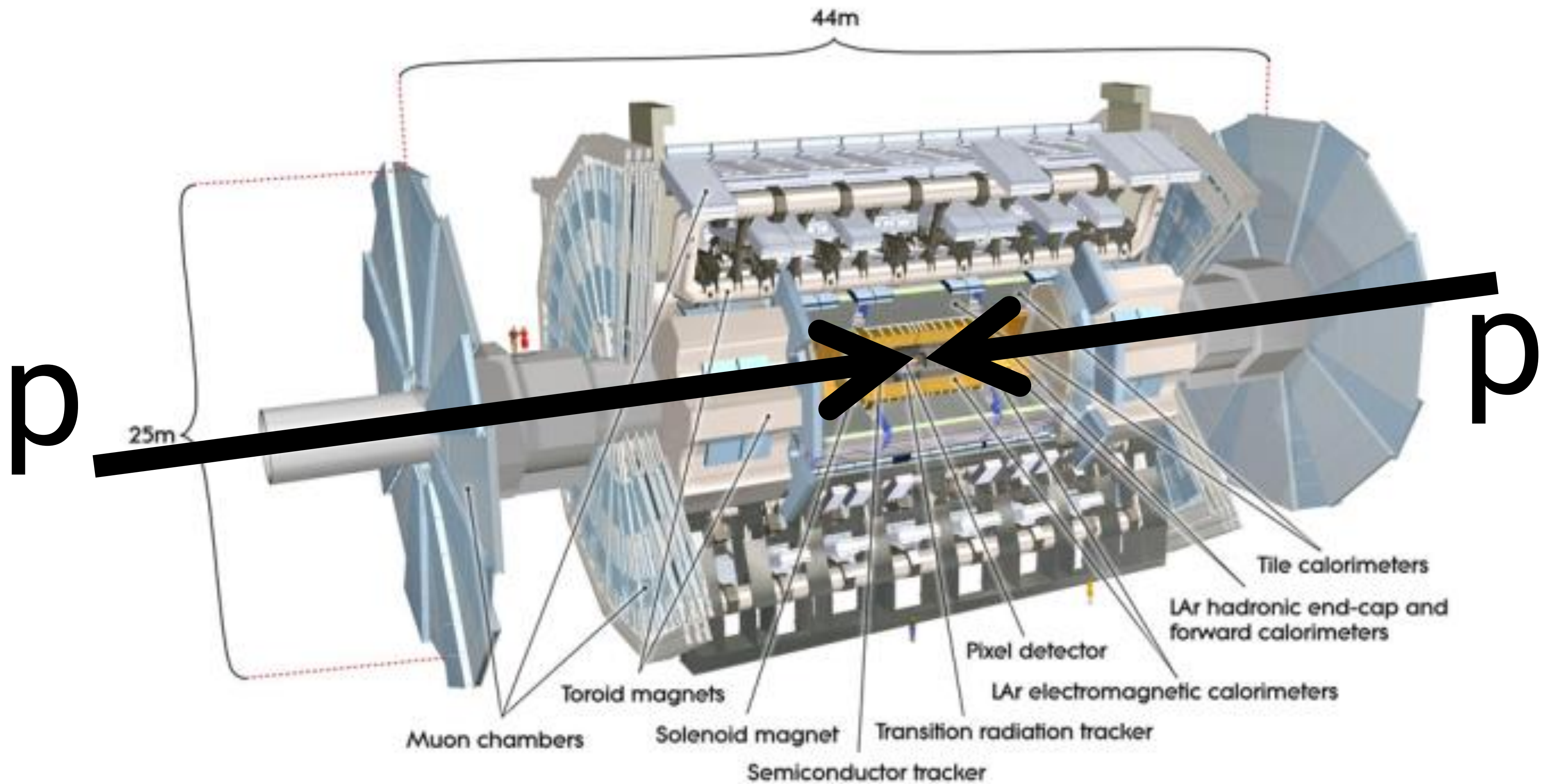




	current	HL-LHC
gluino:	1.7 TeV	→ 2.2 TeV?
stop:	1.2 TeV	→ 1.7 TeV?
stau (GMSB):	660 GeV	→ 1.2 TeV?
stau (DY):	360 GeV	→ 1.0 TeV?

(or discovery?)

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



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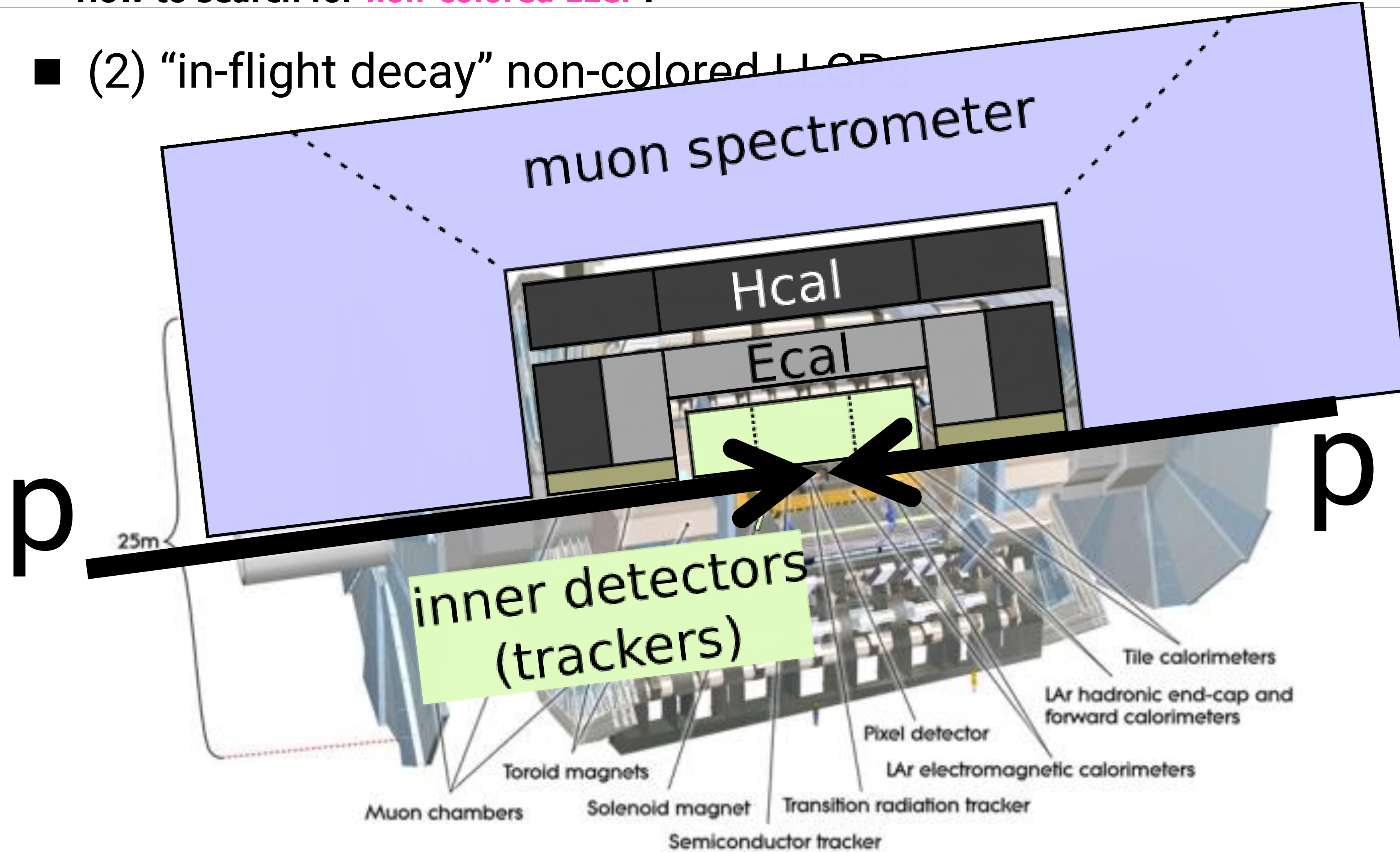

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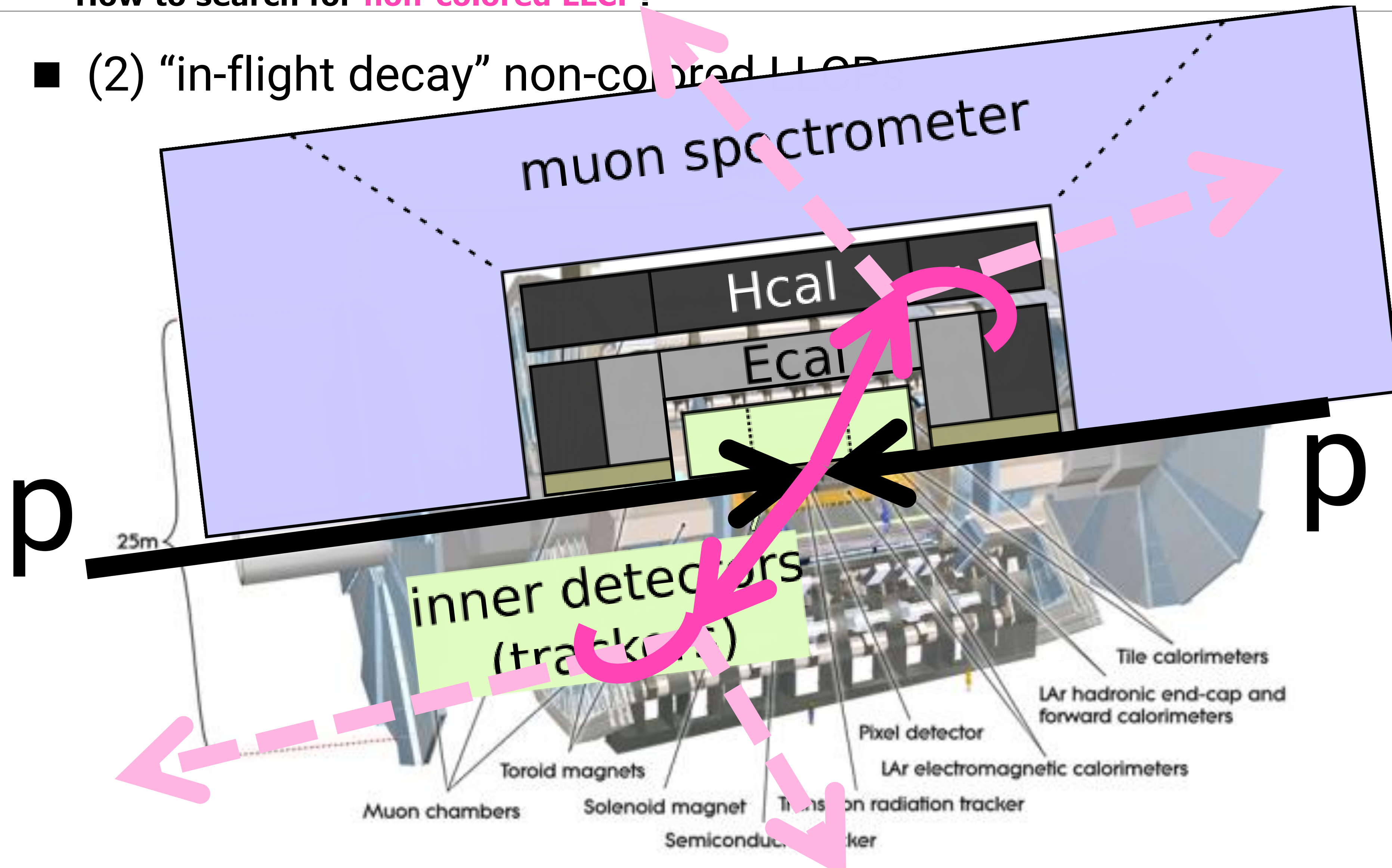

