Title: Signatures of Minimal F-theory GUTs

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Abstract: F-theory based vacua provide a potentially promising starting point for realizing Grand Unified Theories (GUTs) in string theory. In minimal realizations of this framework based on a point of E8 unification, this turns out to be quite constraining, and leads to specific expectations for the form of supersymmetry breaking. We discuss how the parameters of the F-theory GUT determine the sparticle spectrum, and possible signatures at the LHC.

Signatures of Minimal F-theory GUTs

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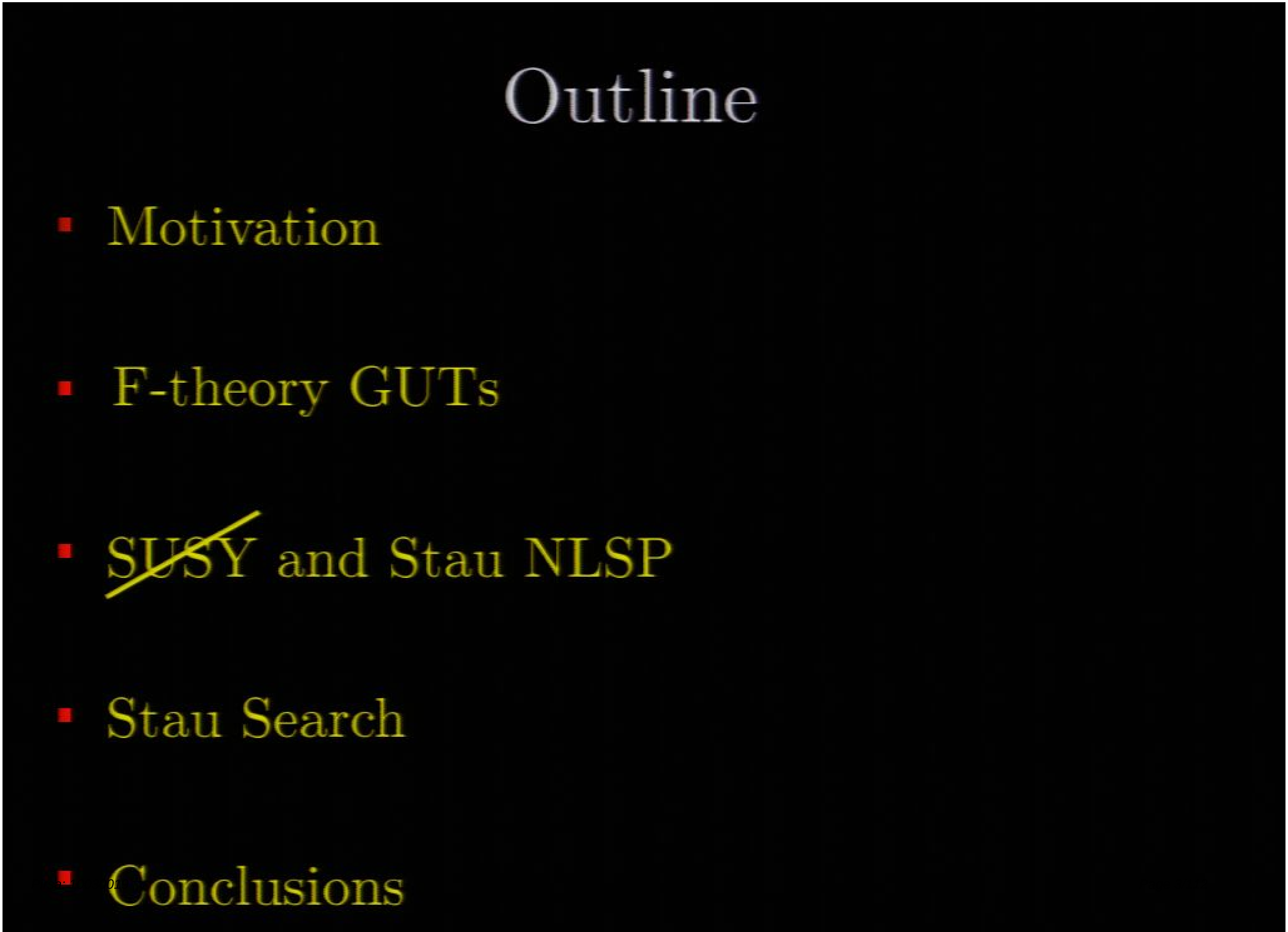
hep-th/0809.1098 w/ C. Vafa

