Long-Lived stau Signature in the LHC

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@ DESY, Deutschland.

Based on

ATLAS collaboration

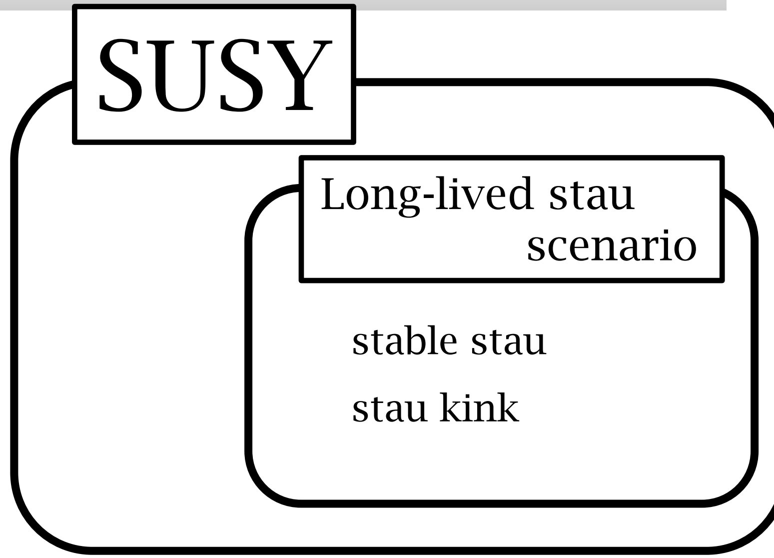
Asai, Azuma, Endo, Hamaguchi, and Iwamoto.

Theory group (Phenomenologists)

Stau Kinks at the LHC.

JHEP 1112 (2011) 077. [arXiv: 1103.1881] (hep-ph)

Talk Plan



1. **SUSY**
   - SUSY search
   - The LHC experiment
2. **Long-lived stau signature**
   - “stable stau” signature
   - “stau kink” signature
3. **Stau Kink in detail**

Based on

Asai, Azuma, Endo, Hamaguchi, and Iwamoto.
Stau Kinks at the LHC.
JHEP 1112 (2011) 077. `[arXiv: 1103.1881](hep-ph)`

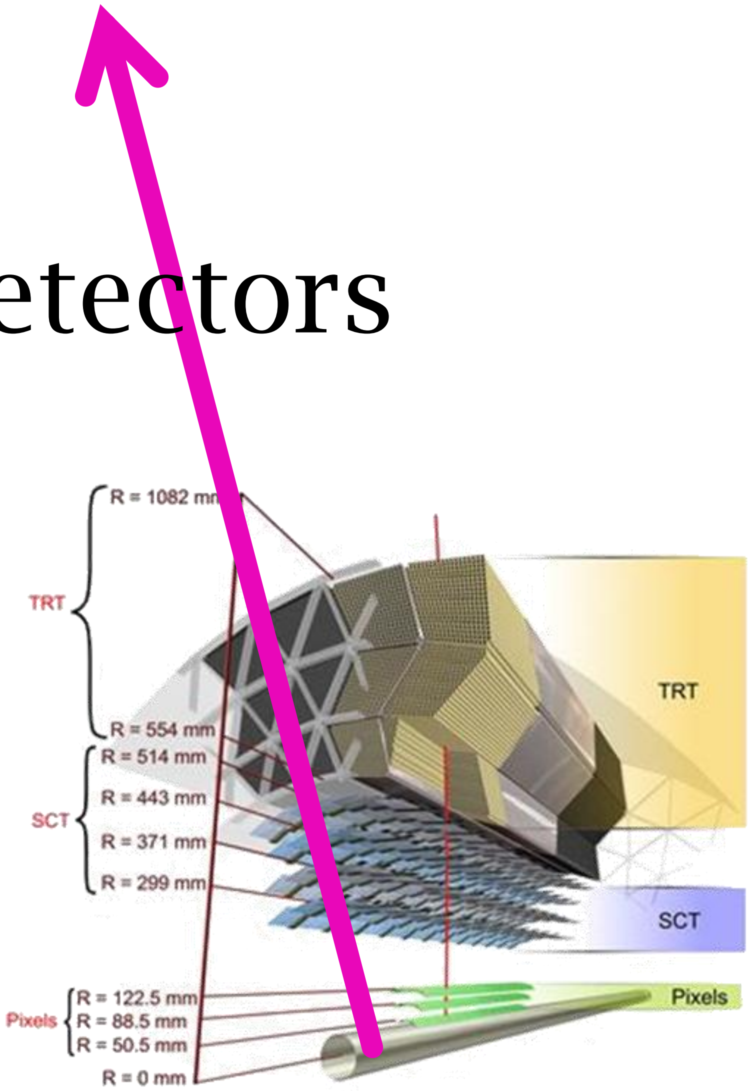
CONCLUSION

or
THE
MAIN
MESSAGE

Stau = Charged

Long-lived stau

⇨ a track in detectors



ATLAS detectors (in the LHC)

Stau = Charged

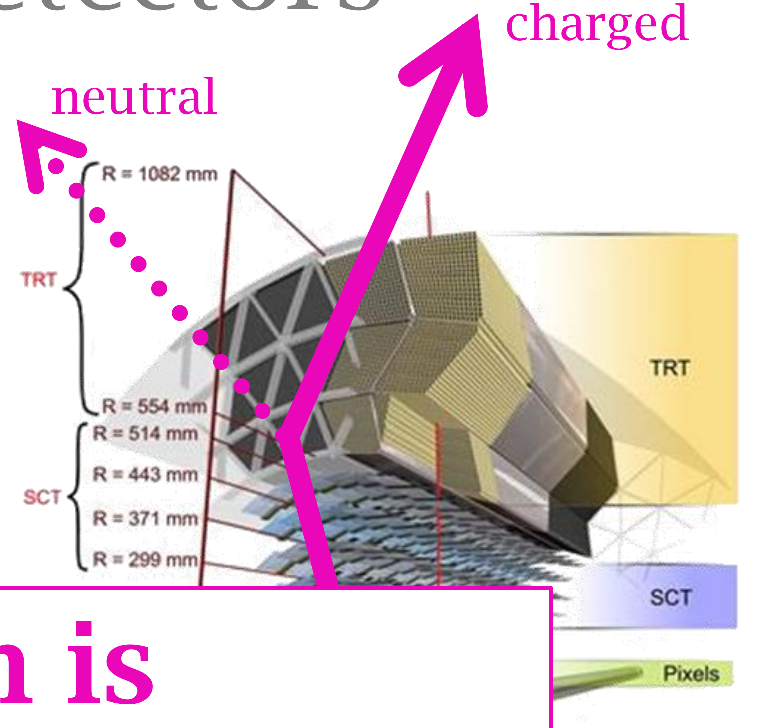
Long-lived stau

⇨ a track in detectors

When decay inside

⇨ track bends

"Stau Kink"



Stau kink search is realistic & interesting.

(…the LHC)

1. SUSY and its Signature

Standard Model

- Successful!
- “Hierarchy problem”

supersymmetry

MSSM [Minimal Supersymmetric Standard Model]

- “Hierarchy” solved.
- GUTs & Dark Matter?

However…

Standard Model

Successful!

“Hierarchy problem”

supersymmetry

MSSM [Minimal Supersymmetric Standard Model]

“…chy” solved

GUTs & Da… …atter?

Hypothetical!

Not discovered yet!

However…

Standard Model

- Successful!
- “Hierarchy problem”

supersymmetry

MSSM [Minimal Supersymmetric Standard Model]

- “… …chy” solved
- GUTs & Da… …atter?

Hypothetical!

Not discovered yet!

We want to discover SUSY.

How to discover SUSY?

What is **characteristic** in SUSY?

Important one: *R*-parity

If R-parity is conserved…

✓Proton decay problem avoided! 

✓LSP becomes **stable**!

- ➢must be **neutral**.
- ➢would be a **Dark Matter** candidate. 

How to discover SUSY?

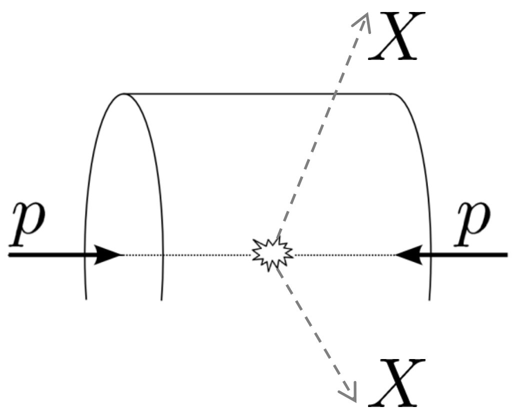
What is **characteristic** in SUSY?

main stream!

Expected in many SUSY models!

[Case 1] Signature from **stable neutral particles**

⇨ **Large missing energy** $\not{E}$



X = escaping (missing) particle;
e.g. $\widetilde{\chi}_1^0$ or $\widetilde{G}$.

[Case 2] Signature from

long-lived charged particles

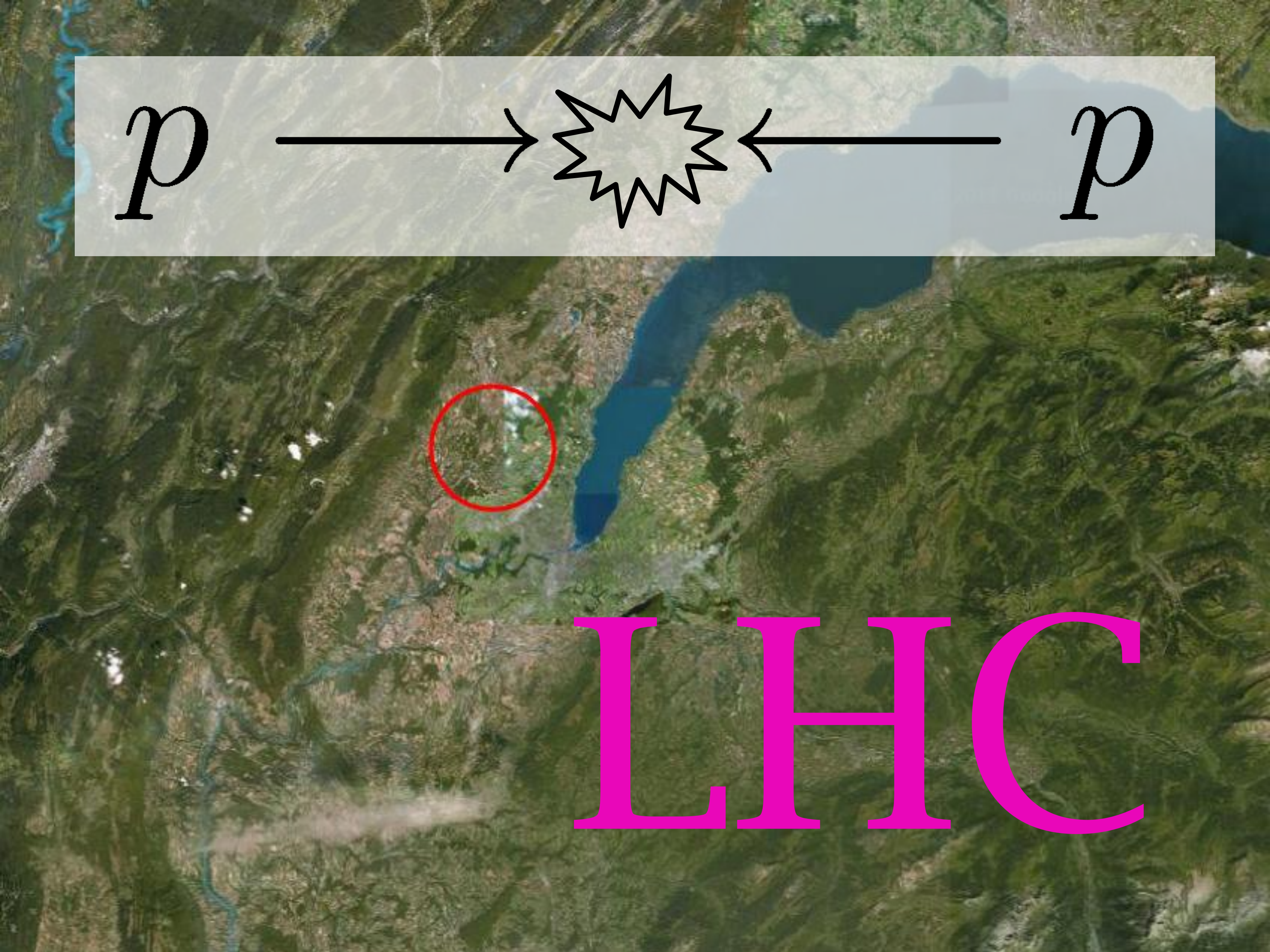
expected in several models.

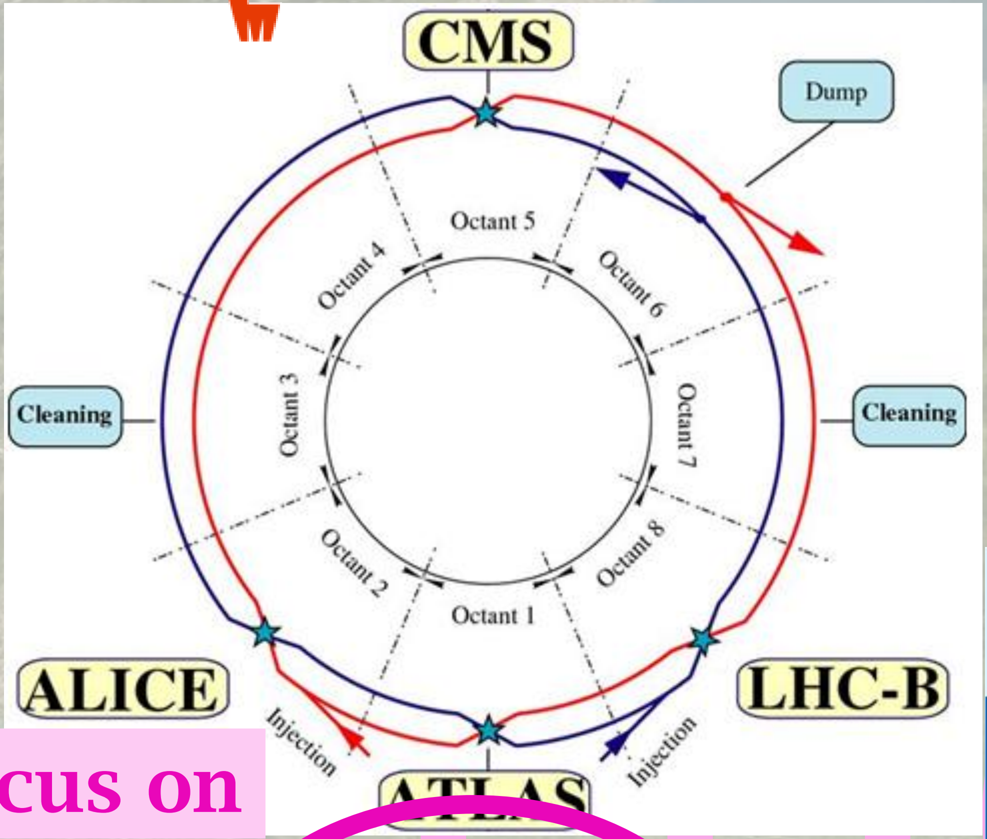
⇨ We will see in the next section.