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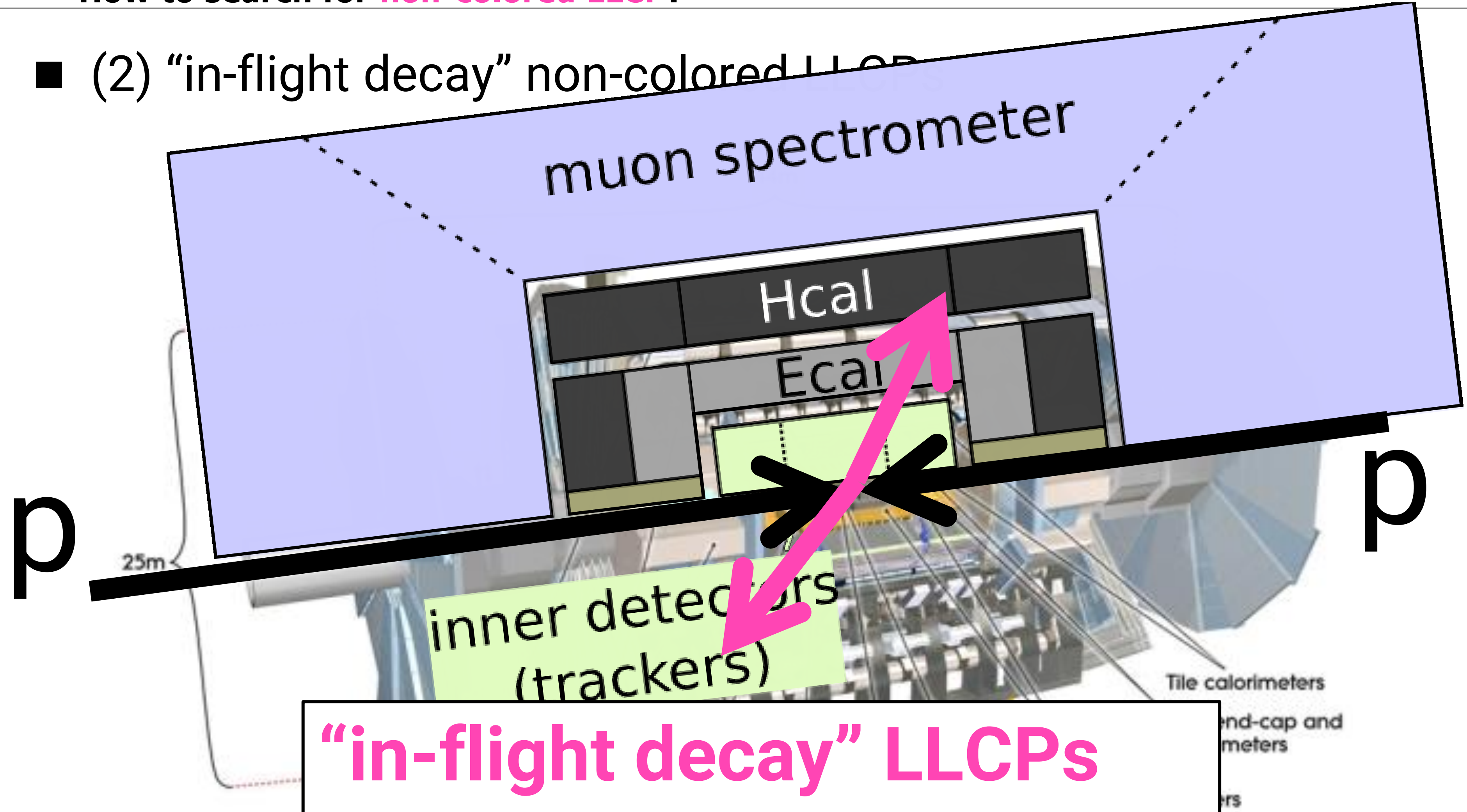
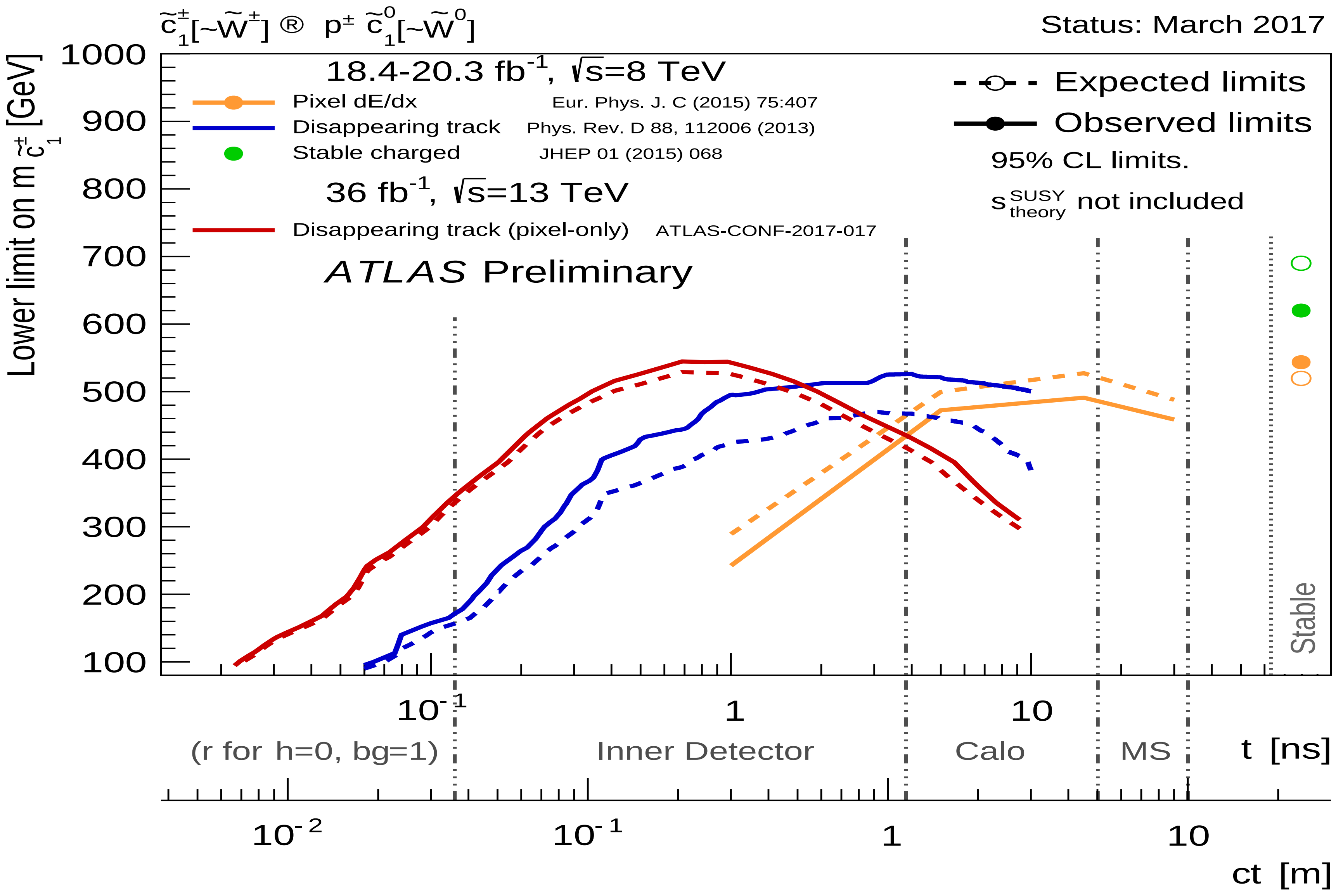


"in-flight decay" LLCPs
= disappearing tracks

($\widetilde{W}^{\pm}$ as the LLCP)



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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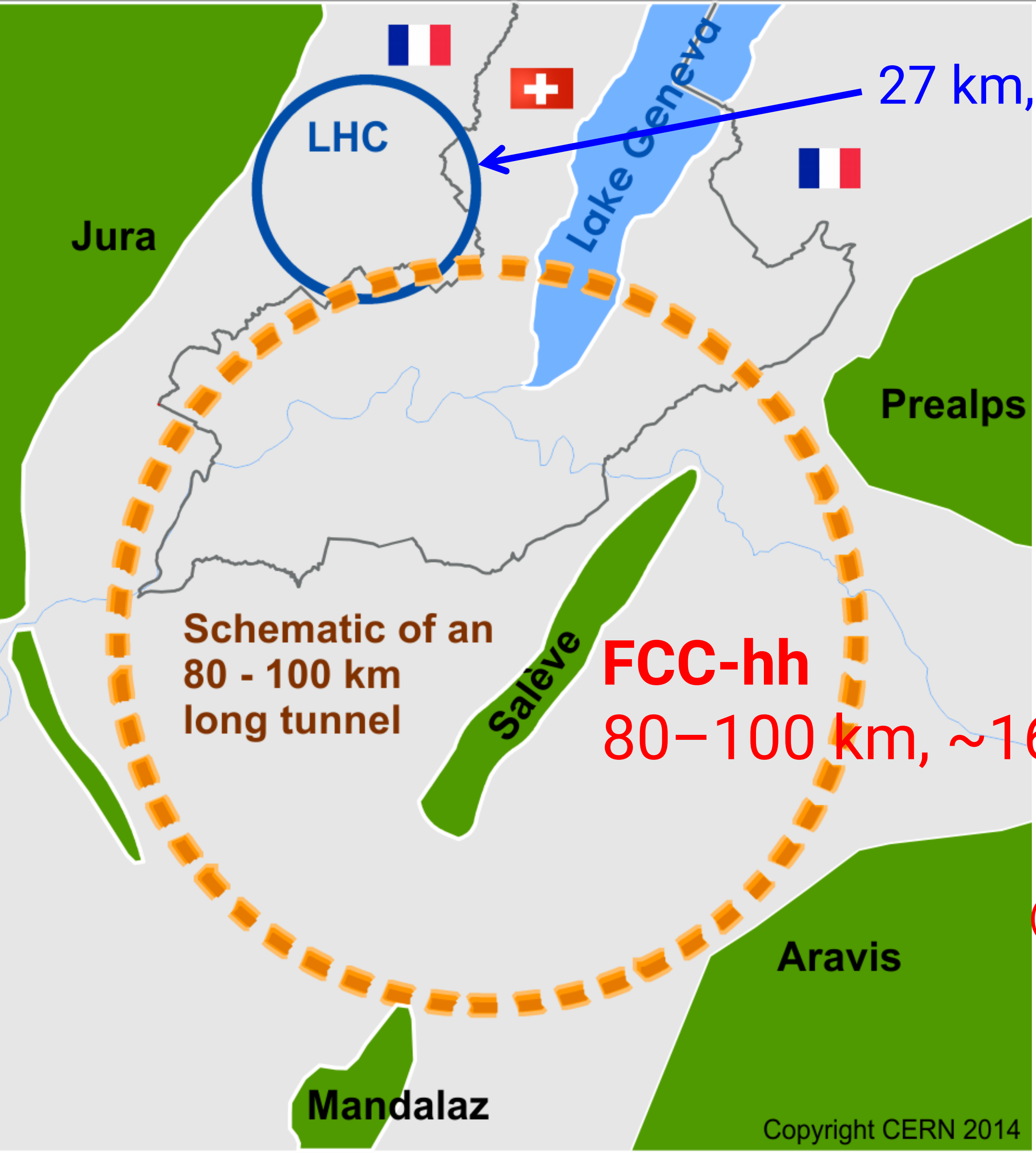


27 km, 8.3 T, beam = 7 TeV

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

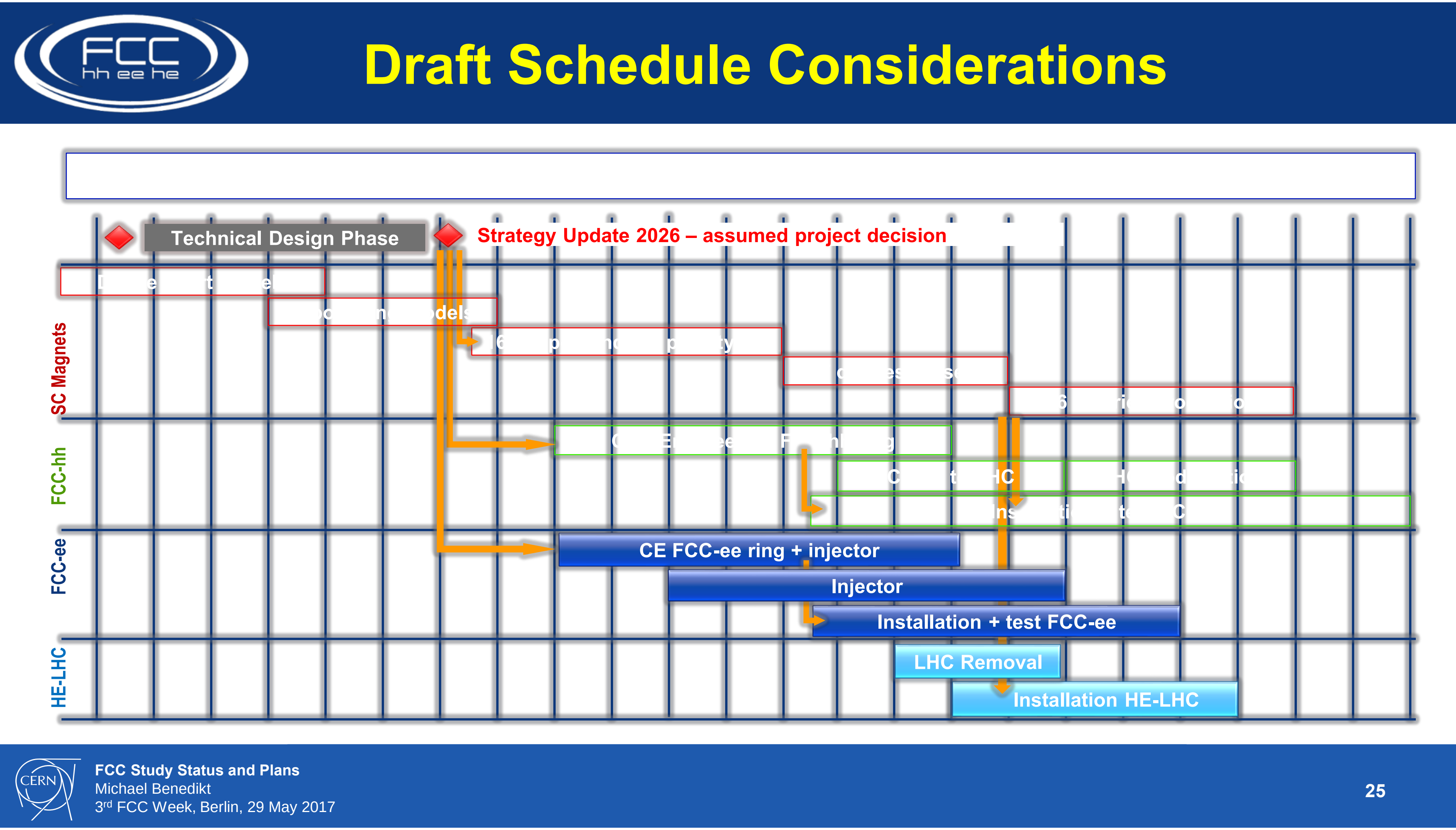
FCC-hh
80–100 km, ~16 T, beam = 50 TeV

($\int \mathcal{L}$ = 5–10 ab^{-1})