hep-th/0906.0581 w/ A. Tavanfar and C. Vafa

hep-th/1001.4084 w/ J. Shao and C. Vafa

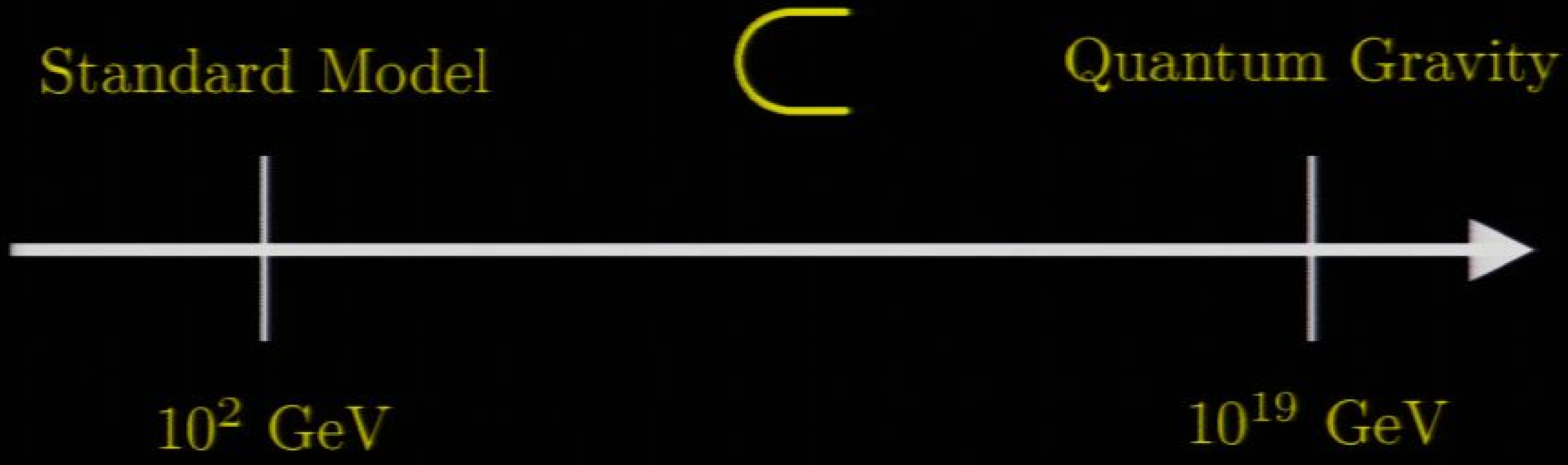
Review: hep-th/1001.0577



Outline

- Motivation
- F-theory GUTs
- ~~SUSY~~ and Stau NLSP
- Stau Search
- Conclusions

Motivation



Standard Model $\subset$ Quantum Gravity

10^2 GeV

10^{19} GeV

High Energy Constraints ⇒ Low Energy Predictions?

Low Energy Observations ⇒ High Energy Constraints?

Local Model Building

There is an entire landscape of string vacua

Presumably some reproduce the Standard Model

But which ones?

A Strategy:

1) Focus on UV motivated gauge theories (local models)