Then, where can we discover SUSY?

… of course,

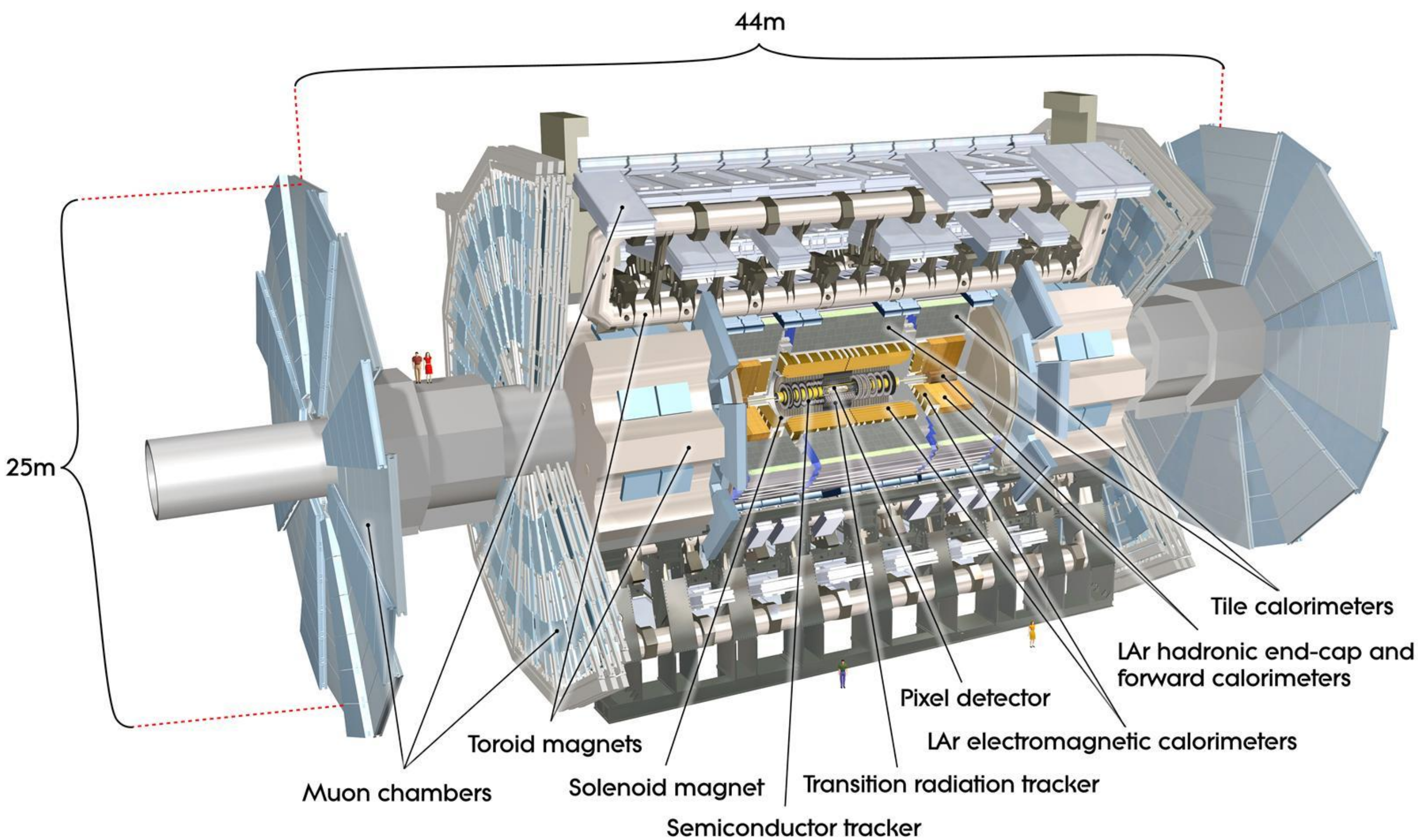

Bonn
LHC
東京

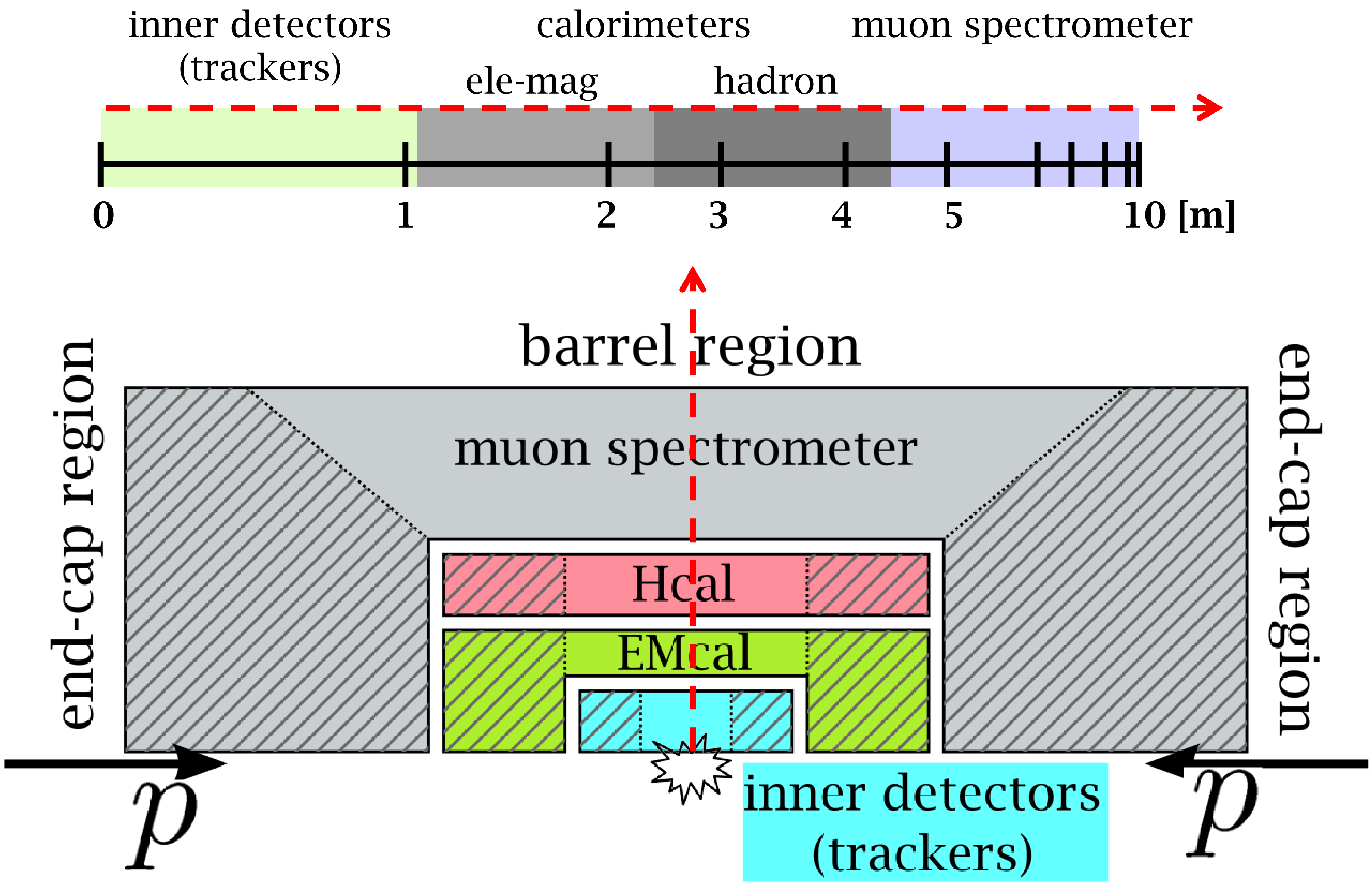

$p \longrightarrow$ ✳ $\longleftarrow p$
LHC


CMS
Dump
Octant 5
Octant 4
Octant 6
Octant 3
Octant 7
Cleaning
Cleaning
Octant 2
Octant 8
Octant 1
ALICE
LHC-B
Injection
Injection
ATLAS

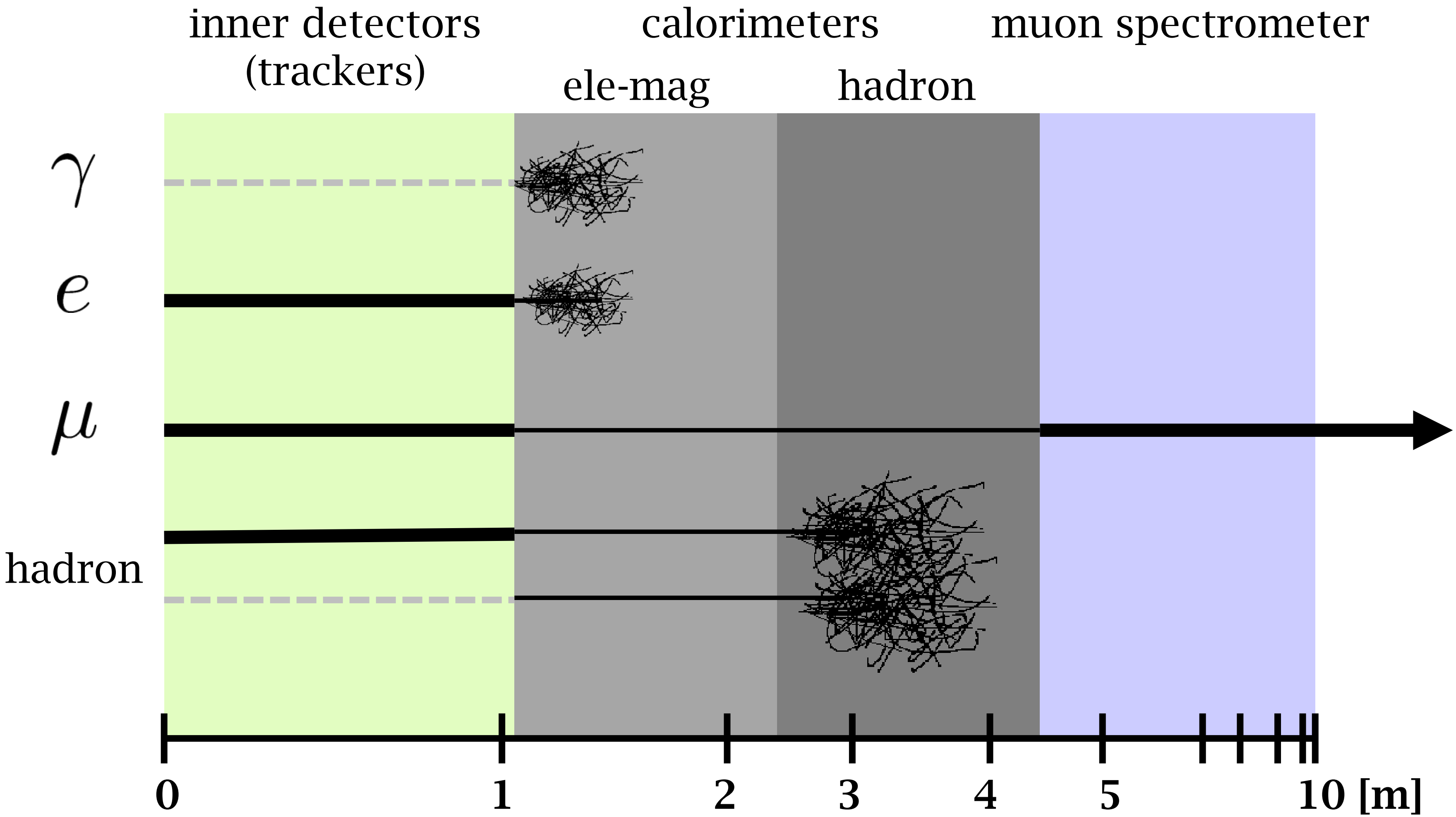
We focus on

ATLAS EXPERIMENT





[sectional (cut-away) view]



Note τ ⇒ immediately decays into
leptons (35%) → e/μ is observed.
hadrons (65%) → hadrons are observed.

2. Long-lived Stau Signature

- Scenario with Long-lived stau
- Its Signature
  1. Stable stau
  2. Stau kink

[Case 2] Signature from

(We don't consider $\widetilde{e}, \widetilde{\mu}$ -case for simplicity.)

long-lived charged particles $\left(\widetilde{\tau}_1\right)$

expected in several models:

A) $\widetilde{G}$-LSP, $\widetilde{\tau}_1$-NLSP model (in GMSB framework) "weakness of gravity"

$$\widetilde{\tau}_1 \to \widetilde{G}\tau : \; c\tau \simeq 0.55\,\mathrm{m}\left(\frac{200\,\mathrm{GeV}}{m_{\widetilde{\tau}_1}}\right)^5\left(\frac{m_{\widetilde{G}}}{1\,\mathrm{keV}}\right)^2$$

B) $\widetilde{\tau}_1$-LSP with tiny R-parity violation "tiny R-parity violation"

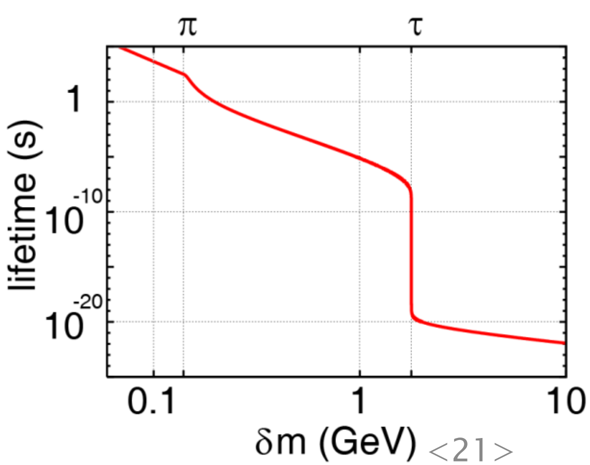
$$c\tau \sim \mathrm{O}(1\,\mathrm{m}) \;\; \text{if RpV couplings} \sim 10^{-8}.$$

C) Coannihilation region "phase-space suppression"

$(\widetilde{\chi}^0_1\text{-LSP}, \widetilde{\tau}_1\text{-NLSP}, m_{\widetilde{\tau}_1} \simeq m_{\widetilde{\chi}^0_1})$

$$\widetilde{\tau}_1 \to \widetilde{\chi}^0_1 l\nu\bar{\nu}, \; \widetilde{\chi}^0_1\pi\nu$$

Right: lifetime @ $m_{\widetilde{\tau}_1} = 300\,\mathrm{GeV}$
$(\theta_\tau = 0.33)$



Jittoh *et al.*, PRD73.055009 [hep-ph/0512197]

[Case 2] Signature from
long-lived charged particles $\left(\widetilde{\tau}_1\right)$

signature depends on **where stau decays.**

a) **outside** detectors

b) **inside** a detector

c) at the very **center**

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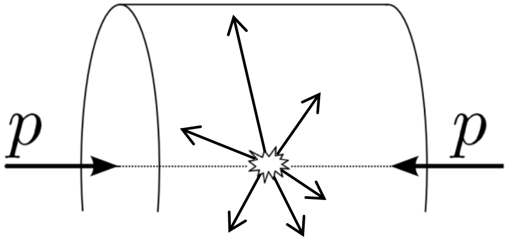

Signature depends on the decay mode.
(tau-rich or lepton-rich signature, etc…)