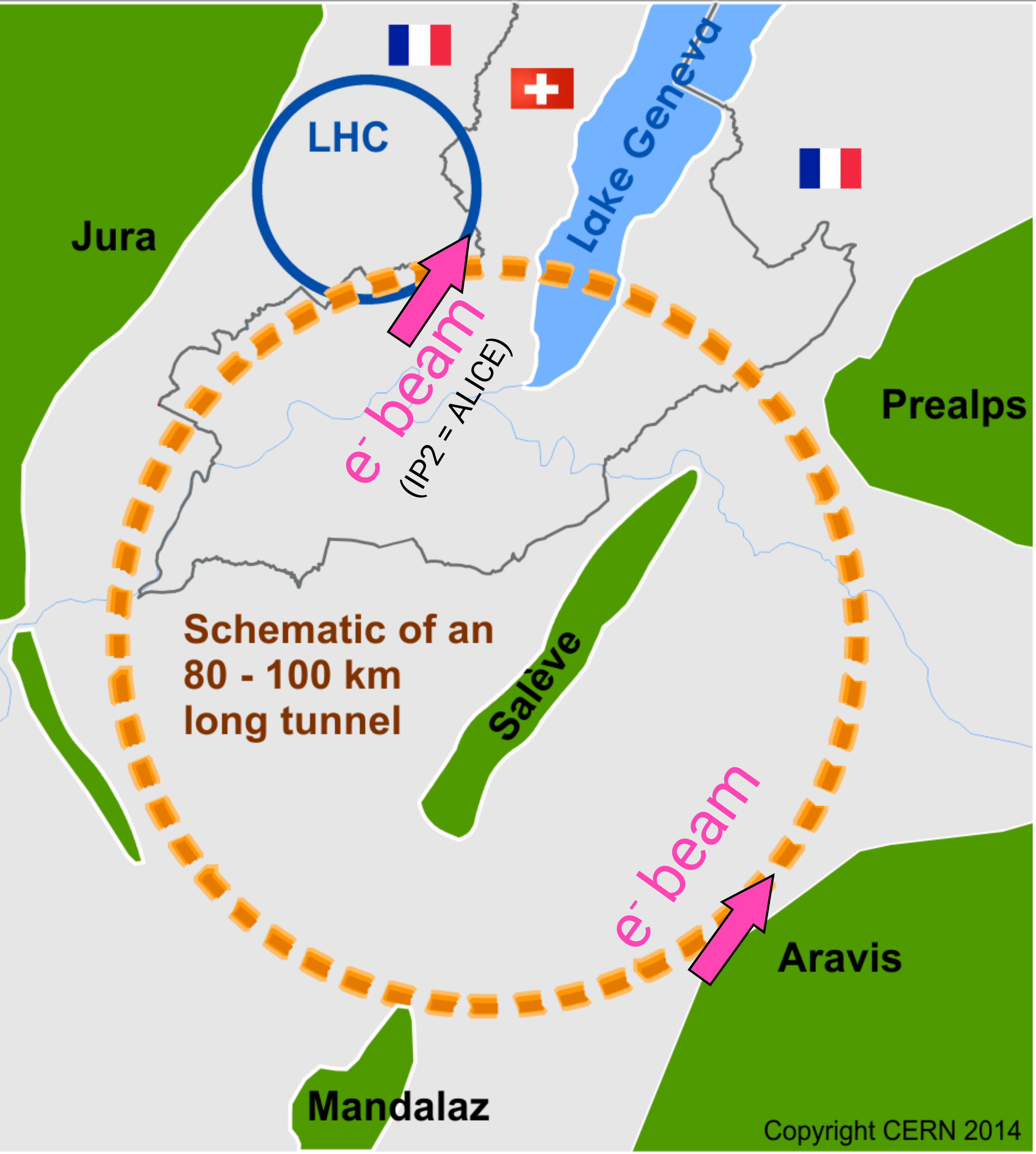
(FCC-ee as a potential first step)

→ 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"

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

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

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

- 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

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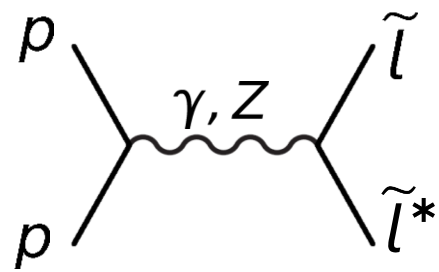
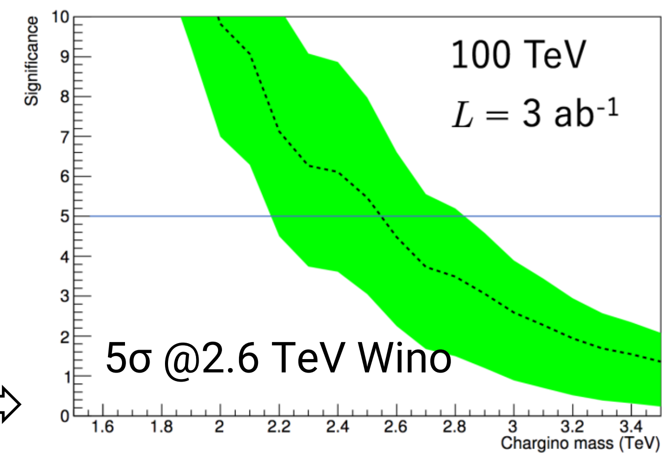
■ LLCPs at FCC-hh $\simeq$ LLCPs at LHC

- ➢ 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]

- ➢ same detection method.
  - "in-flight decay" → disappearing track.
  - "stable" $\tilde{l}$ → muon-like track + β measurement (heavy = slow)
    - dE/dx (ionization energy loss)
    - $\Delta L/\Delta t$ (time-of-flight)
- ➢ Two extras:
  - muon radiative energy loss
  - LLCP momentum resolutions

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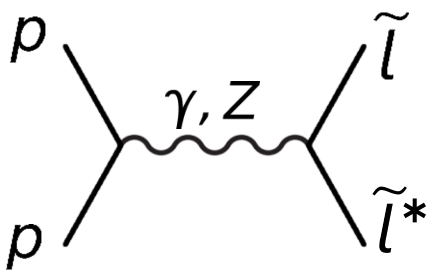

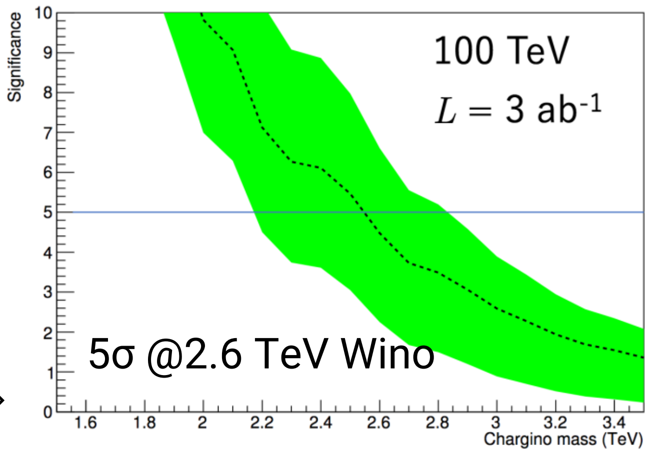

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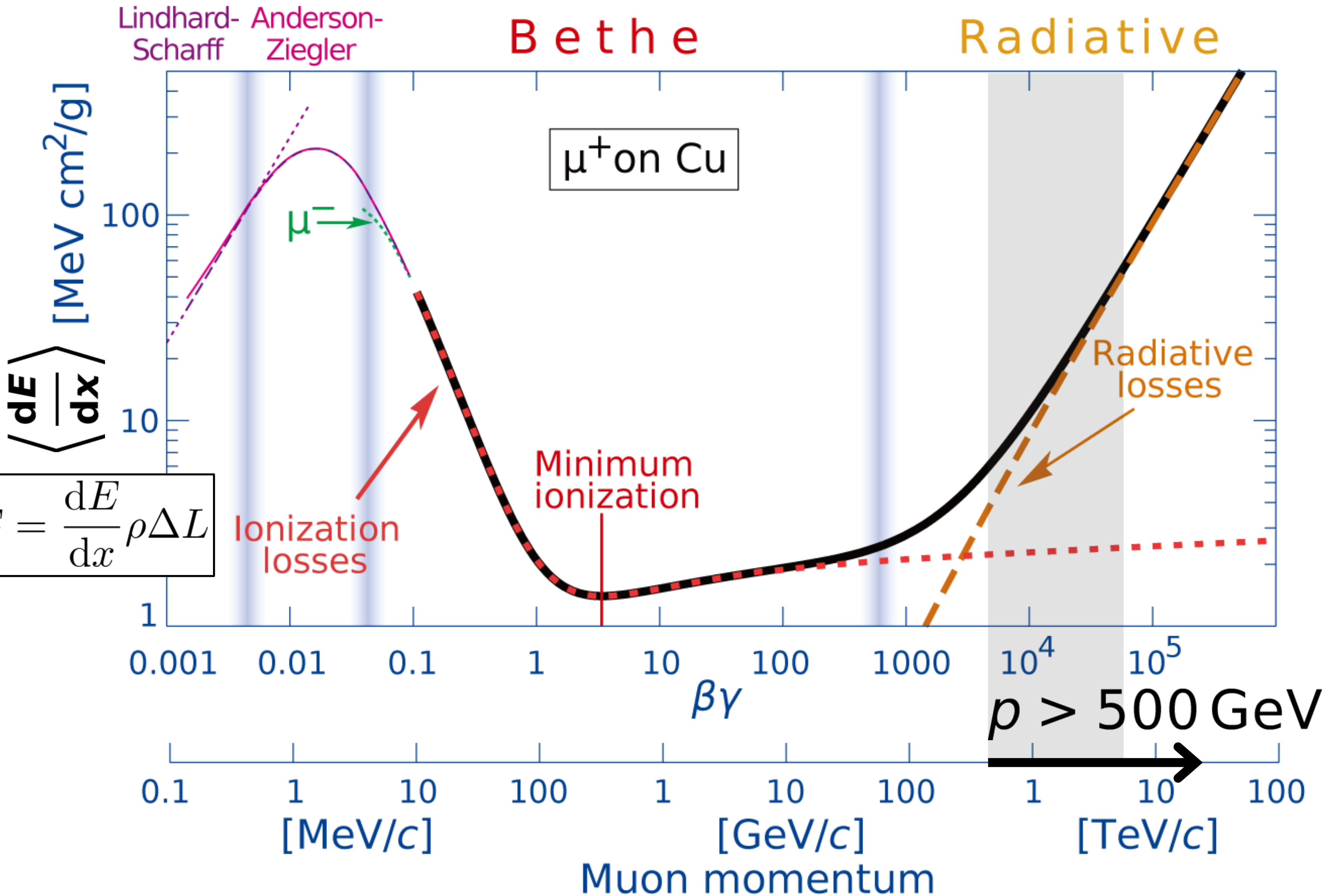