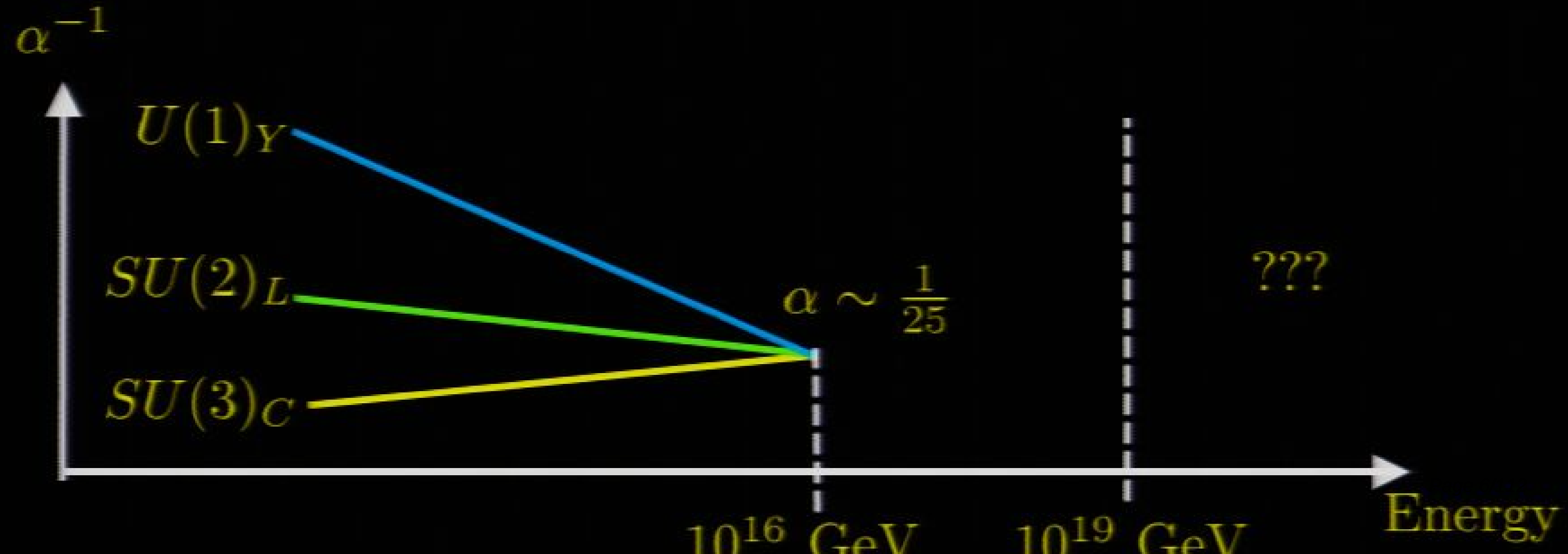
2) Worry about gravity later

UV Motivated Models

String theory predicts supersymmetry

Assume it persists to TeV scale

Supersymmetric Grand Unification:



SUSY GUT Structures

$$SU(5)_{GUT} \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$10_M = \begin{bmatrix} 0 & U & U & Q & Q \\ -U & 0 & U & Q & Q \\ -U & -U & 0 & Q & Q \\ -Q & -Q & -Q & 0 & E \\ -Q & -Q & -Q & -E & 0 \end{bmatrix} \qquad 5_H = \begin{bmatrix} T_u \\ T_u \\ T_u \\ H_u \\ H_u \end{bmatrix}$$

$$\overline{5}_M = \begin{bmatrix} D & D & D & L & L \end{bmatrix}$$

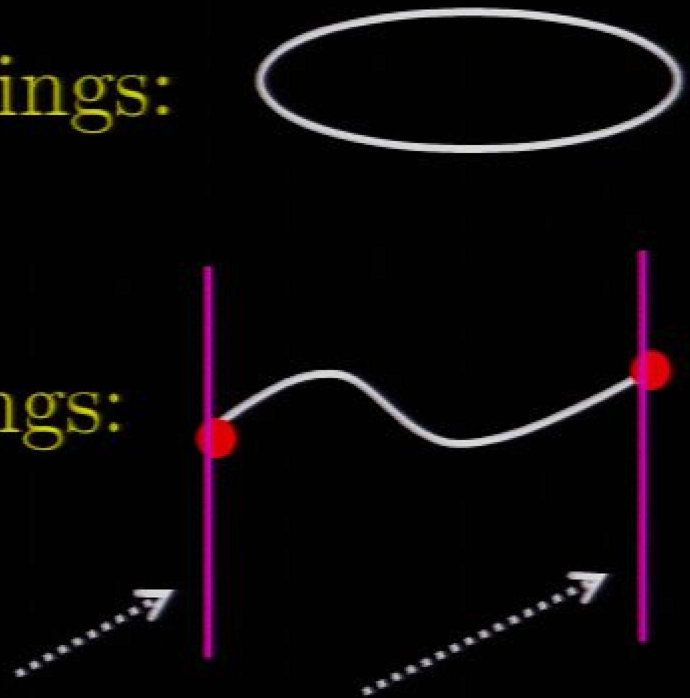
$$\overline{5}_H = \begin{bmatrix} T_d & T_d & T_d & H_d & H_d \end{bmatrix}$$