[Case 2] Signature from
long-lived charged particles $\left(\widetilde{\tau}_1\right)$

signature depends on **where stau decays.**

a) **outside** detectors

⇨ heavy **"μ-like"** track

b) **inside** a detector

c) at the very **center**

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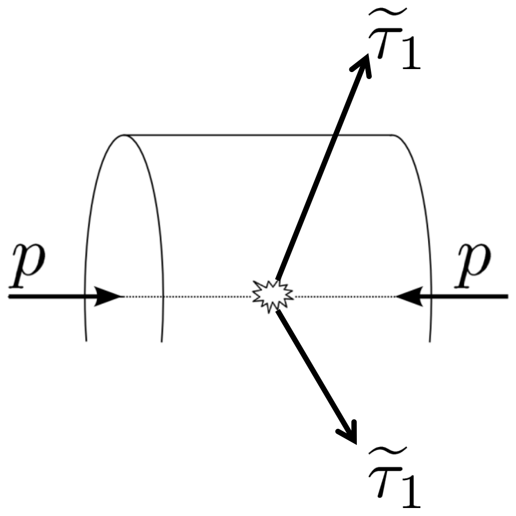
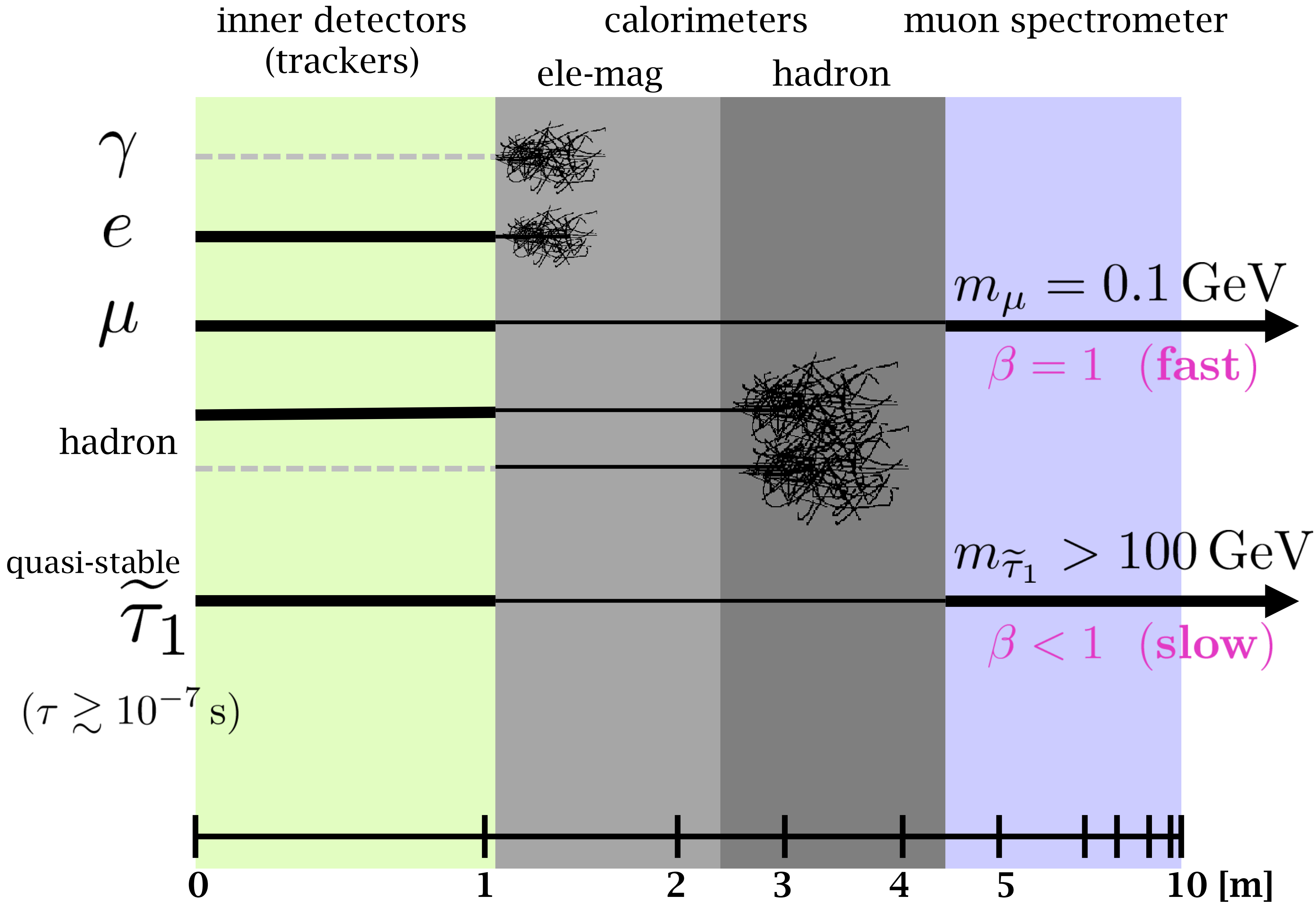
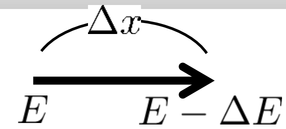




inner detectors
(trackers)
calorimeters
ele-mag
hadron
muon spectrometer
γ
e
μ
$m_\mu = 0.1\,\mathrm{GeV}$
$\beta = 1$ (**fast**)
hadron
quasi-stable
$\widetilde{\tau}_1$
$(\tau \gtrsim 10^{-7}\,\mathrm{s})$
$m_{\widetilde{\tau}_1} > 100\,\mathrm{GeV}$
$\beta < 1$ (**slow**)
0
1
2
3
4
5
10 [m]

How to measure velocity β ?

1. Energy Deposit $\frac{\mathrm{d}E}{\mathrm{d}x}$



- Bethe-Bloch formula $\left|\frac{\mathrm{d}E}{\mathrm{d}x}\right| = \frac{N_A Z}{A} \frac{4\pi Q^2 \alpha^2}{m_e} \left(\frac{1}{\beta^2} \log \frac{2 m_e \beta^2}{I(1-\beta^2)} - 1 \right)$
- A function of velocity β !
- measured at an inner detector

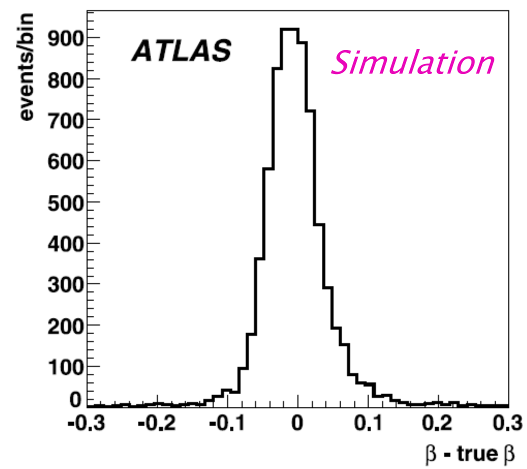
RED: material dependent
BLUE: constants

2. Time of flight (TOF)

- at Tracker and MS
- 1ns resolution

⇨ $\beta \in [0.6, 0.9]$ is distinguishable from $\beta = 1$.

$\Delta\beta \sim 0.05$



ATLAS coll., EPJ C62 (2009) 281

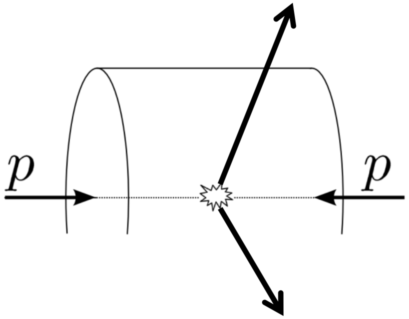
Current Bounds on *STABLE* $\widetilde{\tau}_1$

- **LEP**
  - DELPHI [PLB478.65; hep-ex/0103038]

    $\widetilde{\tau}_{R/L} > 88/87.5\,\mathrm{GeV}$ (direct production)

  - OPAL [PLB572.8; hep-ex/0305031]

    $\widetilde{\tau}_{R/L} > 98.0/98.5\,\mathrm{GeV}$ (direct production)



- **LHC**
  - ATLAS (37pb^{-1}) [PLB703.428; 1106.4495]

    $\widetilde{\tau}_1 > 136\,\mathrm{GeV}$ (assuming a GMSB model)

    $\widetilde{\tau}_1 > 110\,\mathrm{GeV}$ (EW production = generic)

  - CMS (1.1fb^{-1}) [CMS-PAS-EXO-11-022]

    $\widetilde{\tau}_1 > 293\,\mathrm{GeV}$ (assuming a GMSB model)

[Case 2] Signature from
long-lived **charged** **particles** $\left(\widetilde{\tau}_1\right)$

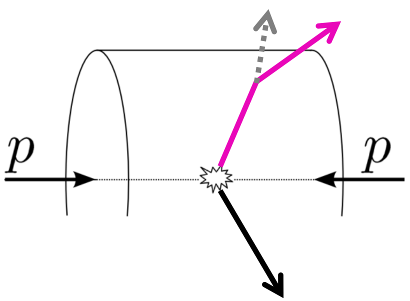
signature depends on **where stau decays**.

a) **outside** detectors

⟹ heavy **"μ-like"** track

b) **inside** a detector

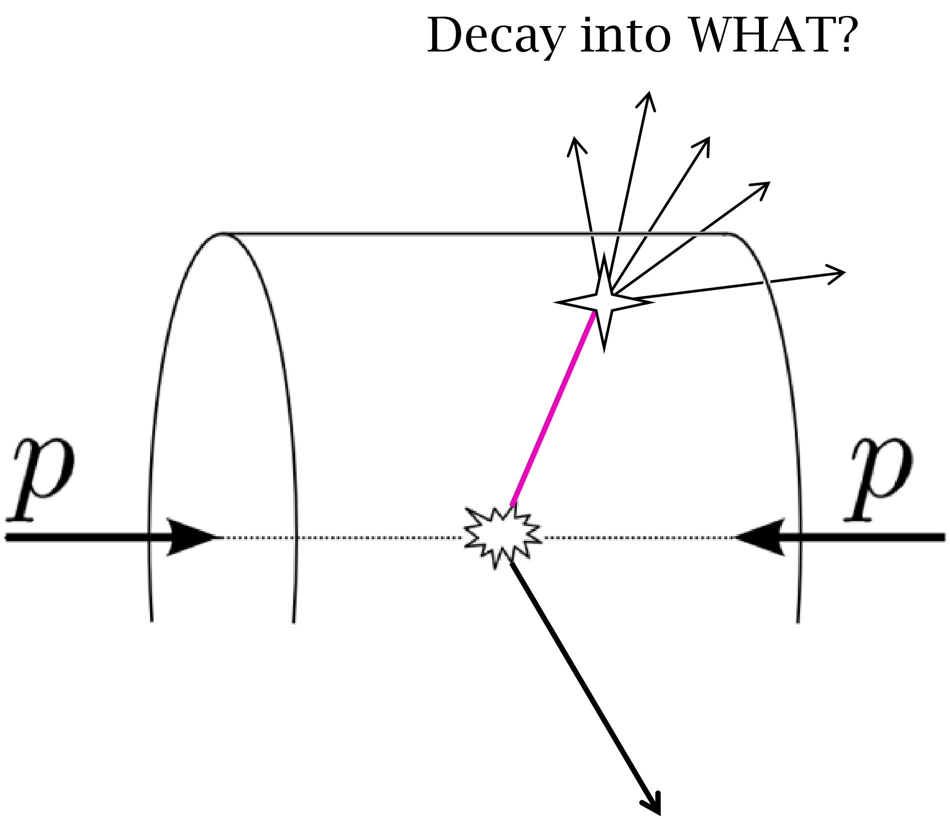
⟹ Kink track etc.



c) at the very **center**

⟹ depends on the decay mode.
(tau-rich or lepton-rich signature, etc…)

Signature depends on…



Complicated,
determined by underlying model…

Long-lived stau scenarios

A) $\widetilde{G}$-LSP, $\widetilde{\tau}_1$-NLSP model $\Longrightarrow$ $\widetilde{\tau}_1 \to \tau \widetilde{G}$

B) $\widetilde{\tau}_1$-LSP with tiny RpV

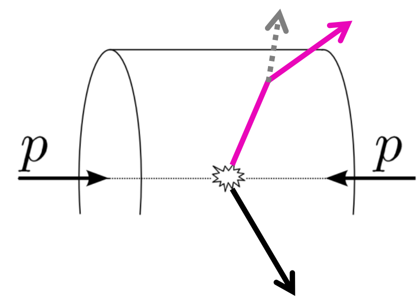
$$W = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

$$\lambda_{i3k}, \lambda_{ij3} \Longrightarrow \widetilde{\tau}_1 \to e\nu,\ \mu\nu,\ \tau\nu$$

$$\lambda_{121}, \lambda_{122} \Longrightarrow \text{4-body decay}$$

$$\lambda' \Longrightarrow \text{hadron or 4-body}$$

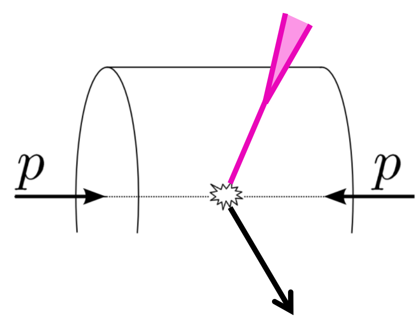
$$\lambda'' \Longrightarrow \text{4-body decay}$$



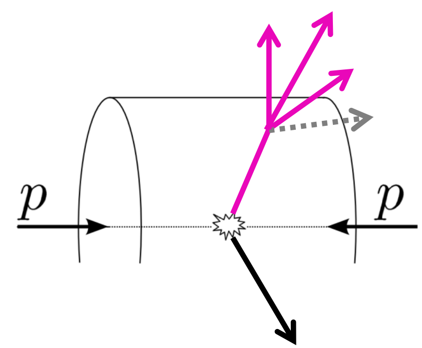
2-body

C) Coannihilation region
($\widetilde{\chi}_1^0$-LSP, $\widetilde{\tau}_1$-NLSP, $m_{\widetilde{\tau}_1} \simeq m_{\widetilde{\chi}_1^0}$)

$$\widetilde{\tau}_1 \to \widetilde{\chi}_1^0 \nu \pi,\ \widetilde{\chi}_1^0 l \nu \bar{\nu}$$



hadron



4-body

Long-lived stau scenarios

$\widetilde{\tau}_1$-τ-kink

A) $\widetilde{G}$-LSP, $\widetilde{\tau}_1$-NLSP model $\Rightarrow$ $\widetilde{\tau}_1 \to \tau \widetilde{G}$

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$$\lambda_{i3k}, \lambda_{ij3} \Longrightarrow \widetilde{\tau}_1 \to e\nu,\ \mu\nu,\ \tau\nu$$

$\widetilde{\tau}_1$-(e, μ, τ)-kink

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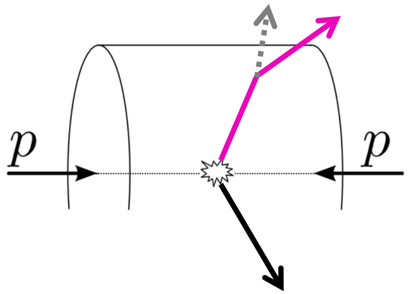
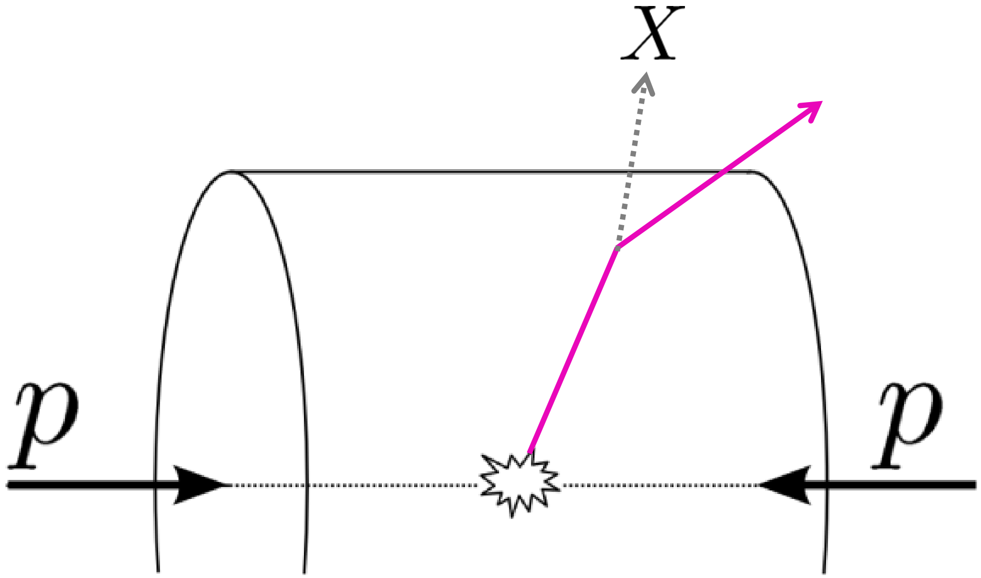
$$\widetilde{\tau}_1 \to \widetilde{\chi}_1^0 \nu \pi,\ \widetilde{\chi}_1^0 l \nu \bar{\nu}$$

kink, but “soft”...