$$\Delta E = \frac{\mathrm{d}E}{\mathrm{d}x}\rho\Delta L$$

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

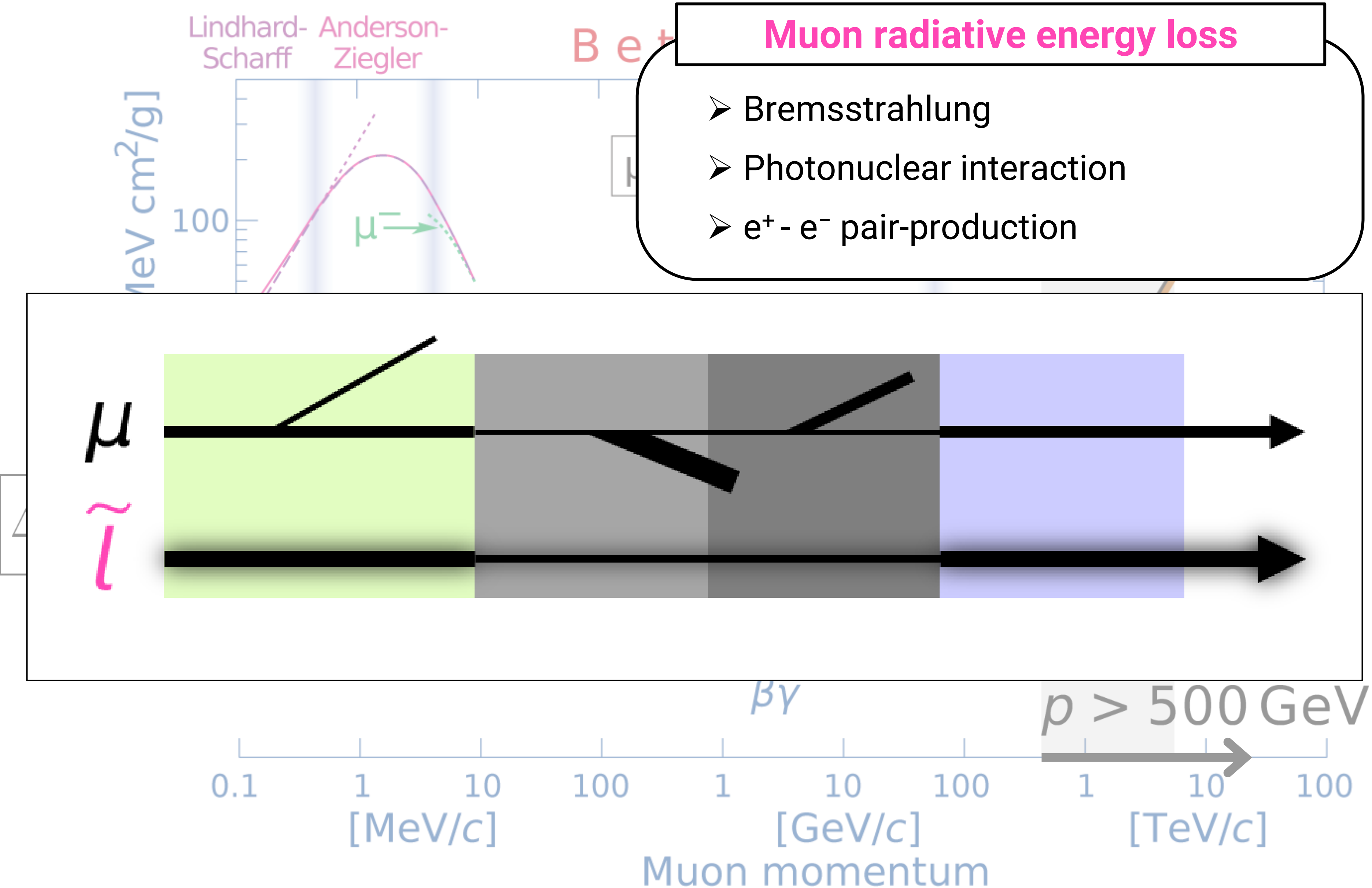
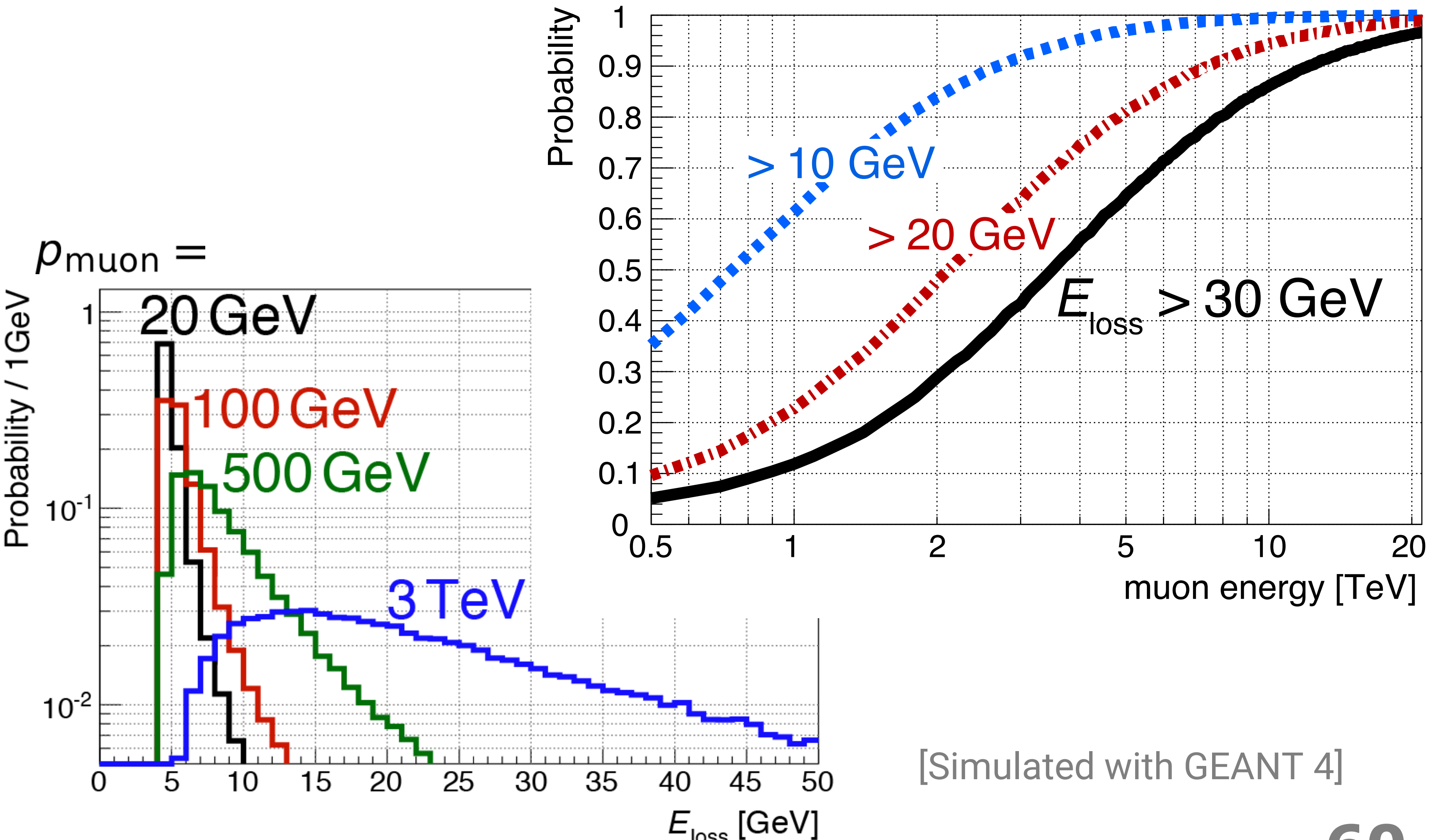


Figure from Groom, Mokhov, Striganov, Atom. Nucl. Data Tab. **78** (2001) 183-356
[also in PDG Review *"Passage of particles through matter"*]

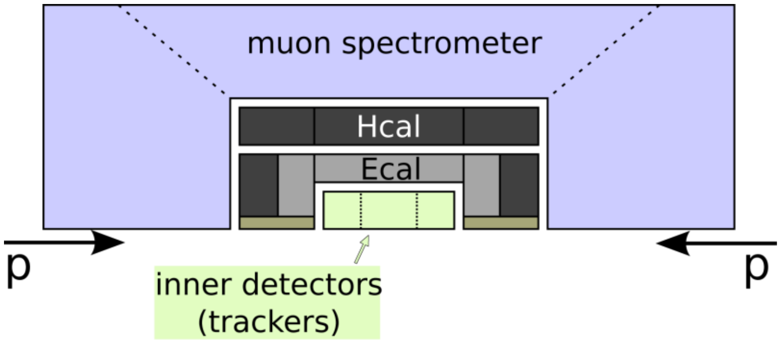
"calorimeter": approximated by iron (Fe) with 3m thickness.

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

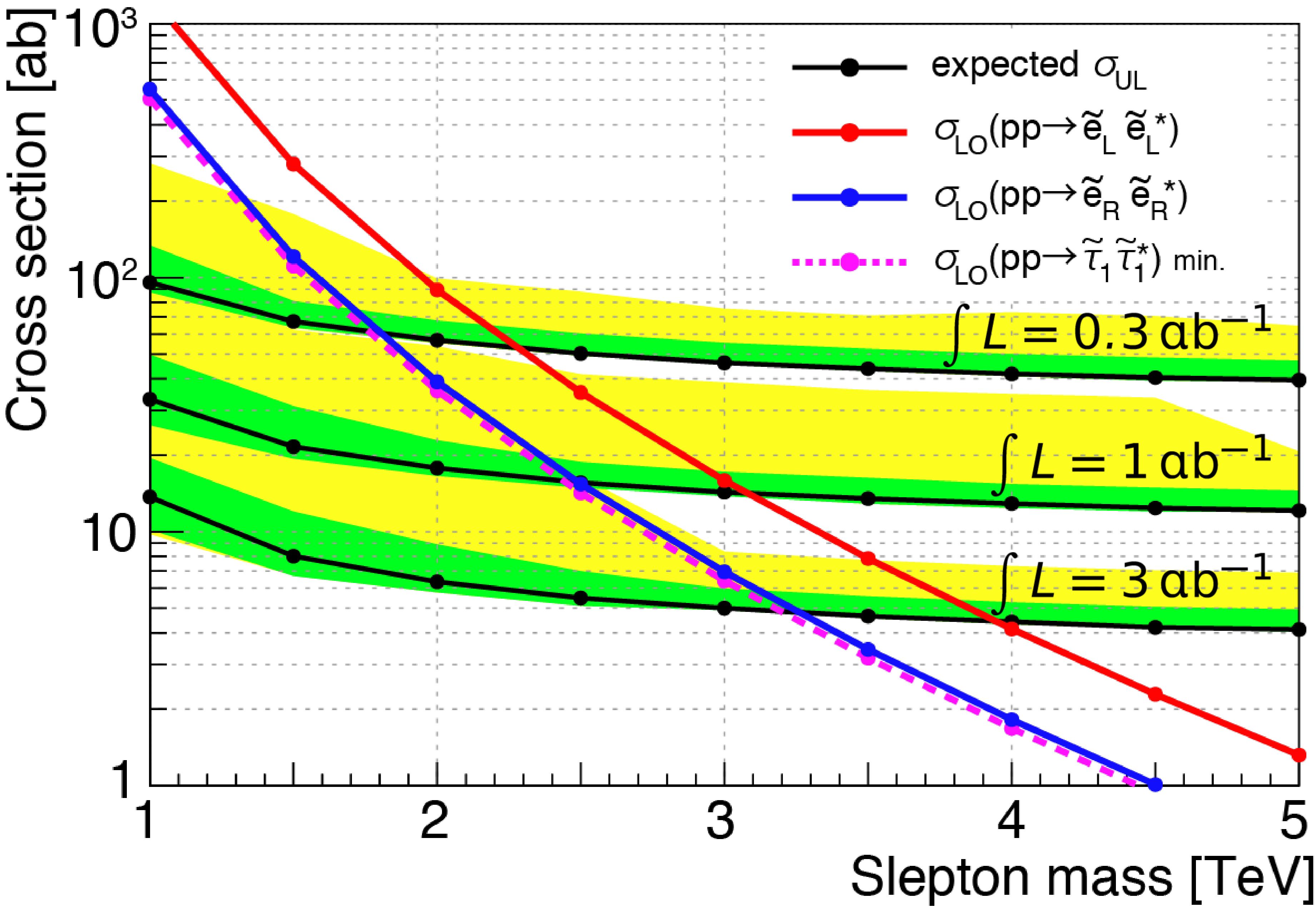
Event categorization $(\int L = 1\,\mathrm{ab}^{-1})$

	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]