$L_{GUT} \supset 5_H \times 10_M \times 10_M \Rightarrow t$ quark mass

$L_{GUT} \supset \overline{5}_H \times \overline{5}_M \times 10_M \Rightarrow b$ quark & τ lepton mass

Focussing on Particle Physics

Gravity and Gauge Fields from Different Strings:



Closed Strings:

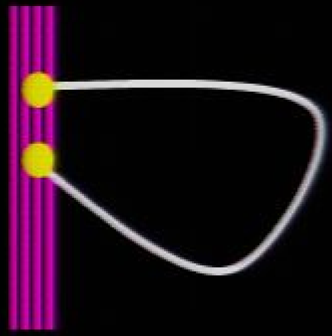
Spin 2 (gravity)

Open Strings:

Spin $0,\frac{1}{2},1$ (matter)

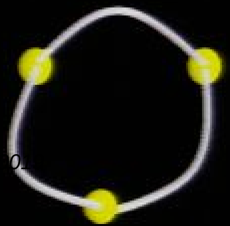
Dirichlet Branes

Open String Building Blocks



$\Rightarrow$ Gauge Groups: $U(N), SO(2N), USp(2N)$

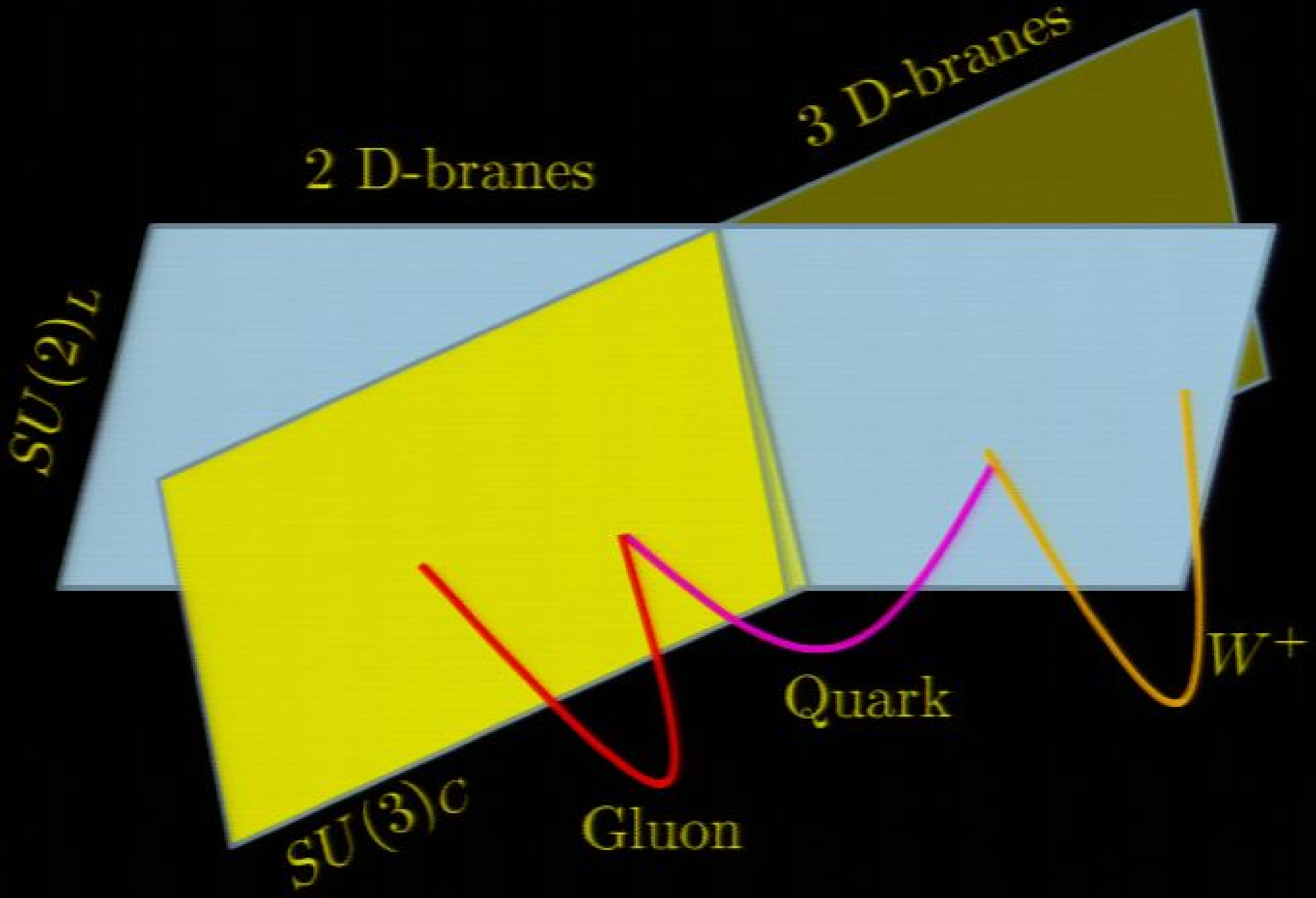
$\Rightarrow$ Matter in $\square \times \overline{\square} \quad \begin{smallmatrix}\square\\\square\end{smallmatrix} \quad \square\!\square$