2-body (kink track)

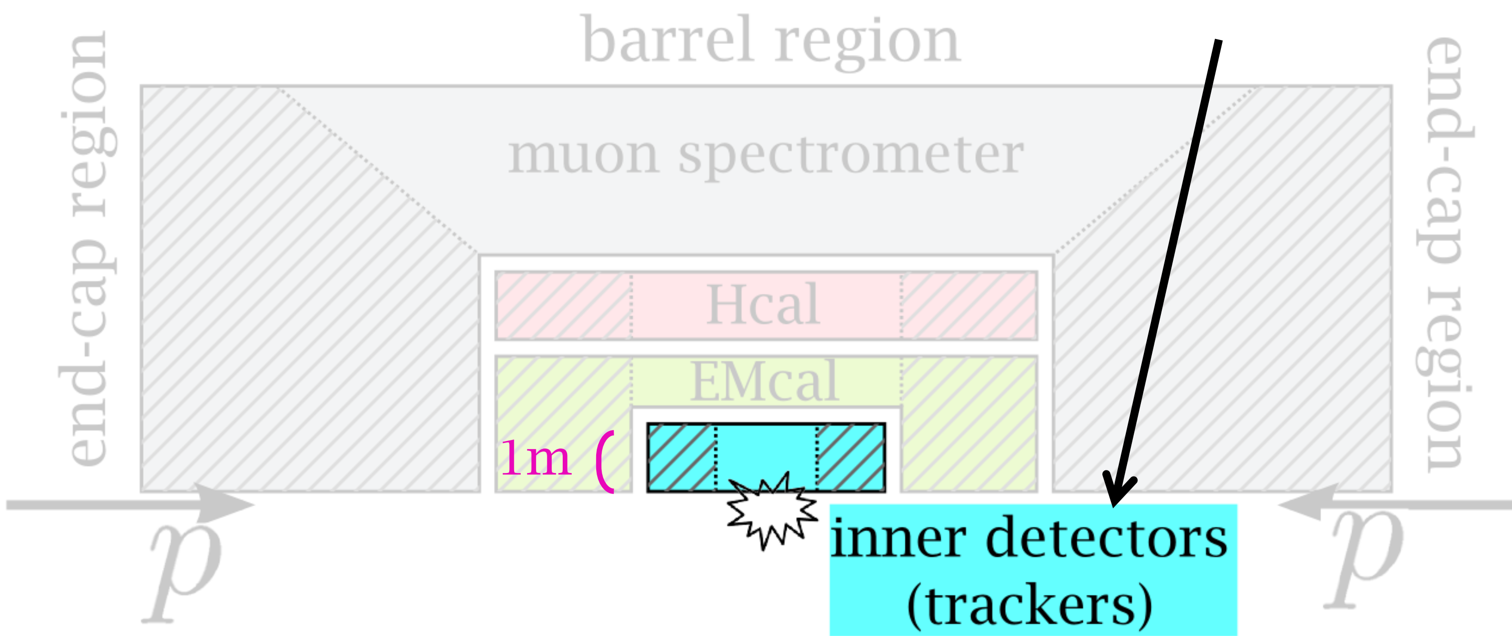
Kink track = stau track (by a tracker) + daughter track (by a tracker)



Kink track id. = id. of stau track (by a tracker) + id. of daughter track (by a tracker)

⇩

We have to do "**two**" id. in



Kink track id. = id. of **stau** track by a tracker + id. of **daughter** track by a tracker

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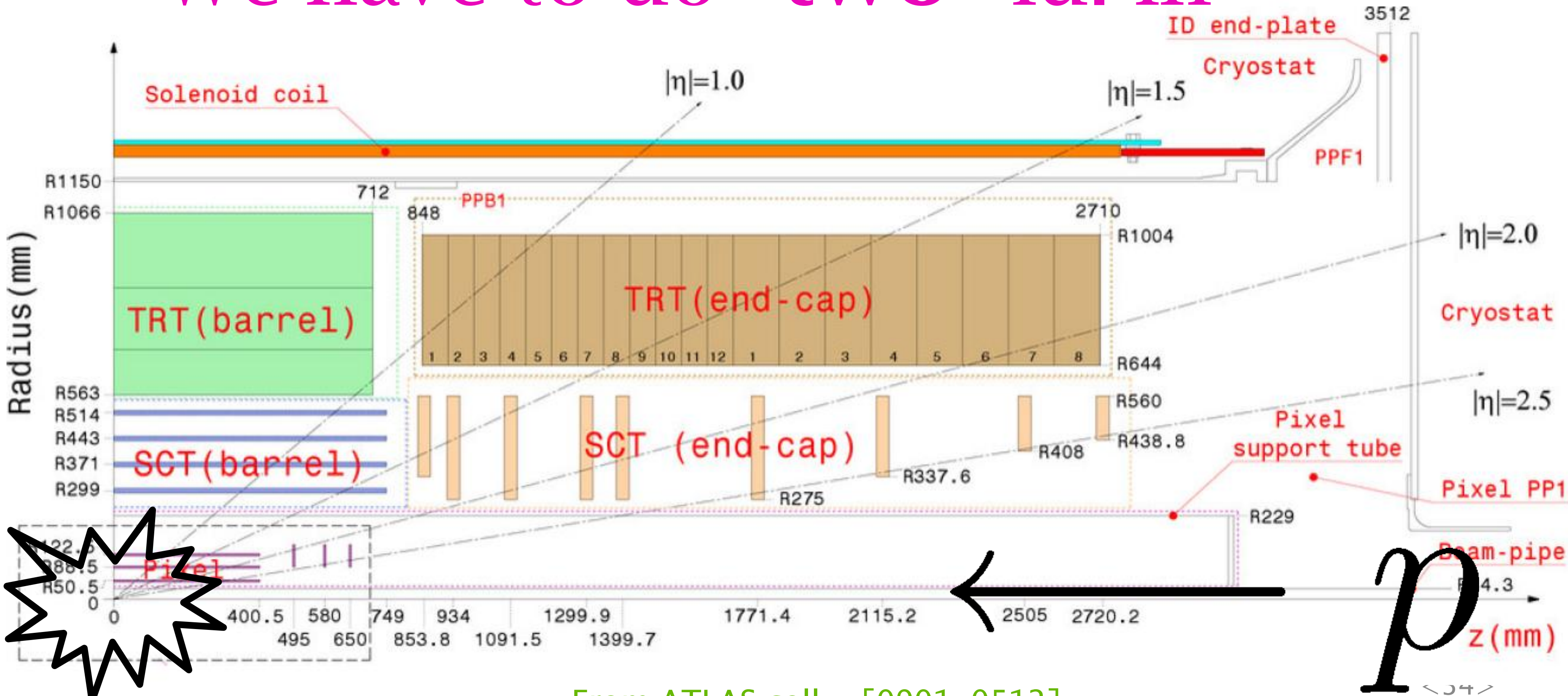

From ATLAS coll. [0901.0512]

Kink track id. **=** id. of stau track (by a tracker) **+** id. of daughter track (by a tracker)

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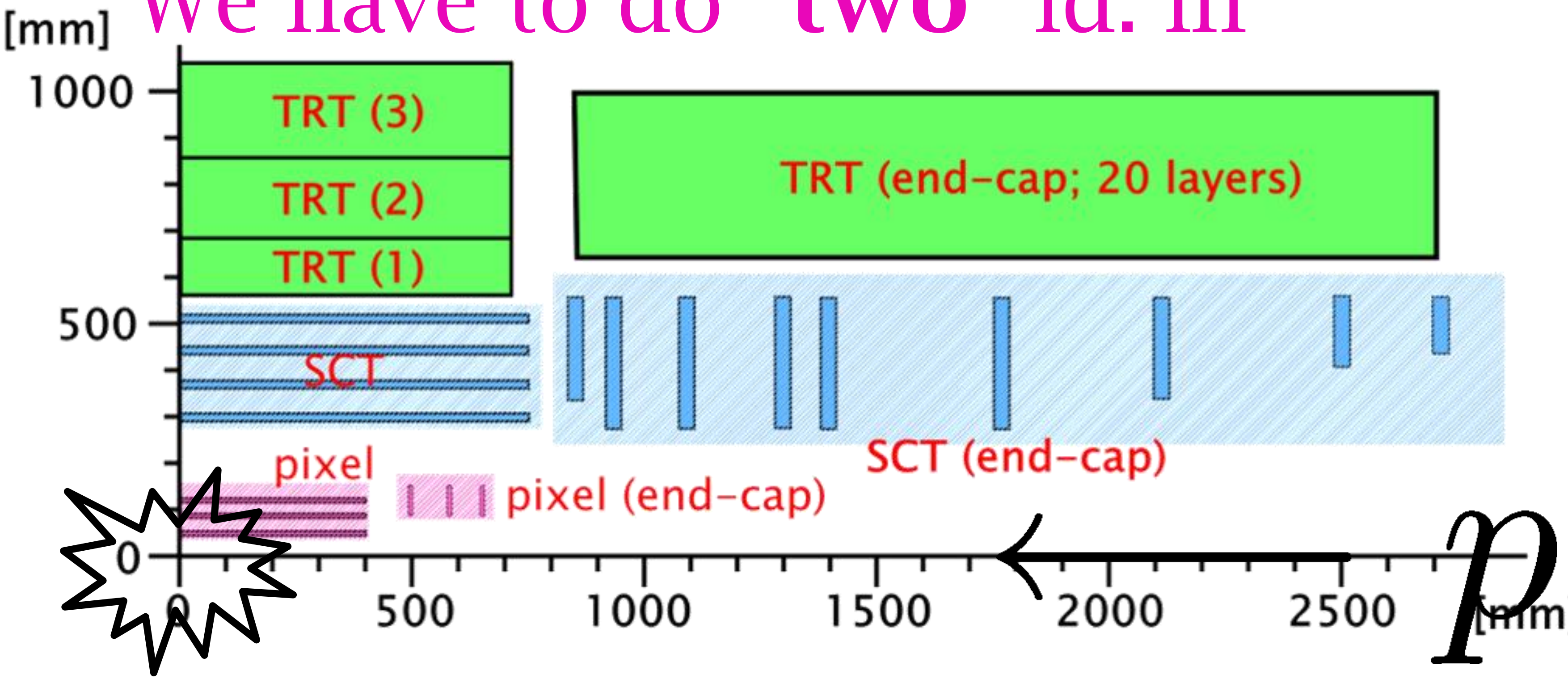