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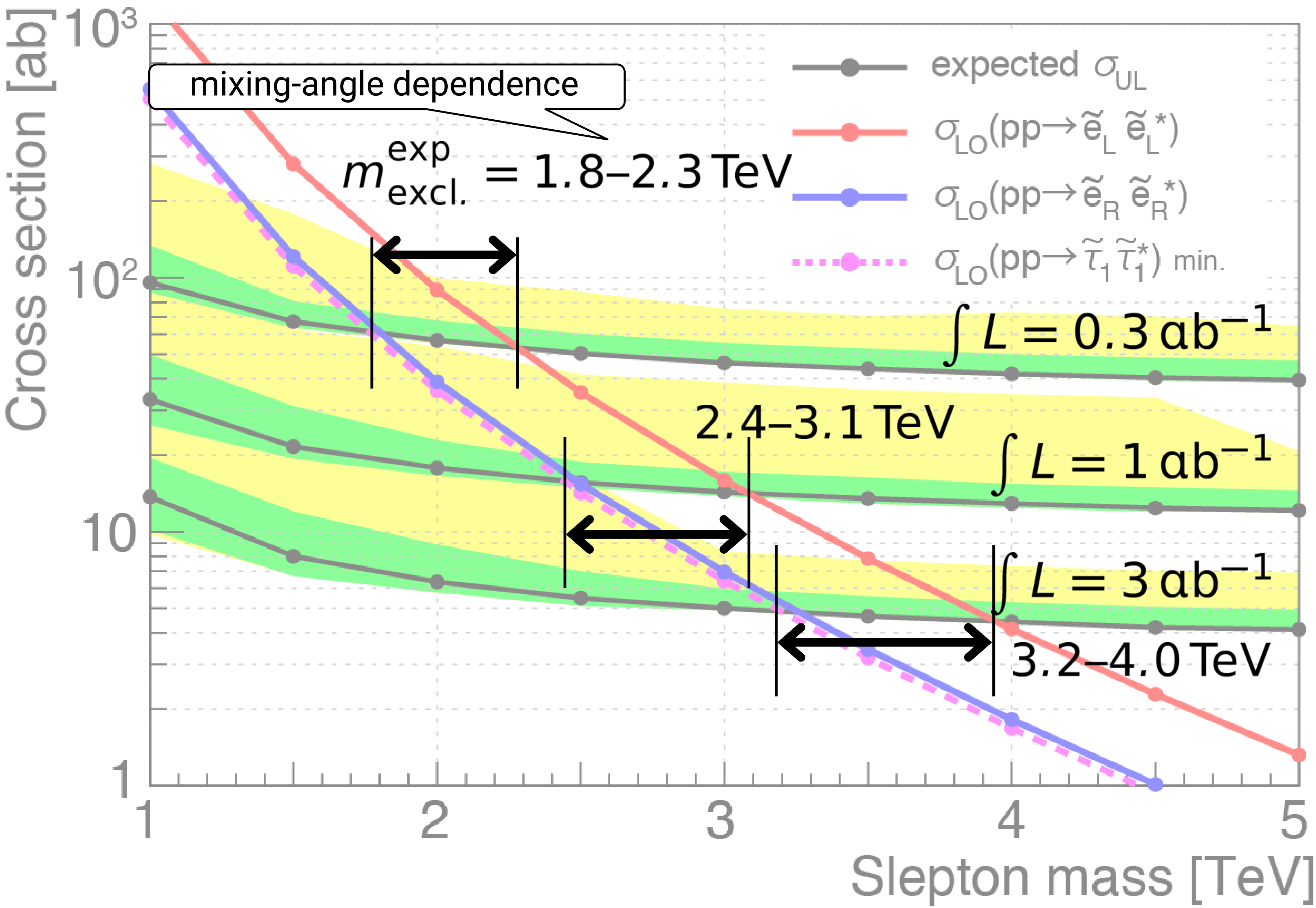

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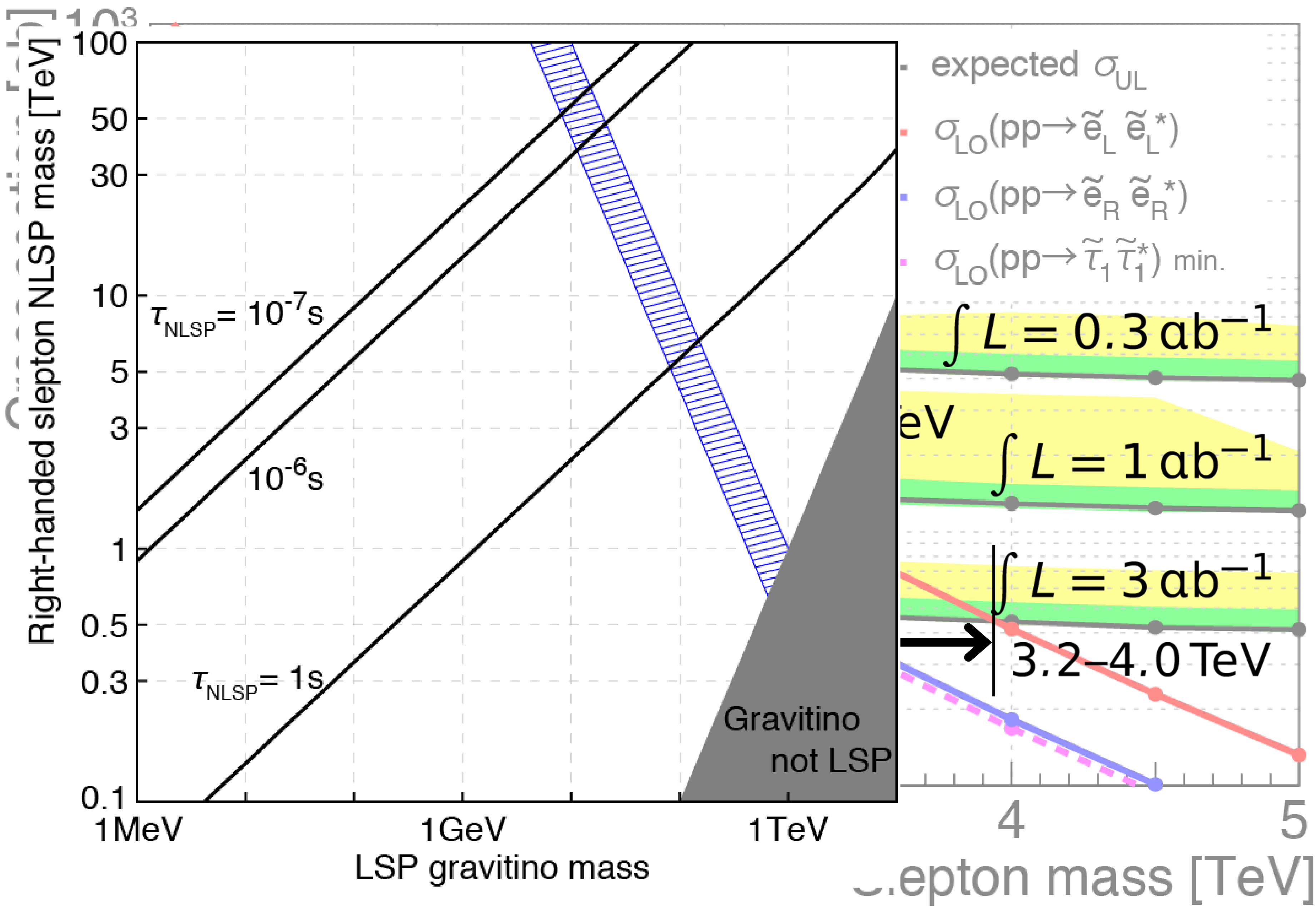

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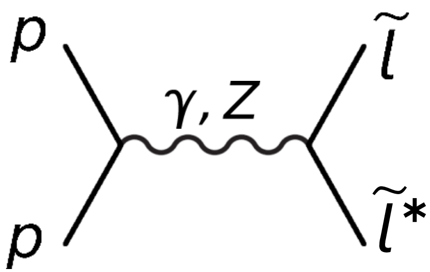

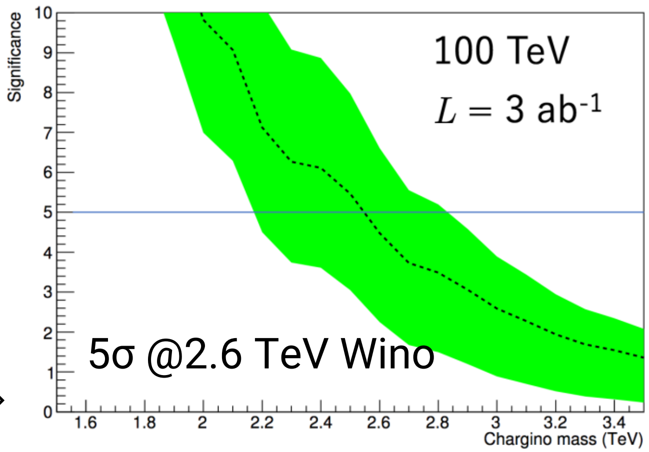

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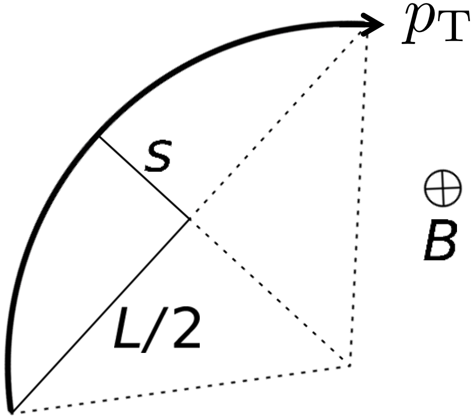


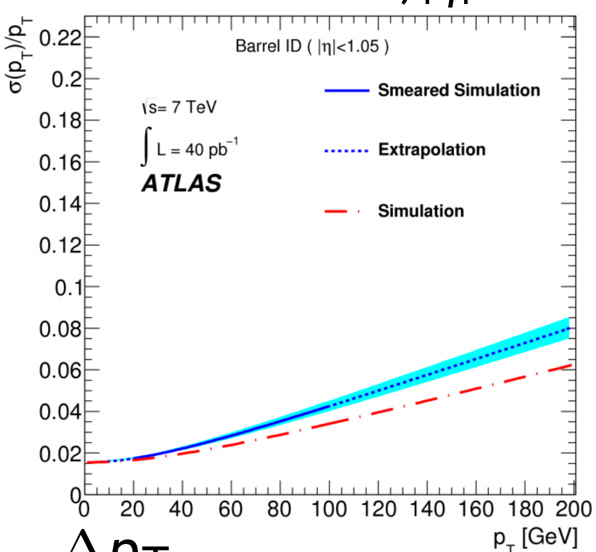
$$p_{\mathrm{T}} = \frac{L^2}{8s}|q|B \Longrightarrow \Delta p_{\mathrm{T}} = \frac{L^2|q|B}{8}\frac{\Delta s}{s^2}$$

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

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

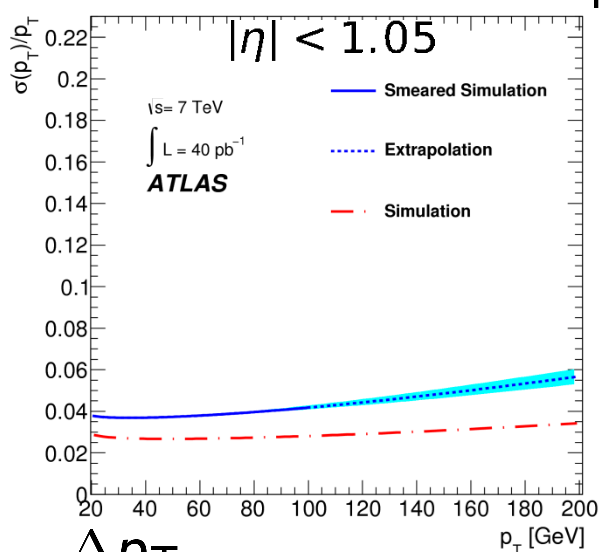
ATLAS 7 TeV results on muon momentum resolution

Inner Detector, $|\eta|<1.05$

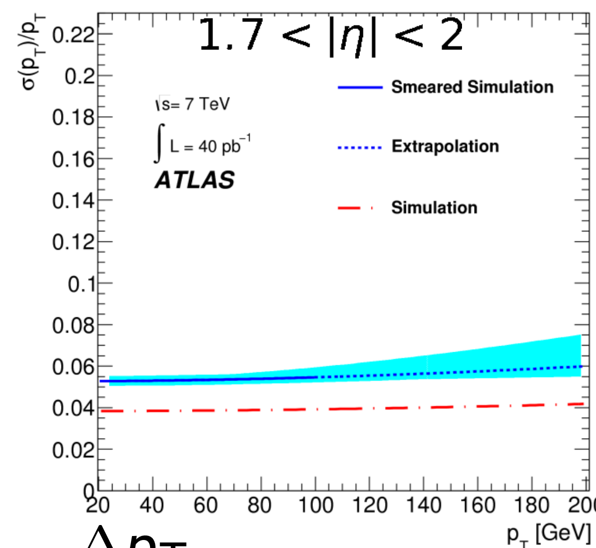


$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \sim 0.38 p_{\mathrm{T}}/\mathrm{TeV}$$