$\Rightarrow$ Interactions Link $\square$ and $\overline{\square}$

Qualitative Features

Aldazabal Ibanez
Quevedo Uranga '00
Verlinde Wijnholt '05
+ many others

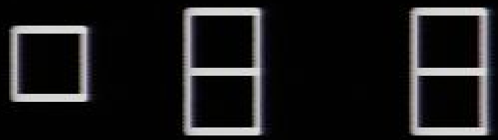


Can this be combined with Grand Unification?

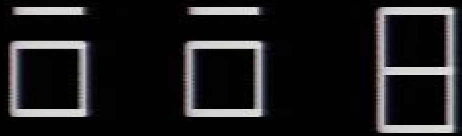
GUTs and Open Strings

Open strings for gauge theory $\Rightarrow$ Problems with GUTs:

No $5_H \times 10_M \times 10_M \Rightarrow$ pert. massless t quark



But $\bar{5}_H \times \bar{5}_M \times 10_M \Rightarrow$ massive b quark

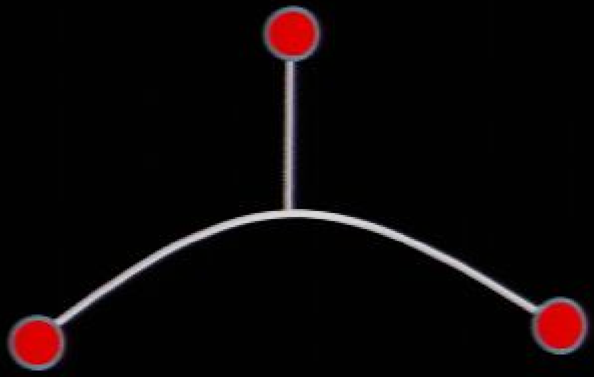


Wrong Prediction: $m_b > m_t$

The Main Idea:

Perturbative open strings somewhat limited

Increasing $g_s \to O(1)$ allows new bound states



Roadmap

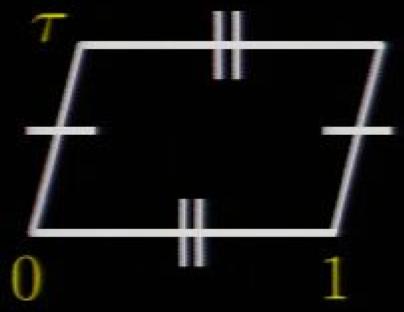
- Motivation
- F-theory GUTs

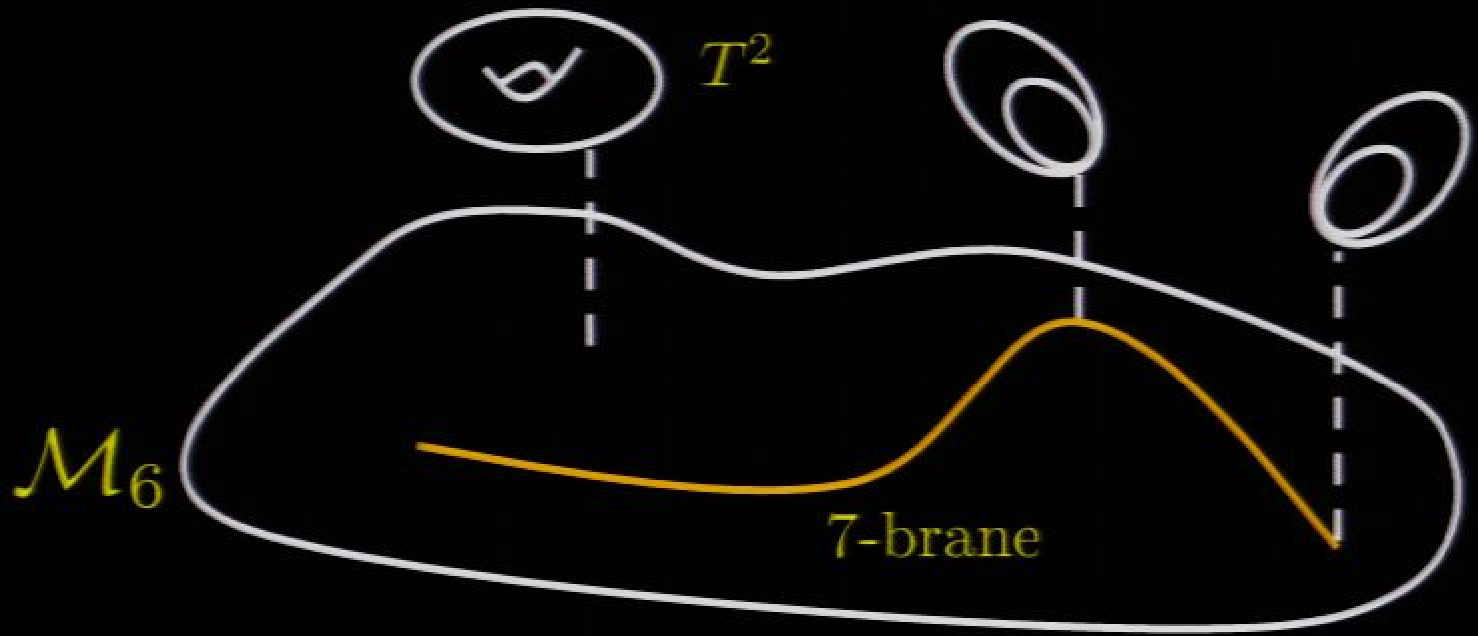
F-theory Review

Vafa '96

F-theory = Strongly Coupled Formulation of IIB in 12d

$\tau(y_6) = C_0 + \frac{i}{g_s}$ is shape of a T^2:





Terminology: p-brane = extended object in p spatial directions

$\cap$ 7-branes

	$R^{3,1}$				$\mathcal{M}_6$					
	0	1	2	3	4	5	6	7	8	9
7_{GUT}	×	×	×	×	×	×	×	×		
$7'$	×	×	×	×	×	×			×	×
$7''$	×	×	×	×			×	×	×	×

$10D$: Gravity

$8D$: Gauge Group (7)

$6D$: Matter ($7 \cap 7'$)

$4D$: Yukawas ($7 \cap 7' \cap 7''$)

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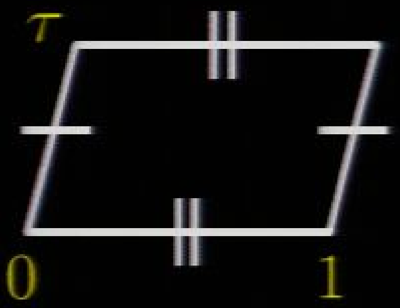