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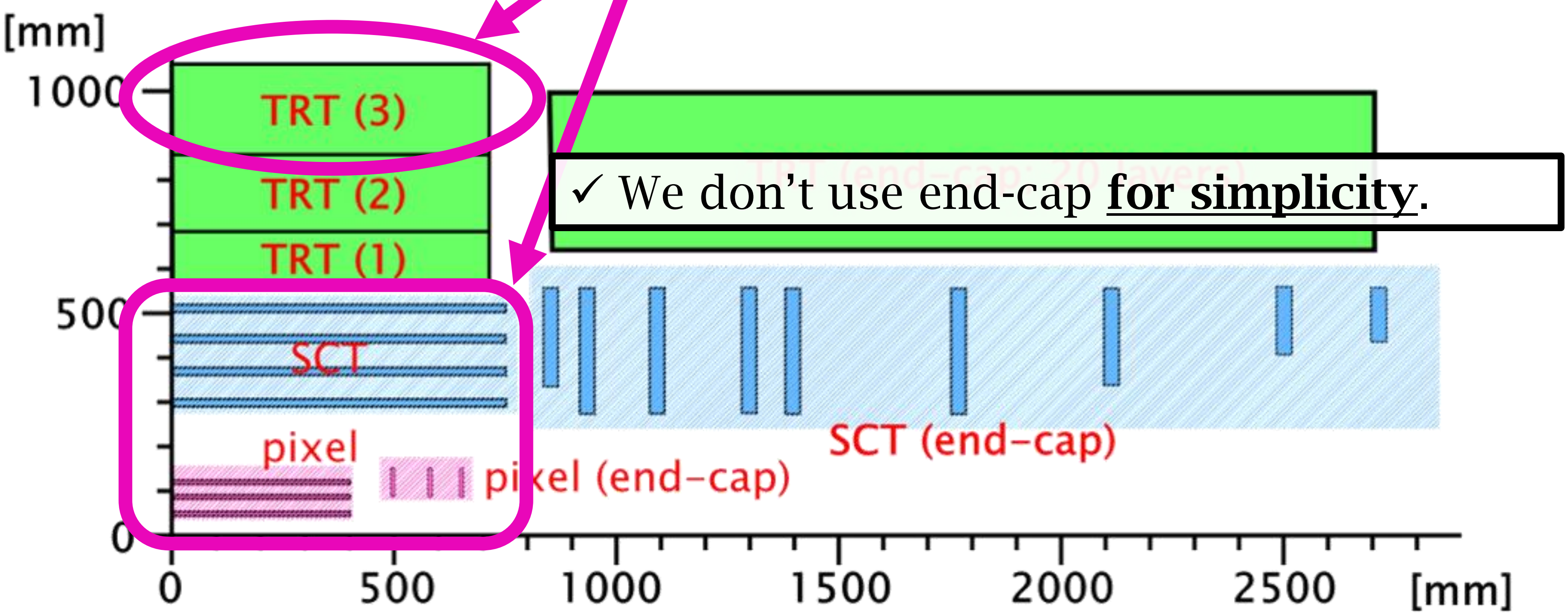
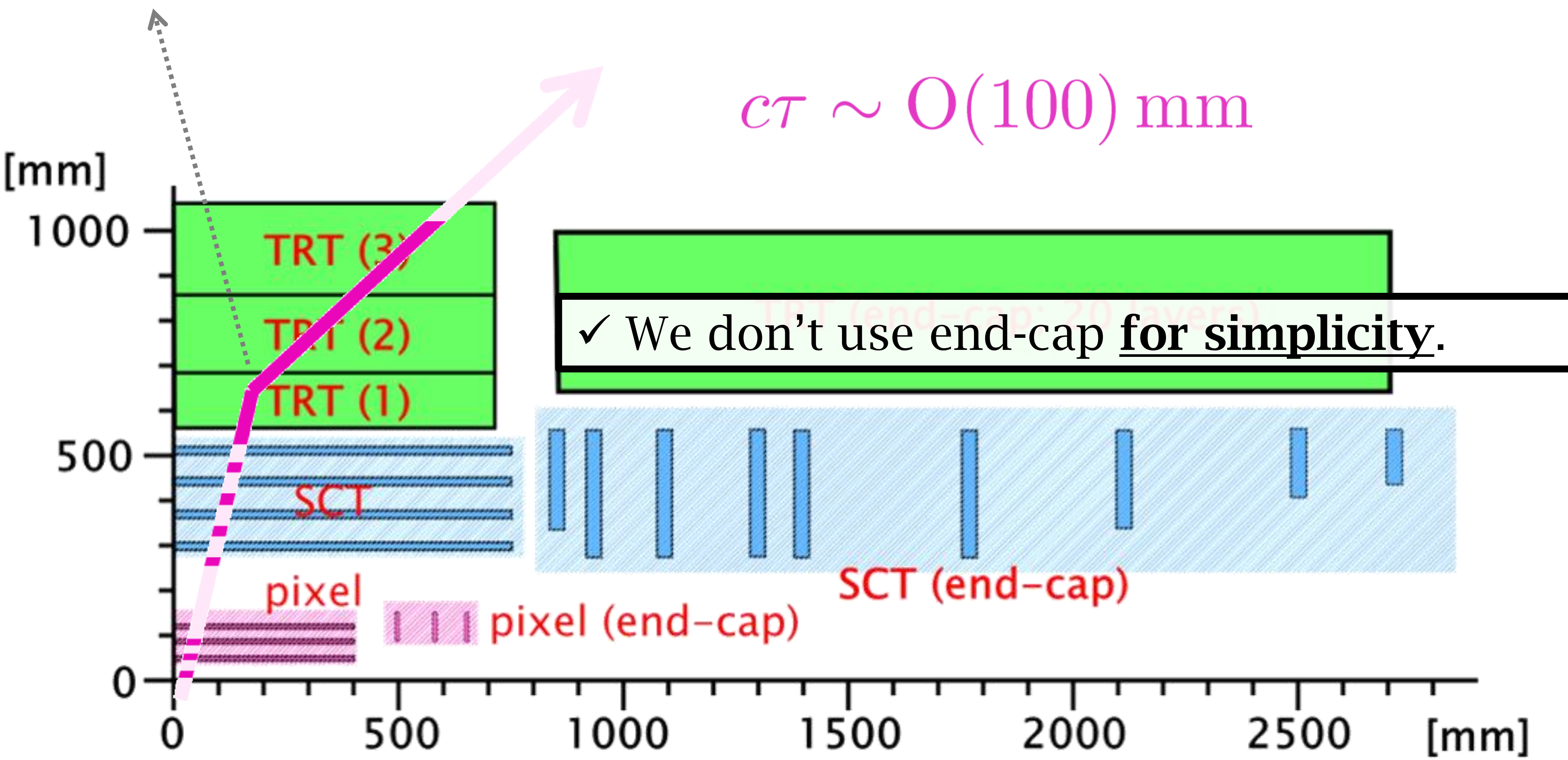


✓ We don’t use end-cap **for simplicity**.

Kink at **TRT 1st or 2nd module** can be observed.

$c\tau \sim \mathrm{O}(100)\ \mathrm{mm}$



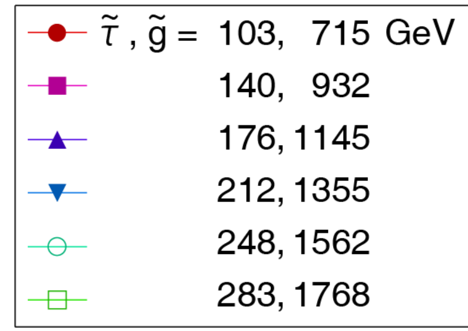
✓ We don't use end-cap **for simplicity**.

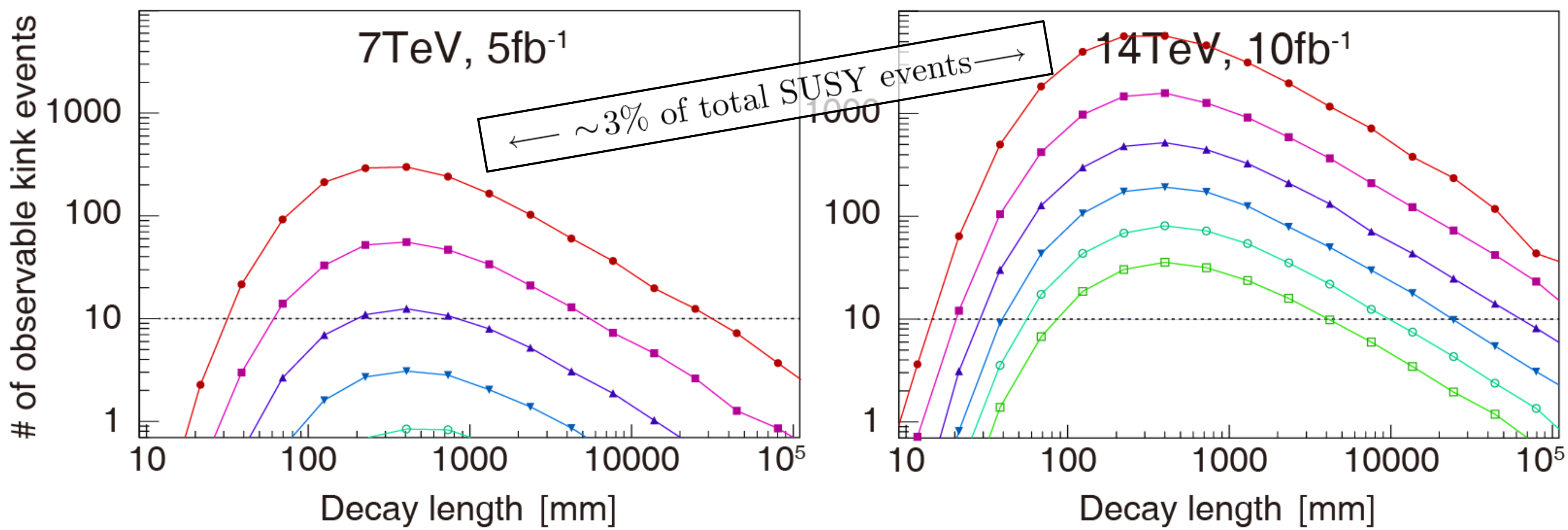
With this method, **we can observe kinks.**

- Sweet range $c\tau$ (of stau) $\sim \mathrm{O}(0.1-10)\ \mathrm{m}$
- **300GeV** stau can be observed.

✓ Some CMSSM-model is assumed.
✓ Efficiencies are considered.
✓ Background events are fairly suppressed.

Let's see in detail.





3. Stau Kinks in detail

Stau kinks *in detail*

- Technical topics **(experiment)**
  - trigger and efficiency
  - track reconstructions and efficiency
  - background events
  - Monte Carlo simulation

  etc…

- Physical topics **(phenomenology)**
  - **We can discriminate the models!!**

Long-lived stau scenarios

A) $\widetilde{G}$-LSP, $\widetilde{\tau}_1$-NLSP model $\Rightarrow$ $\widetilde{\tau}_1 \to \tau \widetilde{G}$ — $\widetilde{\tau}_1$-τ-kink

B) $\widetilde{\tau}_1$-LSP with tiny RpV

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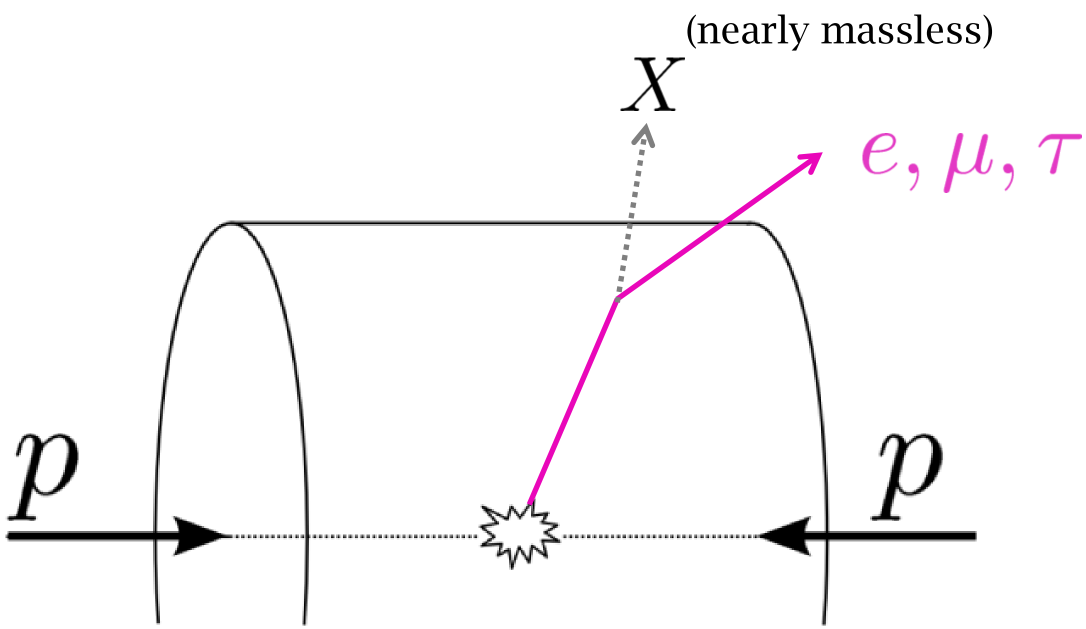
$\widetilde{\tau}_1$-(e,μ,τ)-kink



$$W = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Kink type ⟶ daughter signature

Models	$e : \mu : \tau$	e	μ	τ-jet
Gravitino LSP	0 : 0 : 1	18%	17%	65%
λ_{123}	1 : 1 : 0	50%	50%	–
λ_{i31}	1 : 0 : 0	100%	–	–
λ_{i32}	0 : 1 : 0	–	100%	–
λ_{133}	$\sin^2\theta$: 0 : 1	* 59%	* 9%	*32%
λ_{233}	0 : $\sin^2\theta$: 1	* 9%	* 59%	*32%

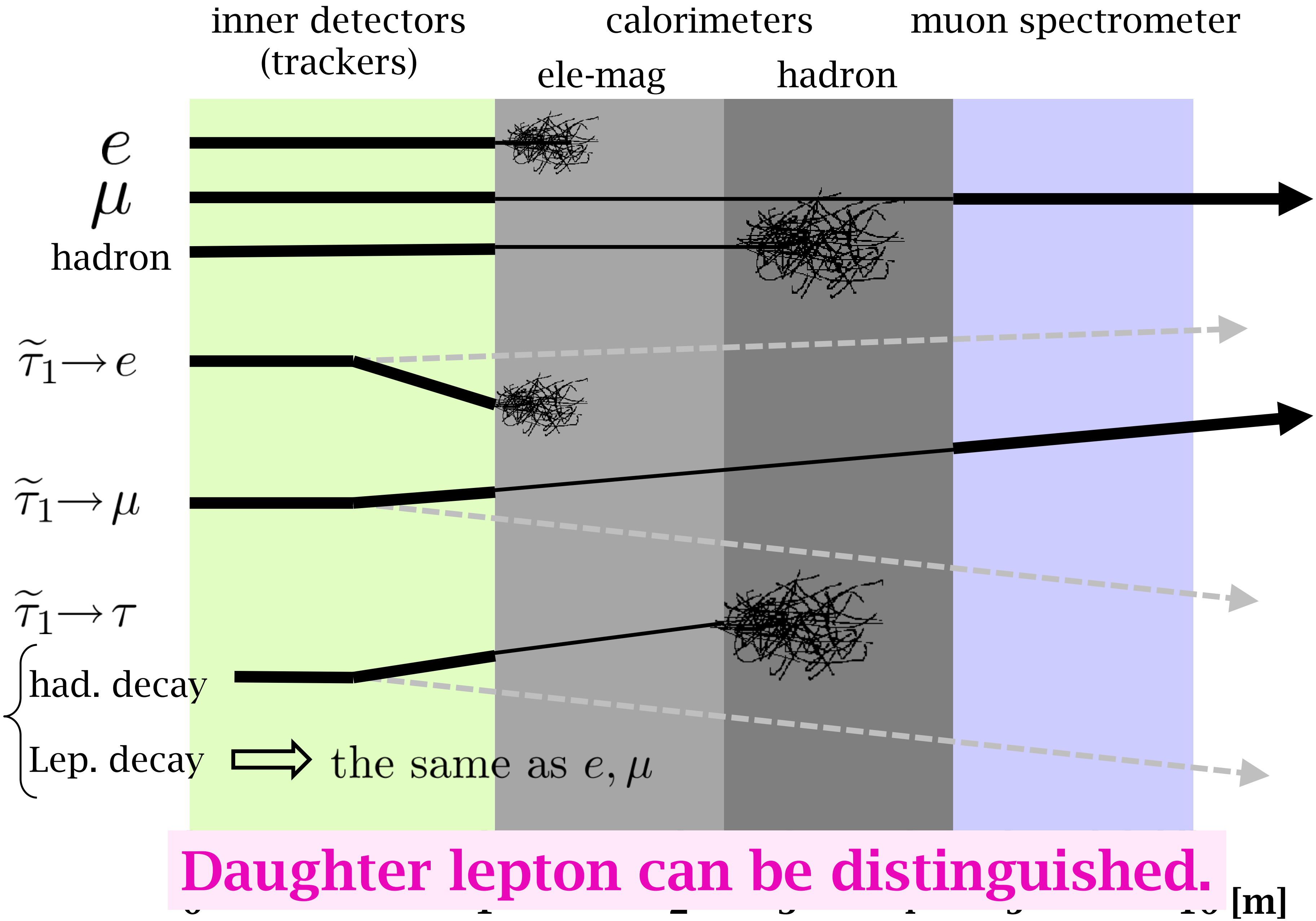
*depending on stau mixing angle θ; values are for $\theta = 1$.