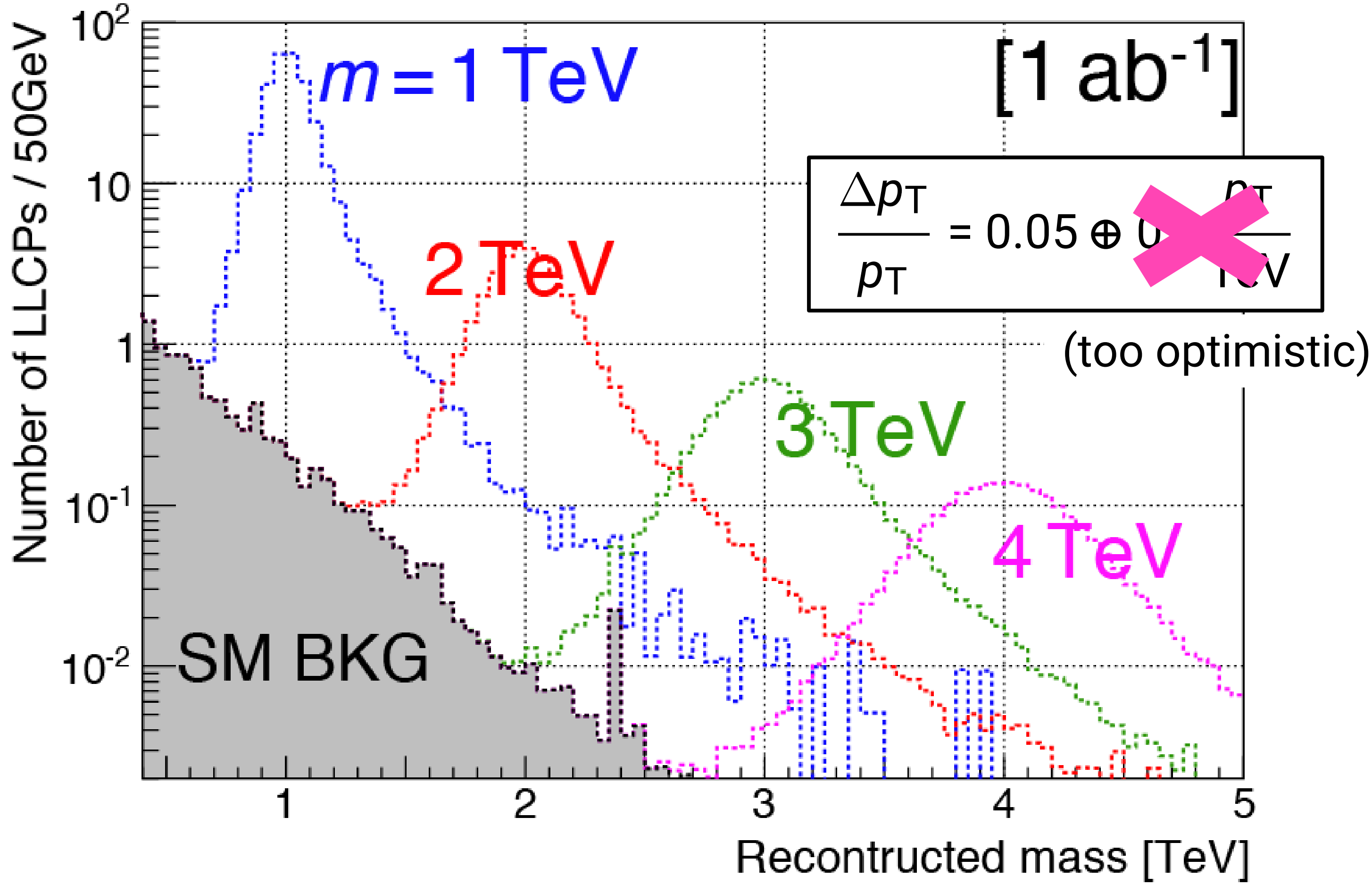
Muon Spectrometer



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



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



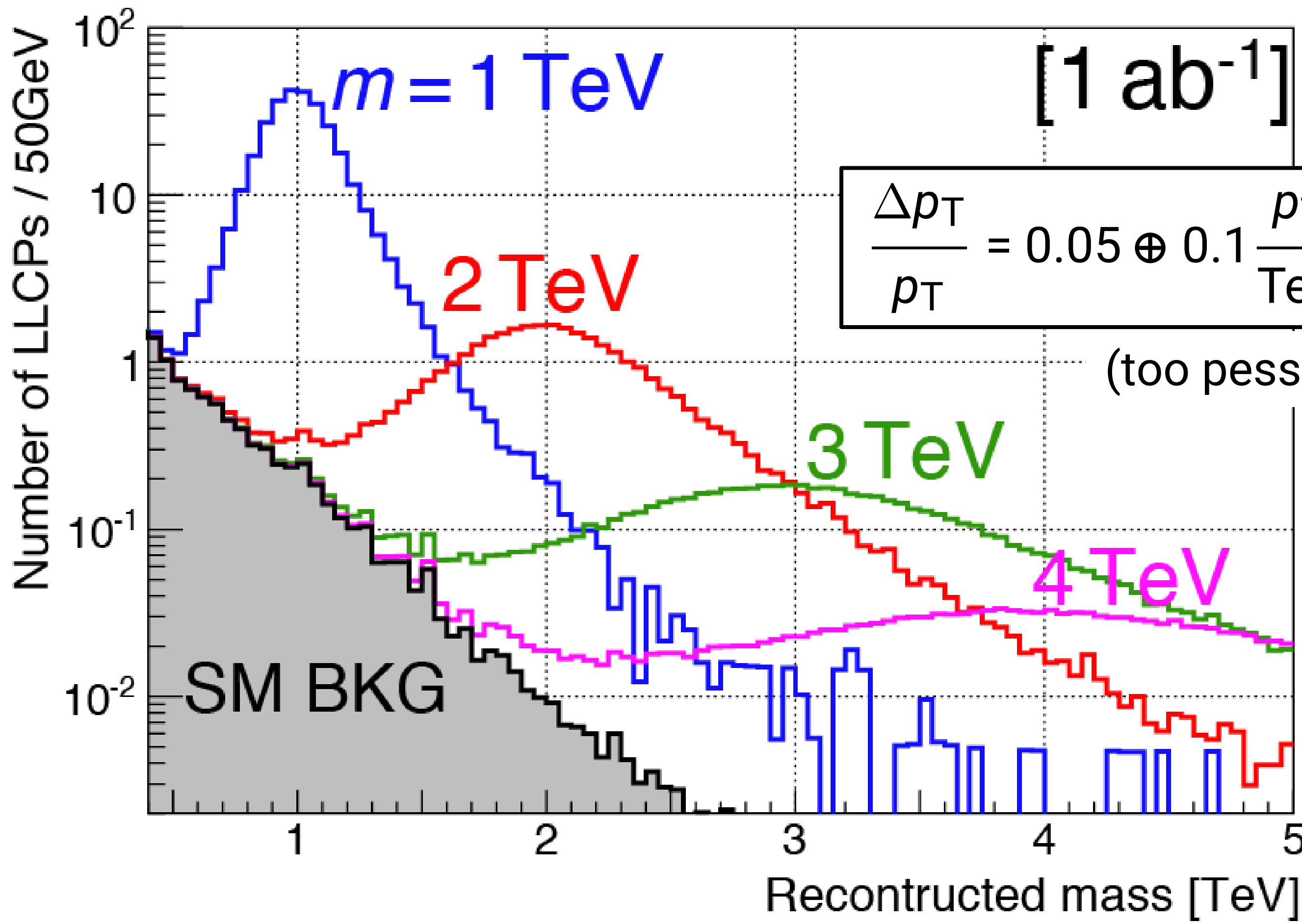
$$\left(= \frac{p}{\beta\gamma} = \frac{p_T \cosh\eta}{\beta\gamma} \right)$$

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



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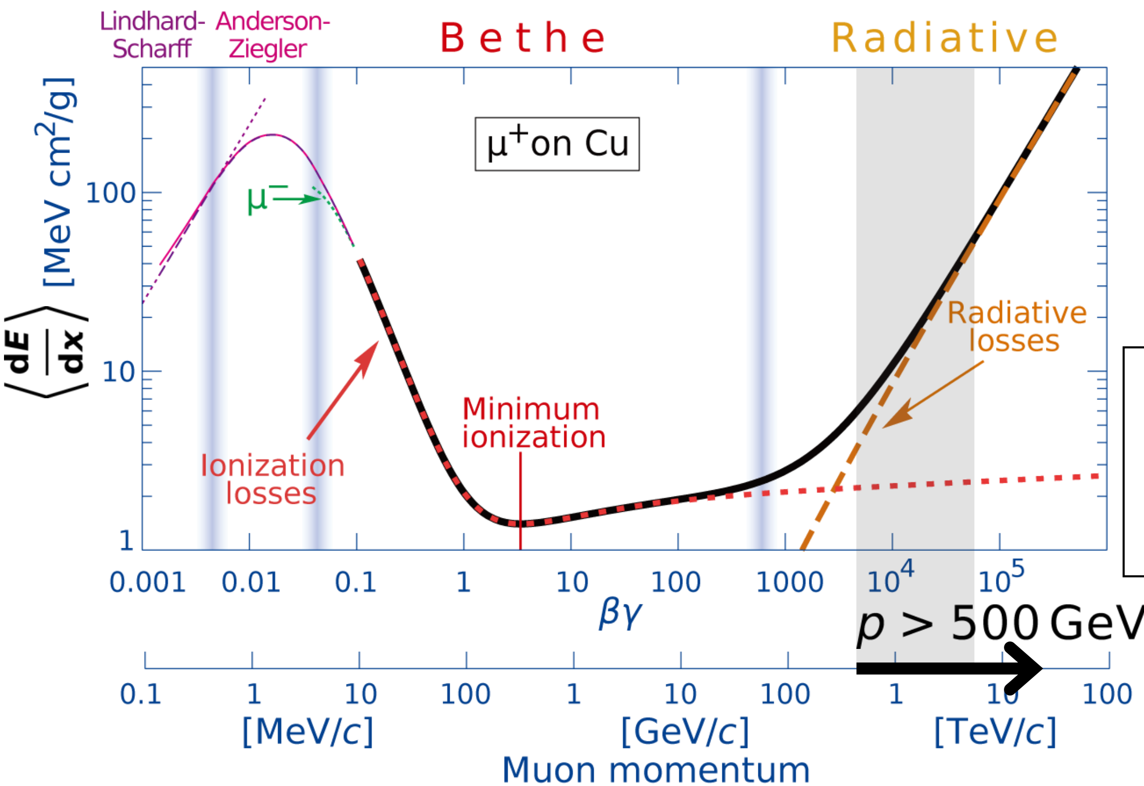
- 100 TeV FCC-hh mass reach (Drell–Yan $\tilde{l}$ or $\tilde{\tau}$)

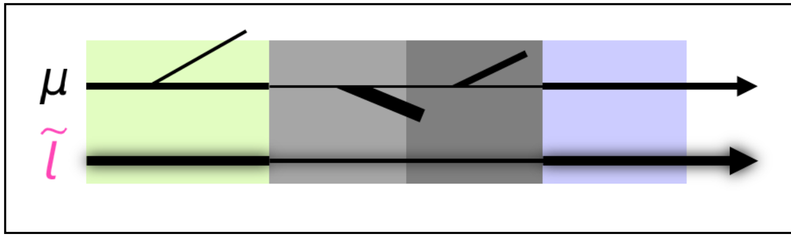
	$0.3ab^{-1}$	$1ab^{-1}$	$3ab^{-1}$
Exclusion	1.8–2.3	2.4–3.1	3.2–4.0
Discovery	1.6–2.2	2.3–3.0	3.1–4.0

in TeV

- **"Muon radiative energy loss"**



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



→ **34%** of BKG reduction

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

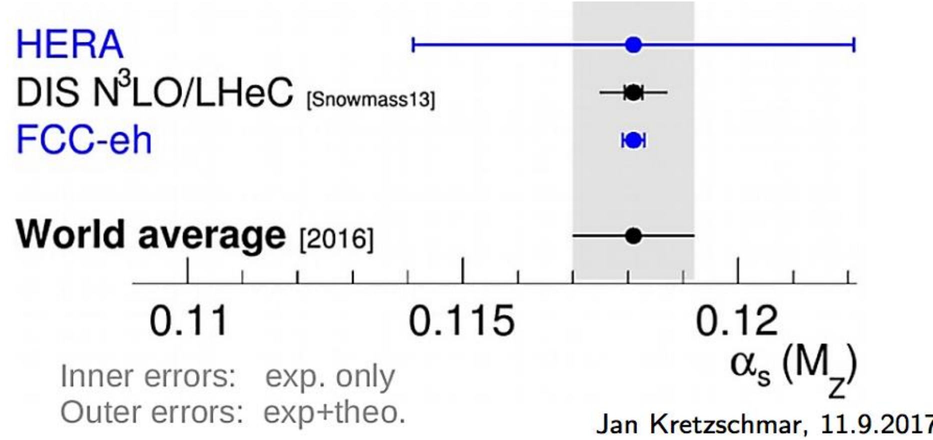
hh: Jonathan L. Feng, SI, Yael Shadmi, Shlomit Tarem [1505.02996]

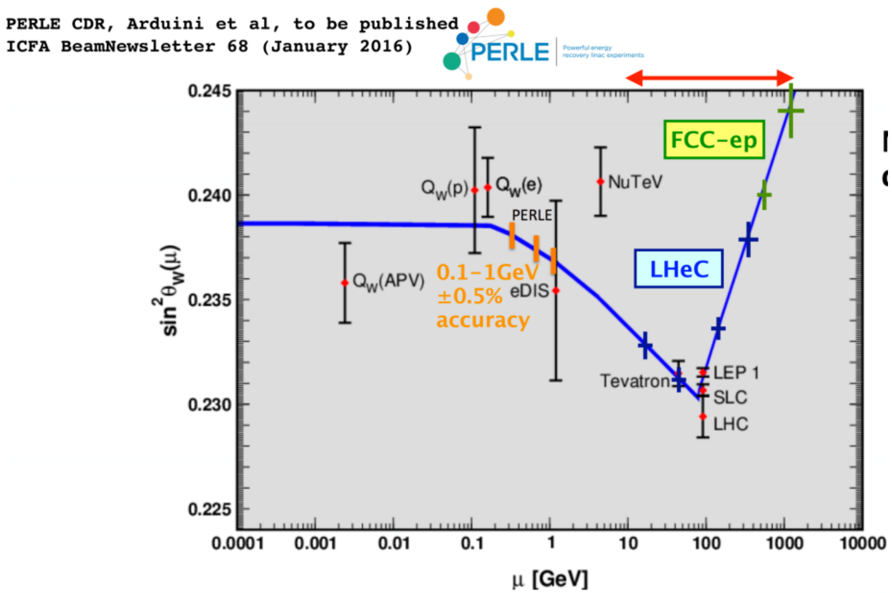
(collected in FCC-hh report [1606.00947])