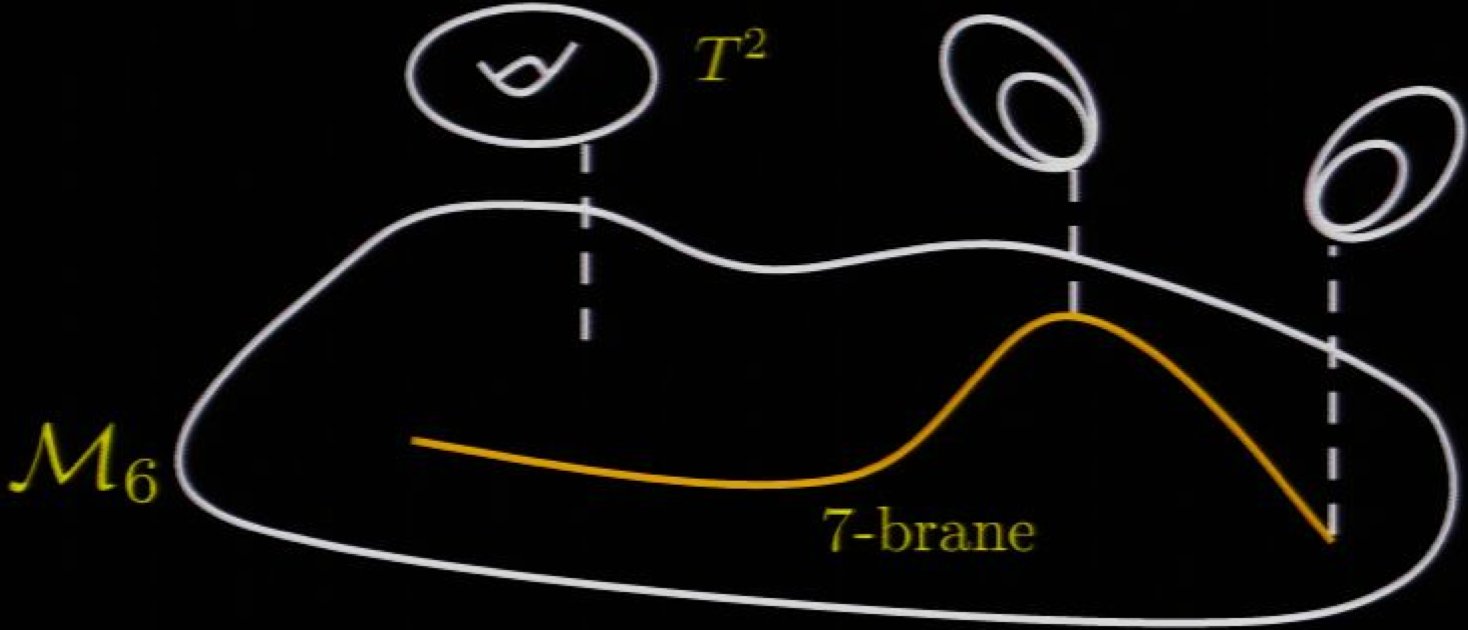

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Geometry ⇒ Gauge Theory

$F-th/R^{3,1}\times S\times C^2/\Gamma_{ADE}\Rightarrow 8d$ SYM w/gp G_{ADE}

Further enhancements generically occur:

Singularity Type	G_S	G_Σ	G_p
$\dim_{\mathbb{C}}$	2	1	0
Ingredient	Gauge Group	Matter	Yukawas

Main Idea: Treat as G_p Higgsed down to G_Σ's and G_S

$g_s \sim O(1) \Rightarrow$ Extra Ingredients

$$\text{Gauge Groups: } \underbrace{SU(N), SO(N), USp(2N)}_{g_s \ll 1}, \underbrace{E_6, E_7, E_8, G_2, F_4}_{g_s \sim O(1)}$$

$$\text{Matter: } \underbrace{5, 10 \text{ of } SU(5)}_{g_s \ll 1}, \underbrace{16 \text{ of } SO(10),\ 27 \text{ of } E_6}_{g_s \sim O(1)}$$

$$\text{Interactions: } \underbrace{\overline{5} \times \overline{5} \times 10 \text{ of } SU(5)}_{g_s \ll 1}, \underbrace{5 \times 10 \times 10 \text{ of } SU(5)}_{g_s \sim O(1)}$$