Daughter lepton discrimination

⇨ Ratio of the daughter leptons

= Underlying models

$$\left(\begin{array}{llll} \underline{\lambda_{123}} & \tilde{\tau} \to L_1 L_2 & \rightsquigarrow & e : \mu = 1 : 1 \\ \underline{\lambda_{i3k}} & \tilde{\tau} \to L_i \bar{E}_k & \rightsquigarrow & l_k + \nu_i \\ \underline{\lambda_{i33}} & \tilde{\tau} \to L_i L_3, L_i \bar{E}_3 & \rightsquigarrow & l_i : \tau = \sin^2\theta : 1 \end{array} \right)$$

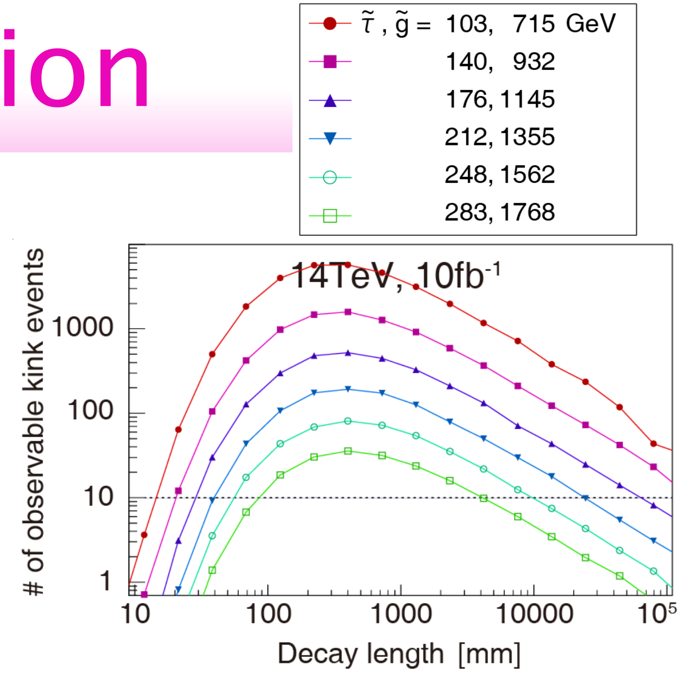


Daughter lepton can be distinguished.

(phenomenological) Conclusion

- Stau (slepton) in-flight-decay
  $\Longrightarrow$ observable as kink events.
  - decay length: $c\tau \sim \mathrm{O}(0.1 - 100)\mathrm{m}$
  - Stau mass: $m \lesssim 300\,\mathrm{GeV}$

  (Much more luminosity allows us to go further.)



- This decay length corresponds to
  - gravitino model: $m_{\tilde{G}} \sim 0.1 - 10\,\mathrm{keV}$
  - R-parity violation: $\lambda \sim \mathrm{O}(10^{-8} - 10^{-9})$

- Model discrimination is possible.

Stau kinks *in detail*

- Technical topics **(experiment)**
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  - track reconstructions and efficiency
  - background events
  - Monte Carlo simulation

  etc…

- Physical topics **(phenomenology)**

  - **We can discriminate the models!!**

Monte Carlo Simulation

mass spectrum:	SUSY-HIT
event generation:	Pythia6
fast detector sim.:	PGS4

Method

- Benchmark Point: CMSSM model

M_0	$M_{1/2}$	$\tan\beta$	A_0	$\operatorname{sgn}\mu$
0 GeV	varied	13	0 GeV	$+$

$M_{1/2}$	$\widetilde{\tau}$	$\widetilde{g}$
300	103,	715
400	140,	932
500	176,	1145
600	212,	1355
700	248,	1562
800	283,	1768

[GeV]

- PGS4-based fast detector simulation

Monte Carlo Simulation

Event selection

- triggering issue
  - 1 jet with $P_{\mathrm{T}} > 120\,\mathrm{GeV}$.
  - $\not{E}_{\mathrm{T}} > 100\,\mathrm{GeV}$.
- $\widetilde{\tau}_1$ must be
  - $|\eta| < 0.63$.
  - $P_{\mathrm{T}} > 100\,\mathrm{GeV}$.
  - decay in TRT 1st or 2nd module.
- The kink must be
  - azimuthal opening angle $0.1 < \Delta\phi < \pi/2$.
- daughter particle must be
  - not into end-cap; stay in barrel region.
  - $P_{\mathrm{T}} > 10\,\mathrm{GeV}$ (efficiency 0.6) or $> 20\,\mathrm{GeV}$ (0.7).

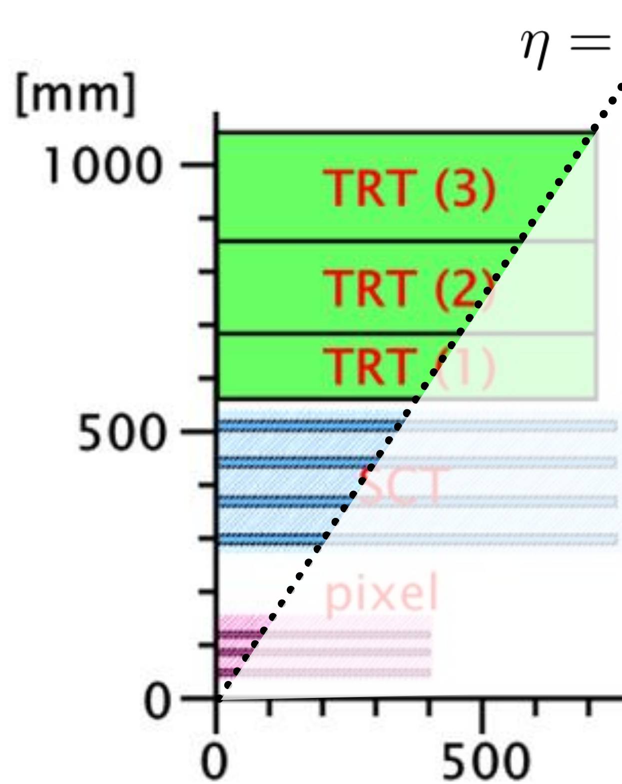
Monte Carlo Simulation

Event selection

- triggering issue
  - 1 jet with $P_{\mathrm{T}} > 120\,\mathrm{GeV}$.
  - $\not{E}_{\mathrm{T}} > 100\,\mathrm{GeV}$.

⇦ Trigger: 1jet(70) + MET(40) is "stable" (90% eff.) above this point.

- $\widetilde{\tau}_1$ must be
  - $|\eta| < 0.63$.
  - $P_{\mathrm{T}} > 100\,\mathrm{GeV}$.
  - decay in TRT 1st or 2nd module.
- The kink must be
  - azimuthal opening angle $0.1 < \Delta\phi$
- daughter particle must be
  - not into end-cap; stay in barrel reg
  - $P_{\mathrm{T}} > 10\,\mathrm{GeV}$ (efficiency 0.6) or >



Monte Carlo Simulation

TRT = r-ϕ information

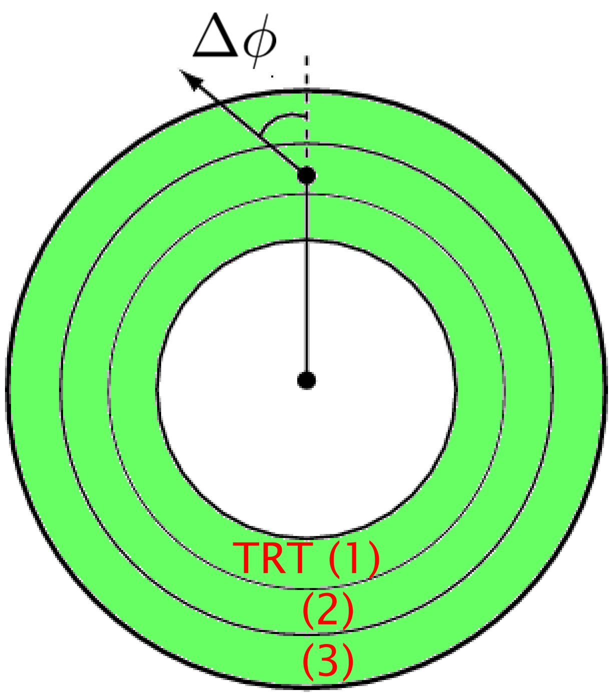
(know nothing about on z-direction.)

⇩

“azimuthal opening angle” can be measured.

- $|\eta| < 0.63$.
- $P_{\mathrm{T}} > 100\,\mathrm{GeV}$.
- decay in TRT 1st or 2nd module.

- The kink must be
  - azimuthal opening angle $0.1 < \Delta\phi < \pi/2$.
- daughter particle must be
  - not into end-cap; stay in barrel region.
  - $P_{\mathrm{T}} > 10\,\mathrm{GeV}$ (efficiency 0.6) or $> 20\,\mathrm{GeV}$ (0.7).



r-ϕ projected plane view

Monte Carlo Simulation

Event selection

- triggering issue
  - 1 jet with $P_{\mathrm{T}} > 120\,\mathrm{GeV}$.
  - $\not{E}_{\mathrm{T}} > 100\,\mathrm{GeV}$.
- $\tilde{\tau}_1$ must be
  - $|\eta| < 0.63$.
  - $P_{\mathrm{T}} > 100\,\mathrm{GeV}$.
  - decay in TRT 1st or 2nd module.
- The kink must be
  - azimuthal opening angle $0.1 < \Delta\phi < \pi/2$.
- daughter particle must be
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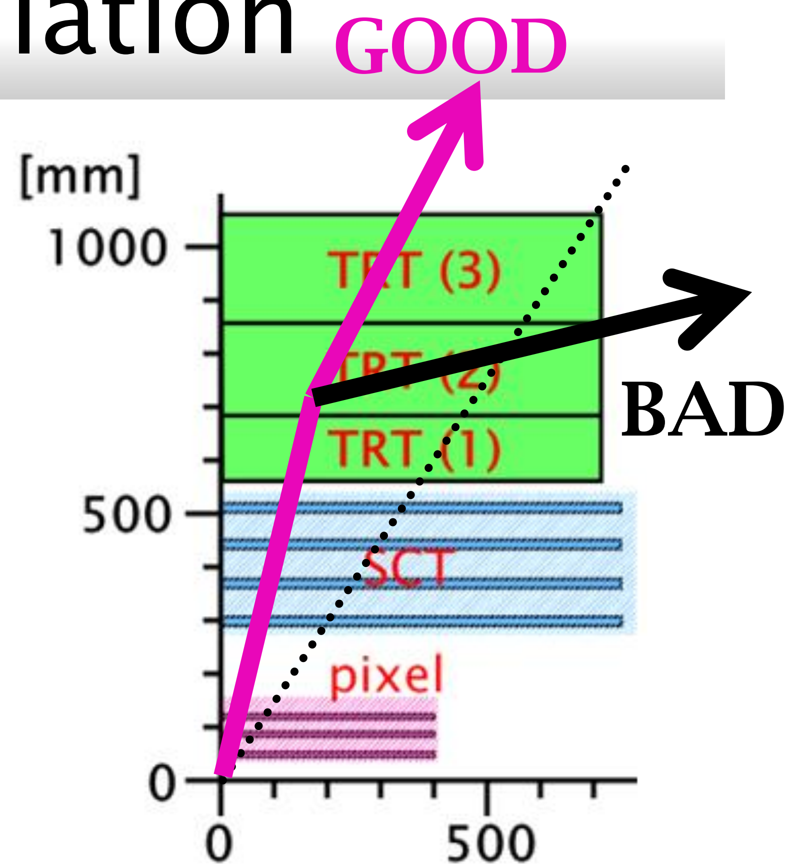
  - $P_{\mathrm{T}} > 10\,\mathrm{GeV}$ (efficiency 0.6) or $> 20\,\mathrm{GeV}$ (0.7).

in order to the daughter reconstruction.



Daughter must go through TRT (3).

Monte Carlo Simulation

Event selection 100%

- triggering issue
  - 1 jet with $P_T > 120\,\mathrm{GeV}$.
  - $\not{E}_T > 100\,\mathrm{GeV}$.

$\sim 85\%$

- $\widetilde{\tau}_1$ must be
  - $|\eta| < 0.63$. $\sim 35\%$
  - $P_T > 100\,\mathrm{GeV}$. $\sim 33\%$
  - decay in TRT 1st or 2nd module.

$\sim 4\%$

- The kink must be
  - azimuthal opening angle $0.1 < \Delta\phi < \pi/2$.

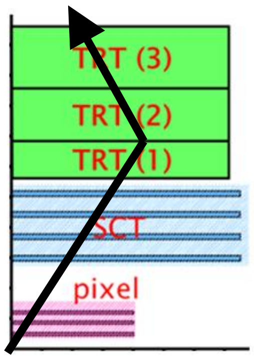
$\sim 3\%$

- daughter particle must be
  - not into end-cap; stay in barrel region.
  - $P_T > 10\,\mathrm{GeV}$ (efficiency 0.6) or $> 20\,\mathrm{GeV}$ (0.7).

$\sim 2\%$

Possible Background Events

- Stable charged hadrons: Hit to detector material



⇨ Few hadrons have $P_{\mathrm{T}} > 100\,\mathrm{GeV}$.
Few hadrons interact with material.

suppressed.

- In-flight-decay of hadrons
  - hadron decay $\cdots$ small Δm
  - small Δm + large $P_{\mathrm{T}} \Longrightarrow$ small kink angle

suppressed.

- "false" tracks from noise

⇨ We require two tracks (mother & daughter)

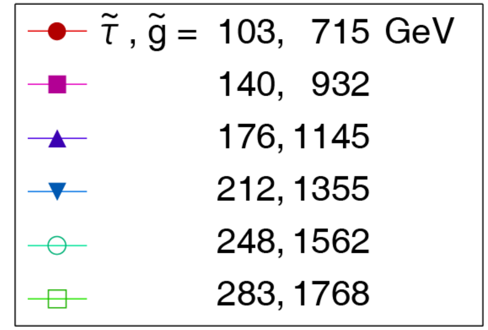
ignorable.

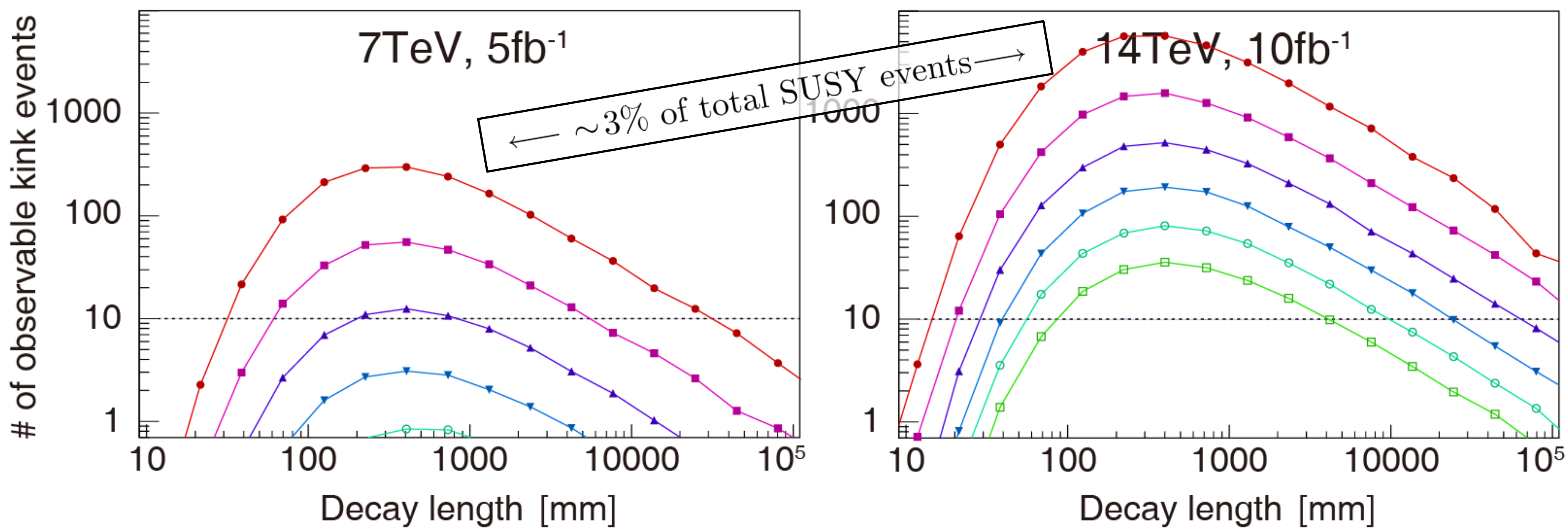
background events are ignorable!