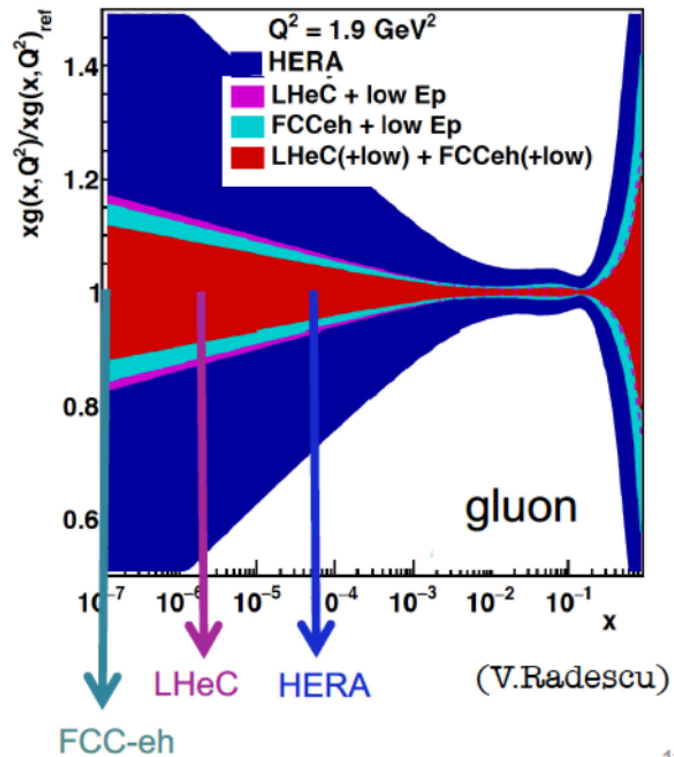
he: Kechen Wang, SI, Monica D'Onofrio, Georges Azuelos [17??.?????]

(subgroup in BSM@ep collaboration)

- 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

    $\tilde{\tau}$-LLCP

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

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

    $\tilde{l}$-LLCP

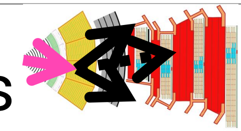
- Li problem
  - MSSM $\tilde{\tau}$ with

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

(δm > 0)

(but DM underabundant for "observable" region)

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

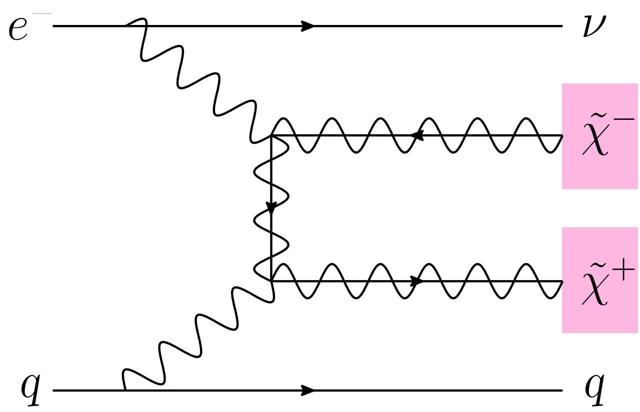
with $\tilde{l}$ -LSP

any cτ

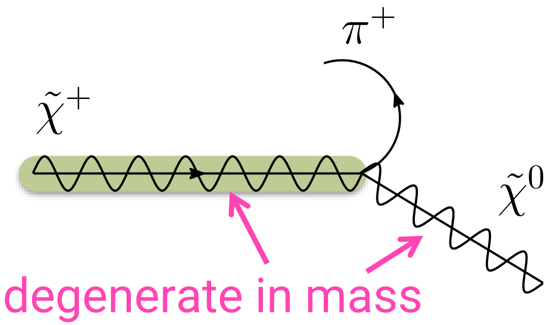
⇨ $\tilde{l}$ long-lived because of tiny couplings.

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

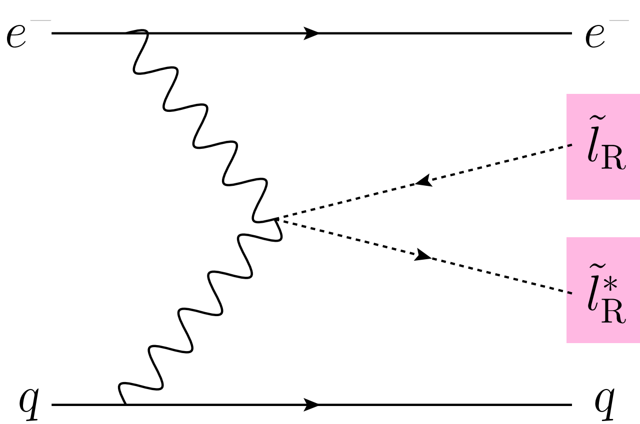
- Simplest models: 4-body production; $\sigma < 1$ fb … (´・ω・`)
  - Pure-Wino / Pure-Higgsino LSP



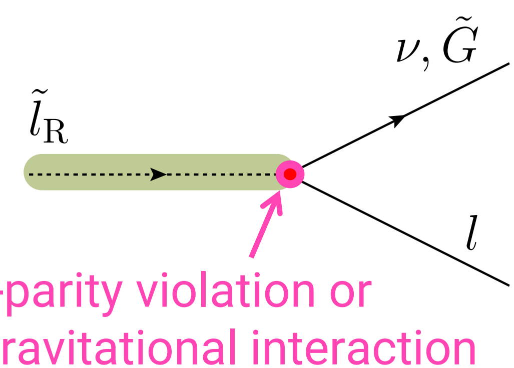
disappearing track



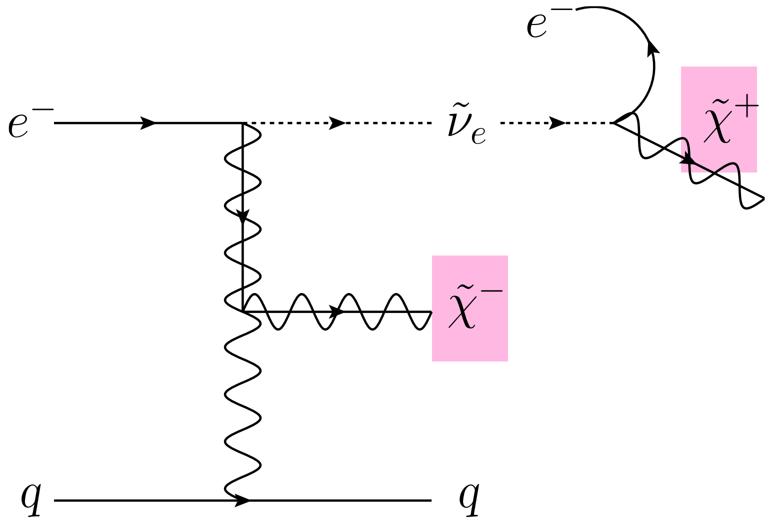
  - Slepton LSP



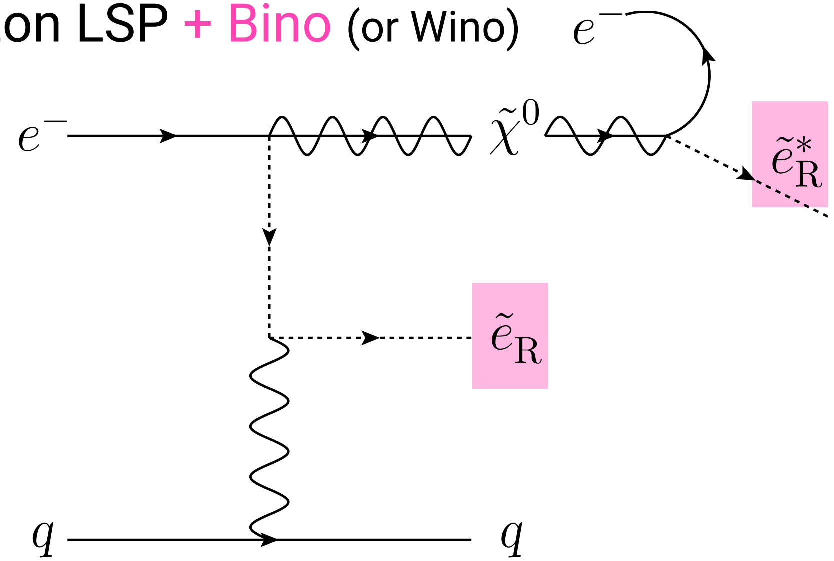
disappearing track (or “kink”)



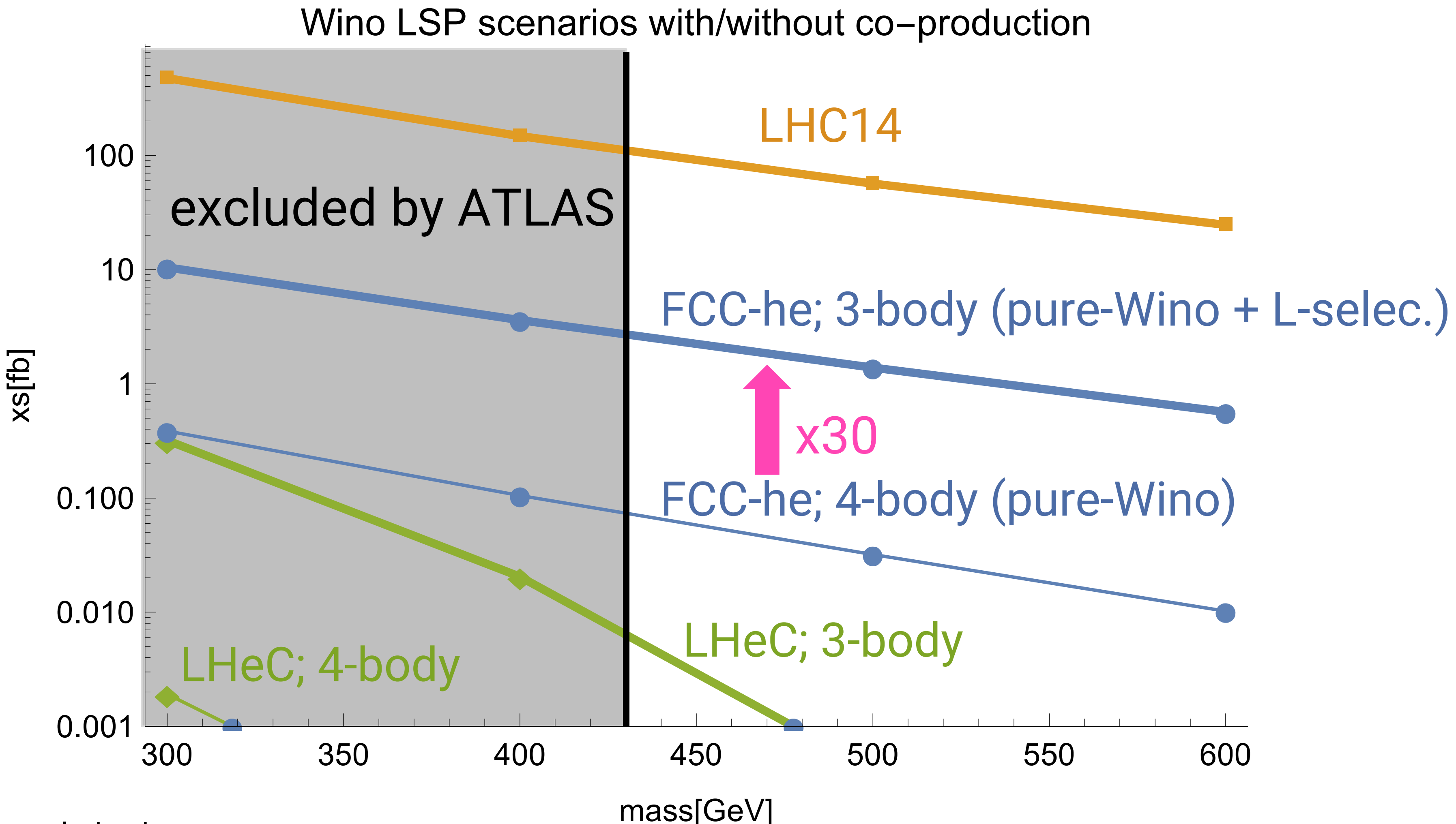
- Introducing co-LSP allows **3-body** production
  - Pure-Wino ~~/ Pure-Higgsino LSP~~ + left-handed selectron



  - Slepton LSP + Bino (or Wino)