Numerical Results (again)

- Sweet range $c\tau$ (of stau) $\sim O(0.1-10)\,\mathrm{m}$
- **300GeV** stau can be observed.

✓ Some CMSSM-model is assumed.
✓ Efficiencies are considered.
✓ Background events are fairly suppressed.

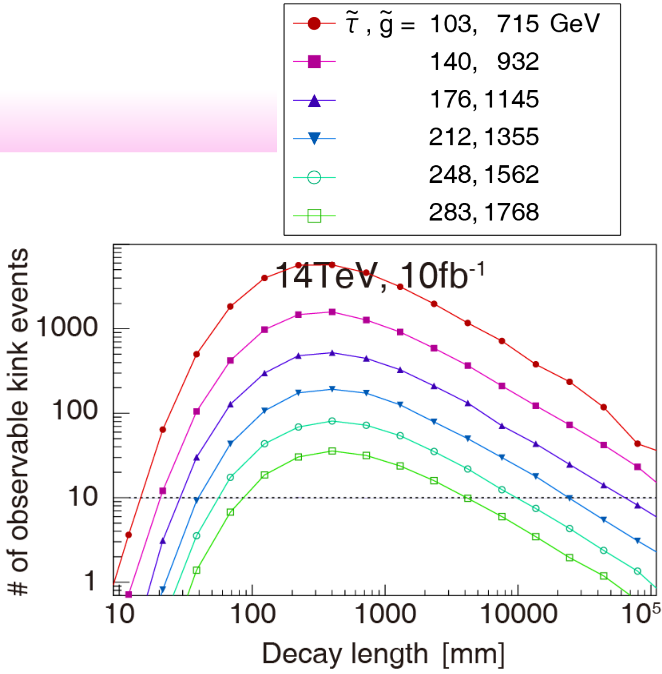




Conclusion (again)

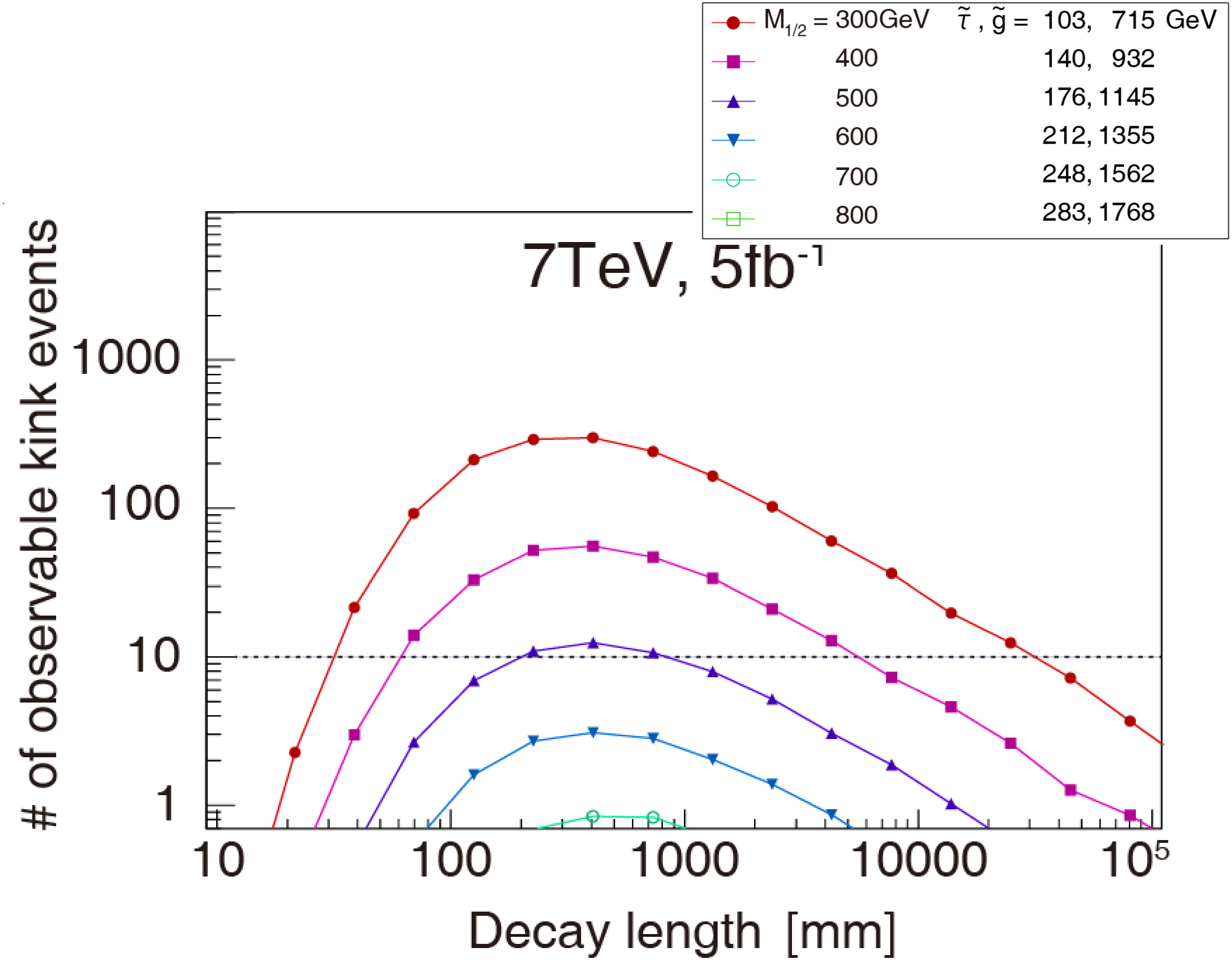
- Stau (slepton) in-flight-decay
  $\Rightarrow$ observable as kink events.
  - decay length: $c\tau \sim \mathrm{O}(0.1 - 100)\mathrm{m}$
  - Stau mass: $m \lesssim 300\,\mathrm{GeV}$

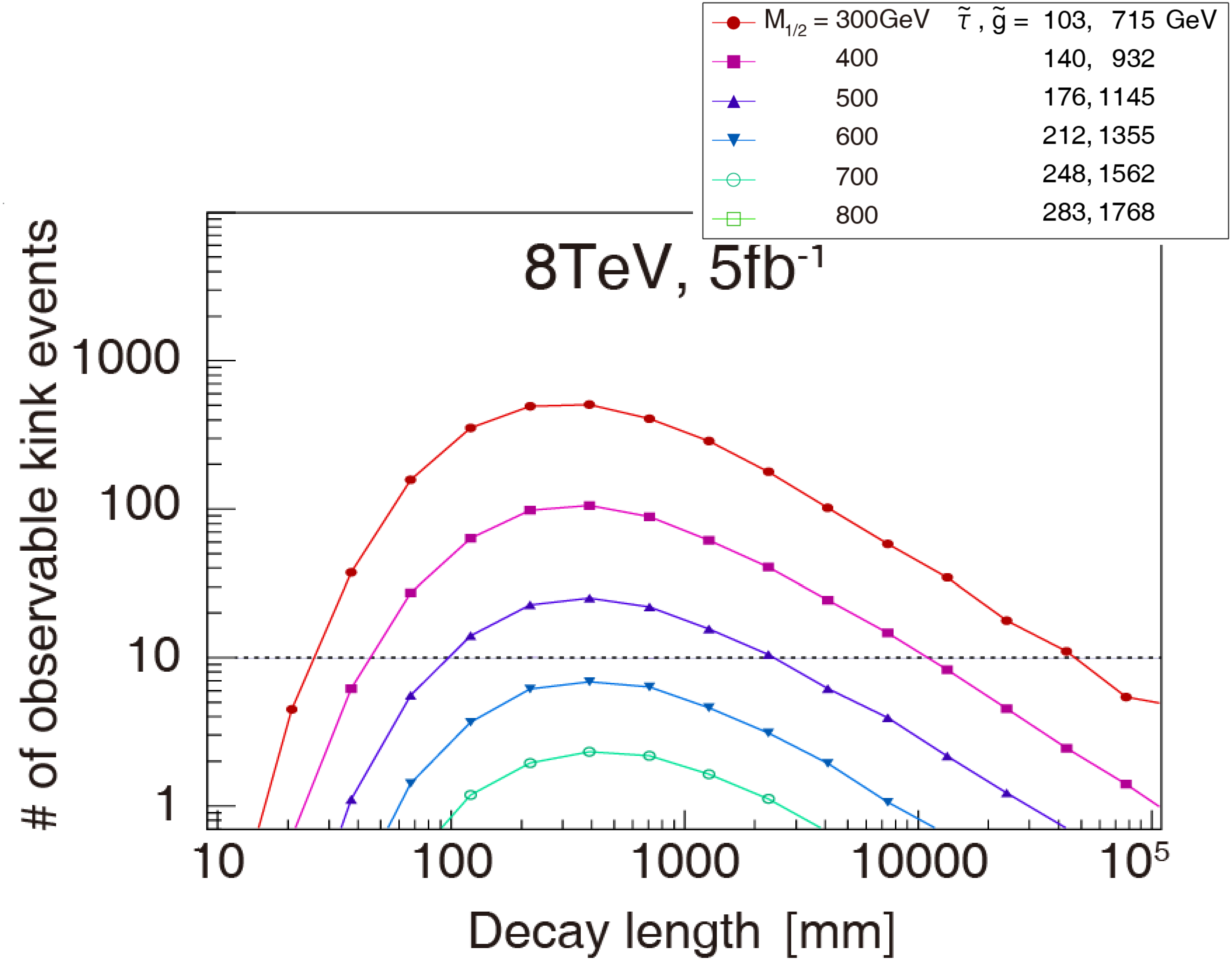
    (Much more luminosity allows us to go further.)

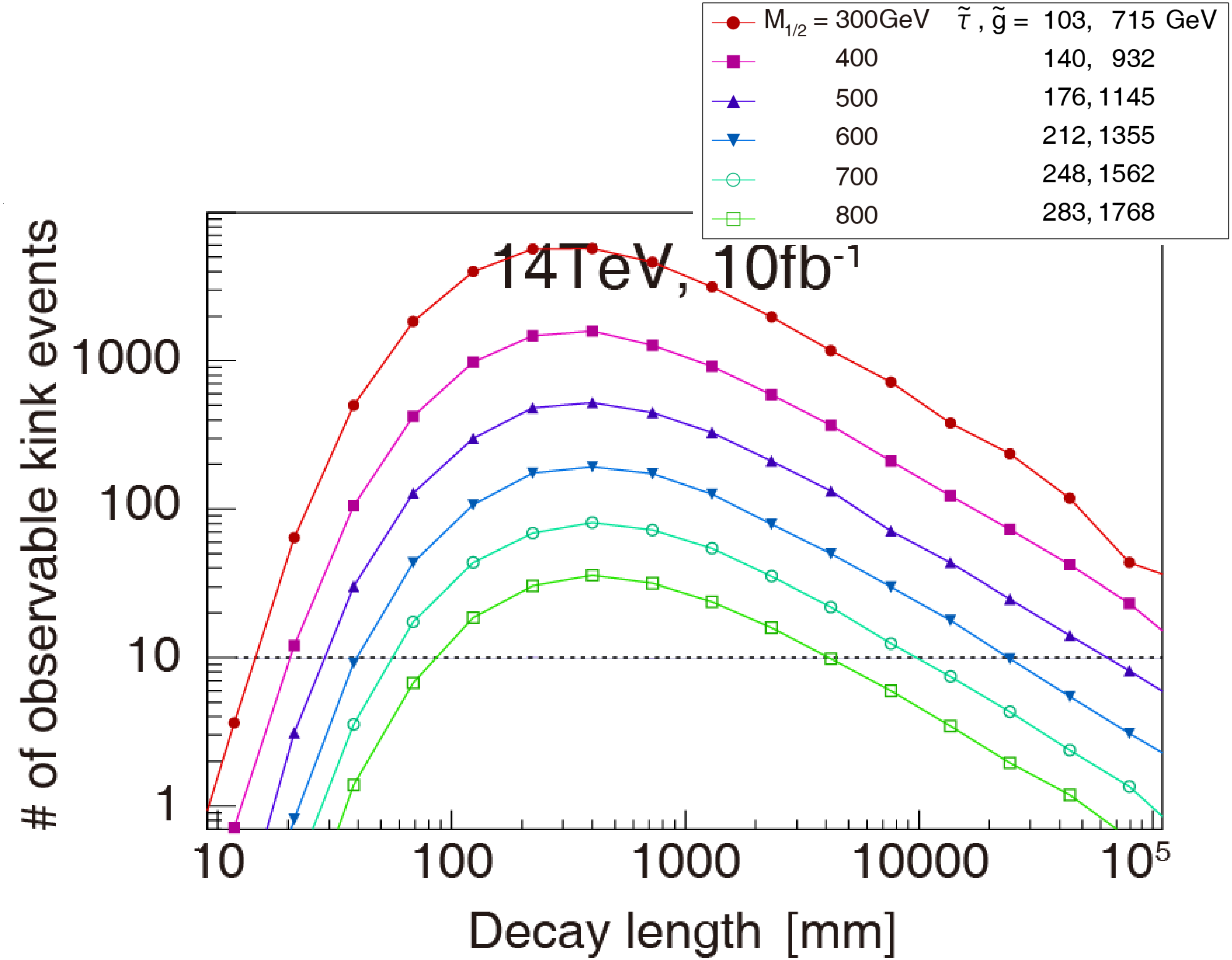


- This decay length corresponds to
  - gravitino model: $m_{\tilde{G}} \sim 0.1 - 10\,\mathrm{keV}$
  - R-parity violation: $\lambda \sim \mathrm{O}(10^{-8} - 10^{-9})$

- Model discrimination is possible.

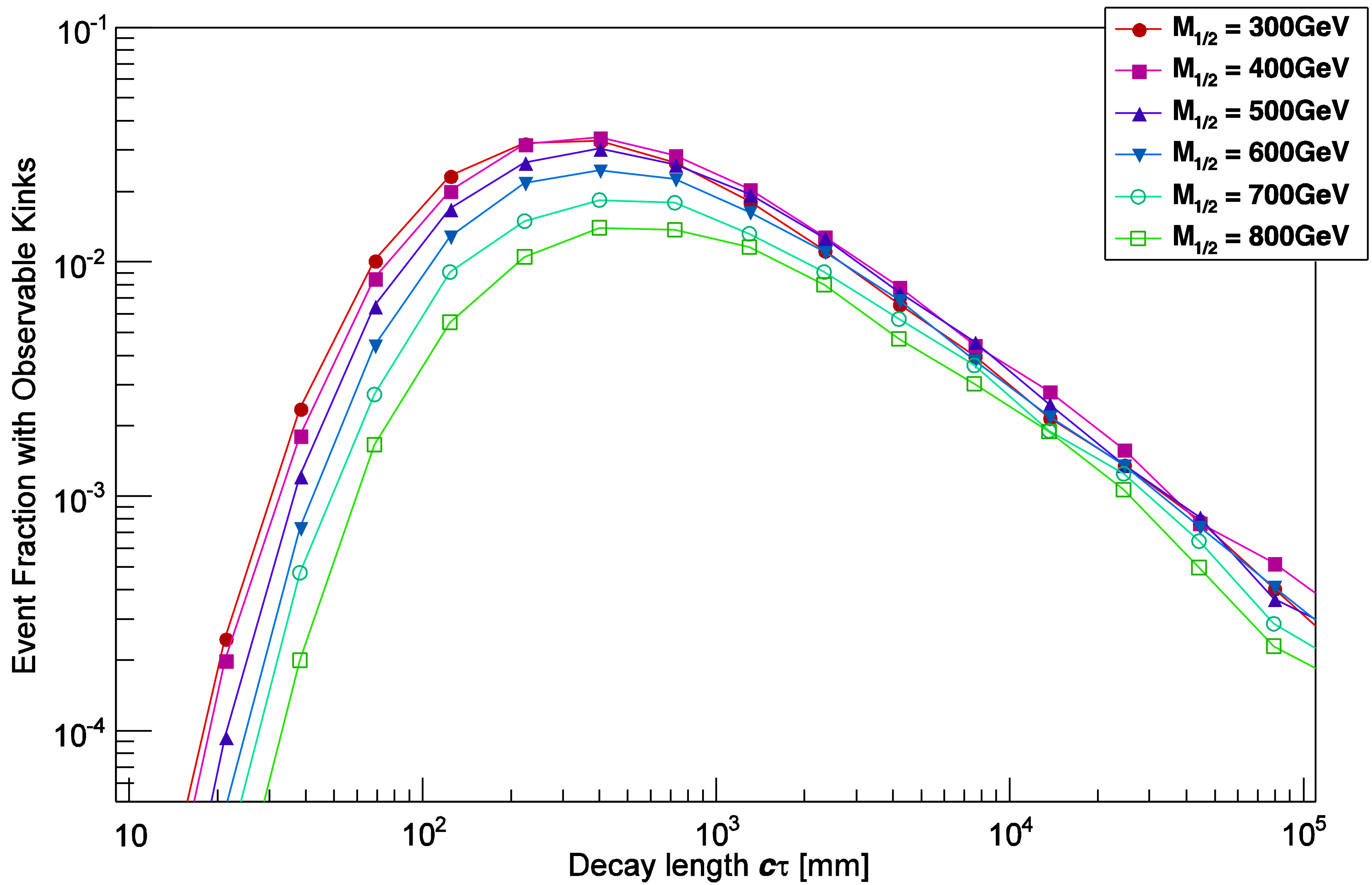

M1/2 = 300GeV τ̃ , g̃ = 103, 715 GeV
400 140, 932
500 176, 1145
600 212, 1355
700 248, 1562
800 283, 1768
7TeV, 5fb-1
# of observable kink events
1000
100
10
1
10
100
1000
10000
10^5
Decay length [mm]


M1/2 = 300GeV τ̃ , g̃ = 103, 715 GeV
400 140, 932
500 176, 1145
600 212, 1355
700 248, 1562
800 283, 1768
8TeV, 5fb-1
# of observable kink events
1000
100
10
1
10
100
1000
10000
10^5
Decay length [mm]



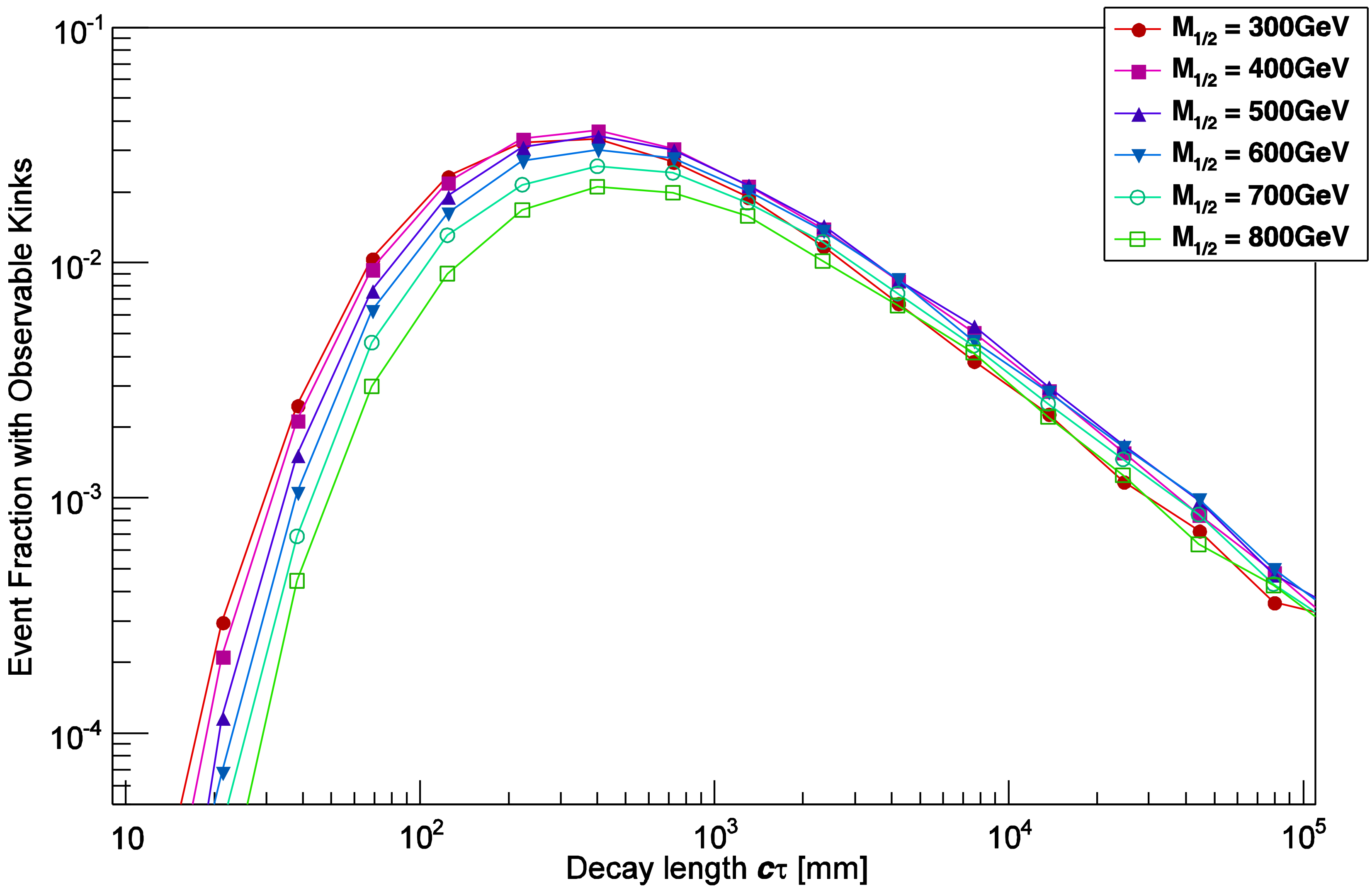
$M_{1/2}$ = 300GeV $\tilde{\tau}$, $\tilde{g}$ = 103, 715 GeV
400 140, 932
500 176, 1145
600 212, 1355
700 248, 1562
800 283, 1768
14TeV, 10fb^{-1}
# of observable kink events
1000
100
10
1
10
100
1000
10000
10^5
Decay length [mm]

7TeV, 5fb^{-1}



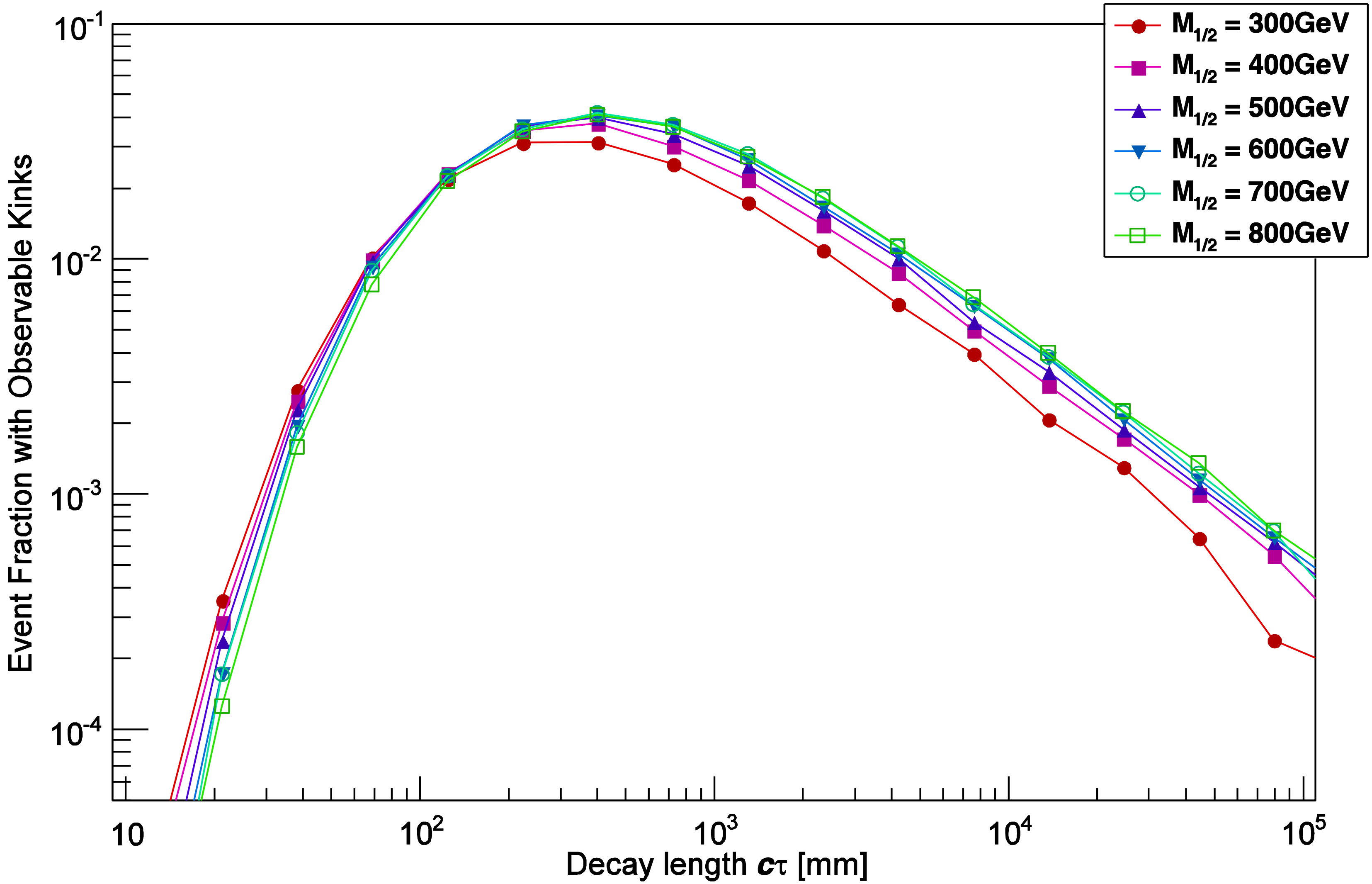
M1/2 = 300GeV
M1/2 = 400GeV
M1/2 = 500GeV
M1/2 = 600GeV
M1/2 = 700GeV
M1/2 = 800GeV
Event Fraction with Observable Kinks
Decay length cτ [mm]
10^-1
10^-2
10^-3
10^-4
10
10^2
10^3
10^4
10^5

8TeV, 5fb^{-1}



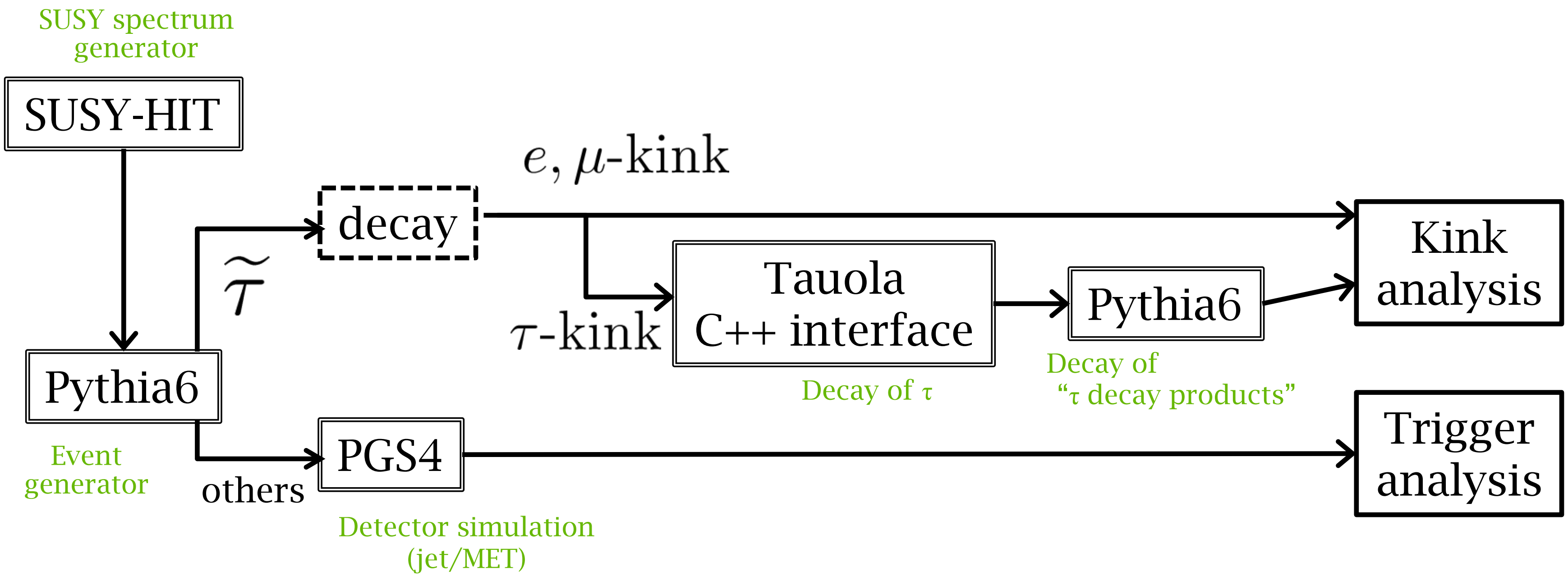
$M_{1/2}$ = 300GeV
$M_{1/2}$ = 400GeV
$M_{1/2}$ = 500GeV
$M_{1/2}$ = 600GeV
$M_{1/2}$ = 700GeV
$M_{1/2}$ = 800GeV
Event Fraction with Observable Kinks
Decay length $c\tau$ [mm]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
10^{2}
10^{3}
10^{4}
10^{5}

14TeV, 10fb^{-1}



Event Fraction with Observable Kinks
Decay length cτ [mm]
M1/2 = 300GeV
M1/2 = 400GeV
M1/2 = 500GeV
M1/2 = 600GeV
M1/2 = 700GeV
M1/2 = 800GeV
10
10^2
10^3
10^4
10^5
10^-1
10^-2
10^-3
10^-4

Monte Carlo System



SUSY spectrum generator
SUSY-HIT
Pythia6
Event generator
$\widetilde{\tau}$
decay
e, μ-kink
τ-kink
Tauola C++ interface
Decay of τ
Pythia6
Decay of "τ decay products"
Kink analysis
others
PGS4
Detector simulation (jet/MET)
Trigger analysis