- Nominal production cross section (without acceptances / efficiencies)

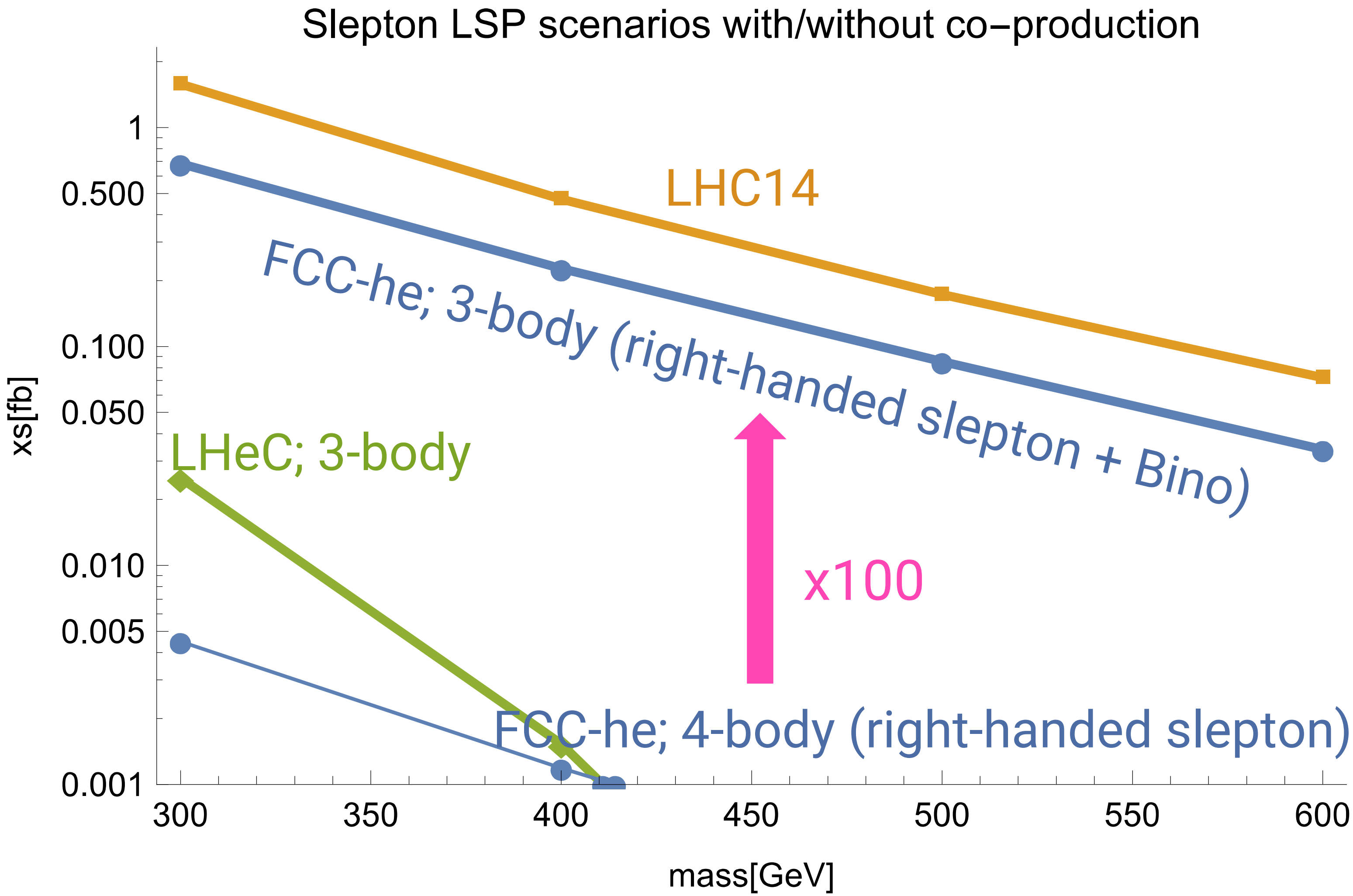


With no polarization.

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

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

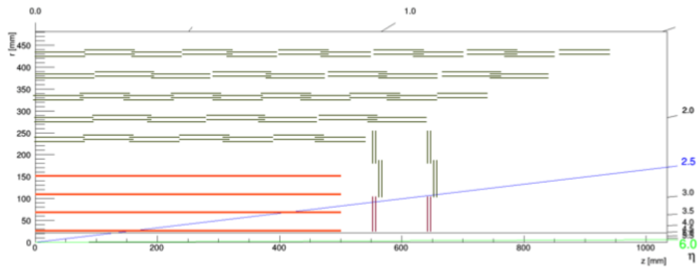
- Nominal production cross section (without acceptances / efficiencies)

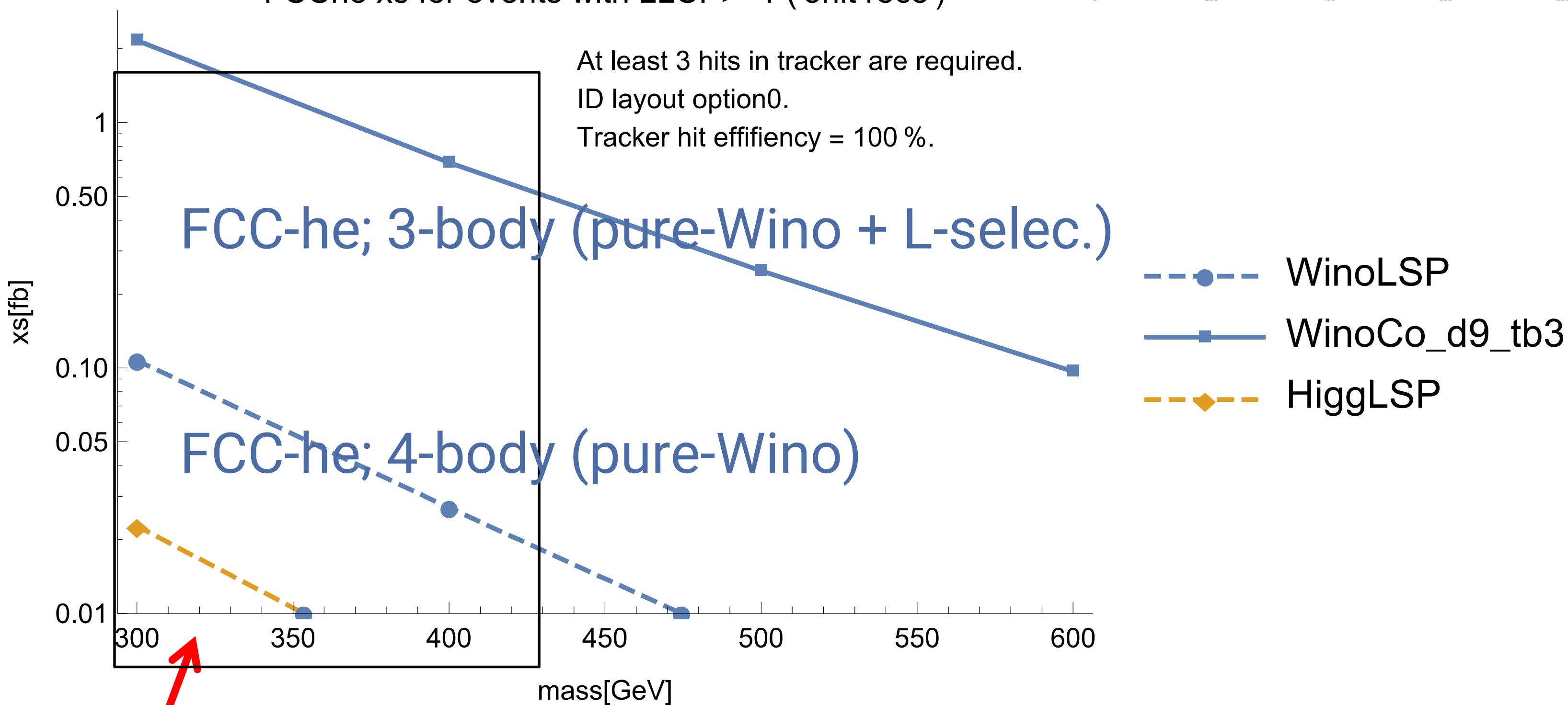


With no polarization.

"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.

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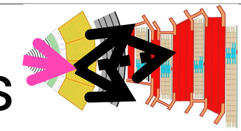
“3-body” process assumes $m_{\tilde{e}_L} = m_{\tilde{\chi}_1^0} + 9$ GeV.

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



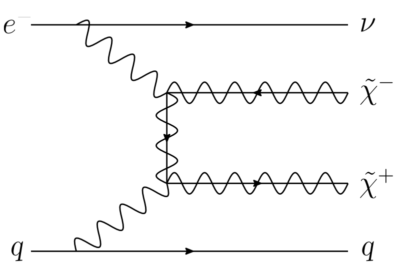
"single SUSY particle"

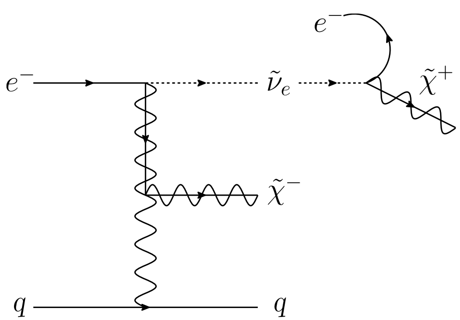
→ tiny σ due to 4-body process; HL-LHC will be better.

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**
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lifetime too short

→ trying to improve by identifying daughter particles…

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

any cτ

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

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in TeV

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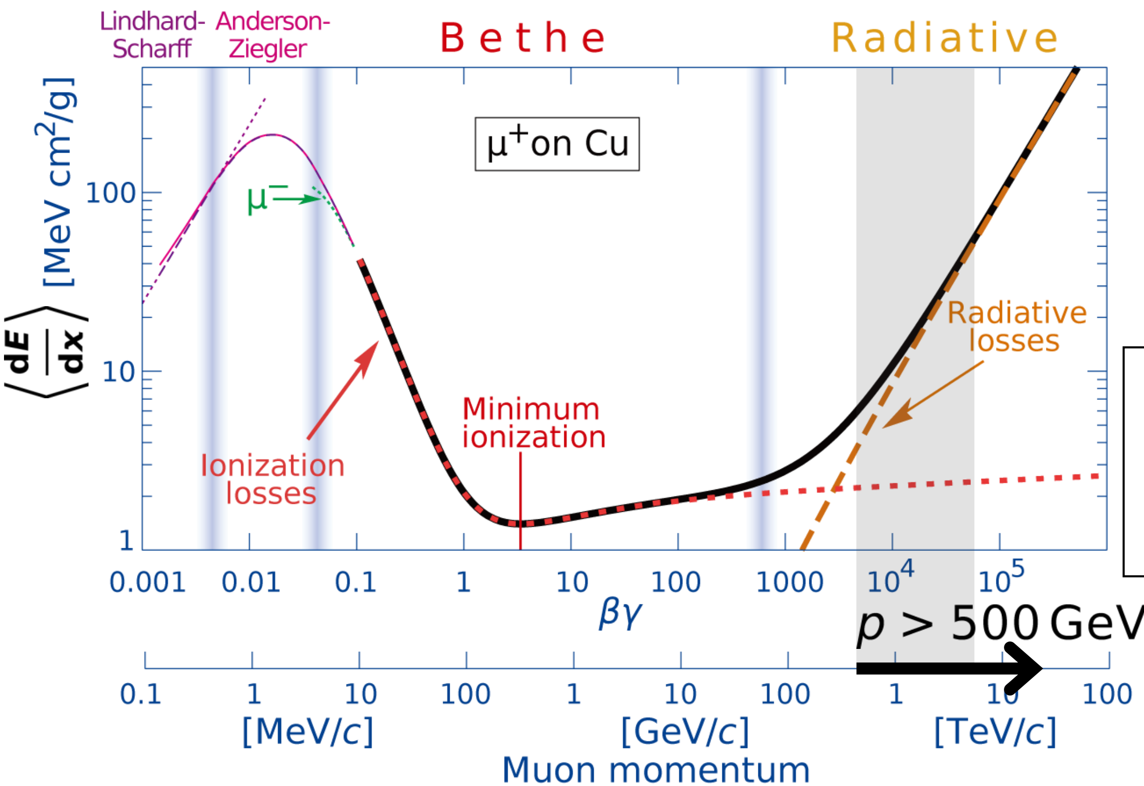

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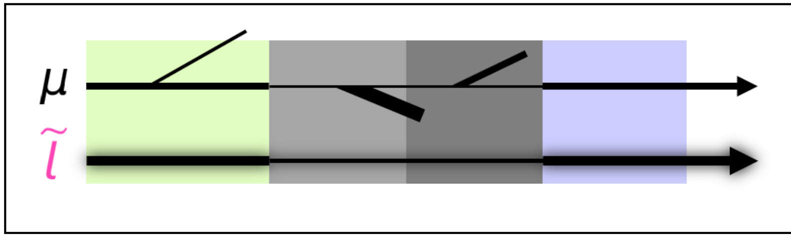

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