∩ 7-branes

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	0	1	2	3	4	5	6	7	8	9
7_{GUT}	×	×	×	×	×	×	×	×		
$7'$	×	×	×	×	×	×			×	×
$7''$	×	×	×	×			×	×	×	×

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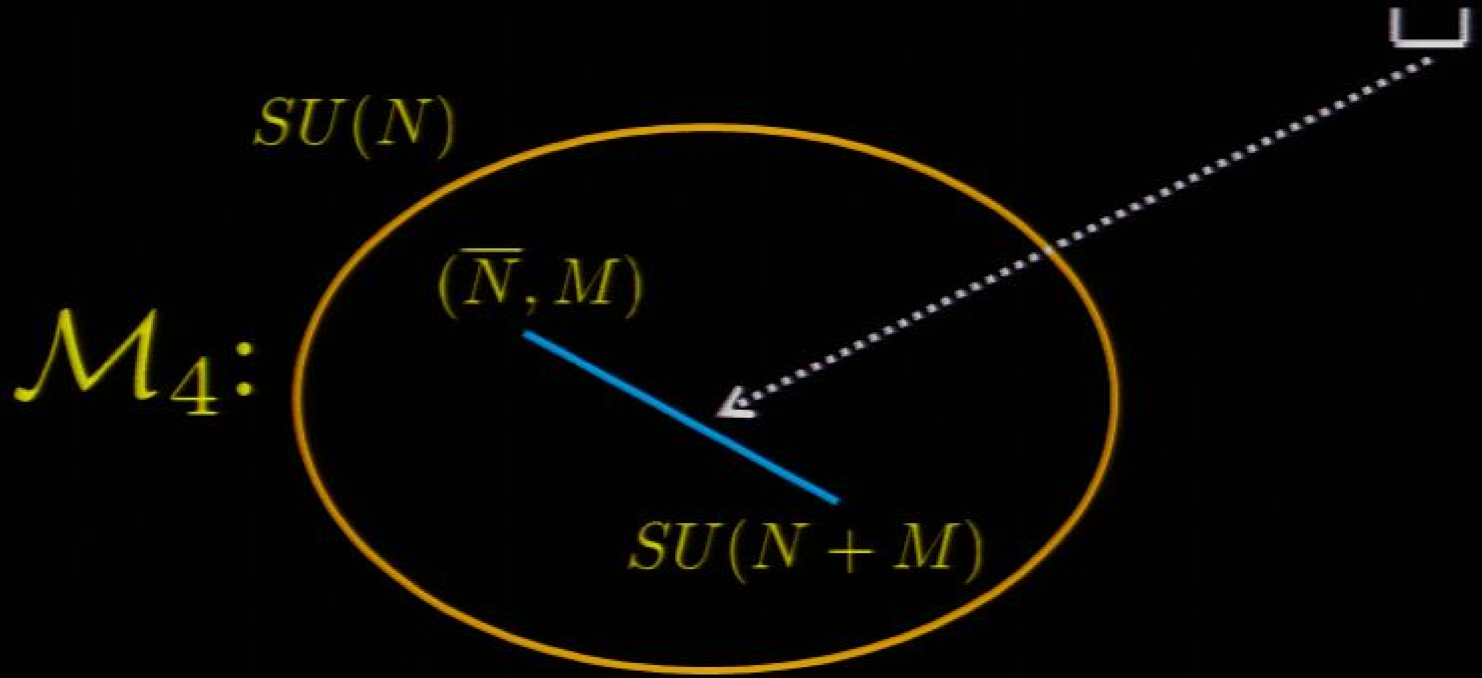
Higgsing By Geometry I

Example: Intersecting D7-branes:

$7_{SU(N)}$: 0 1 2 3 4 5 6 7

$7_{SU(M)}$: 0 1 2 3 4 5 $\quad$ 8 9



$SU(N)$

$\mathcal{M}_4$:

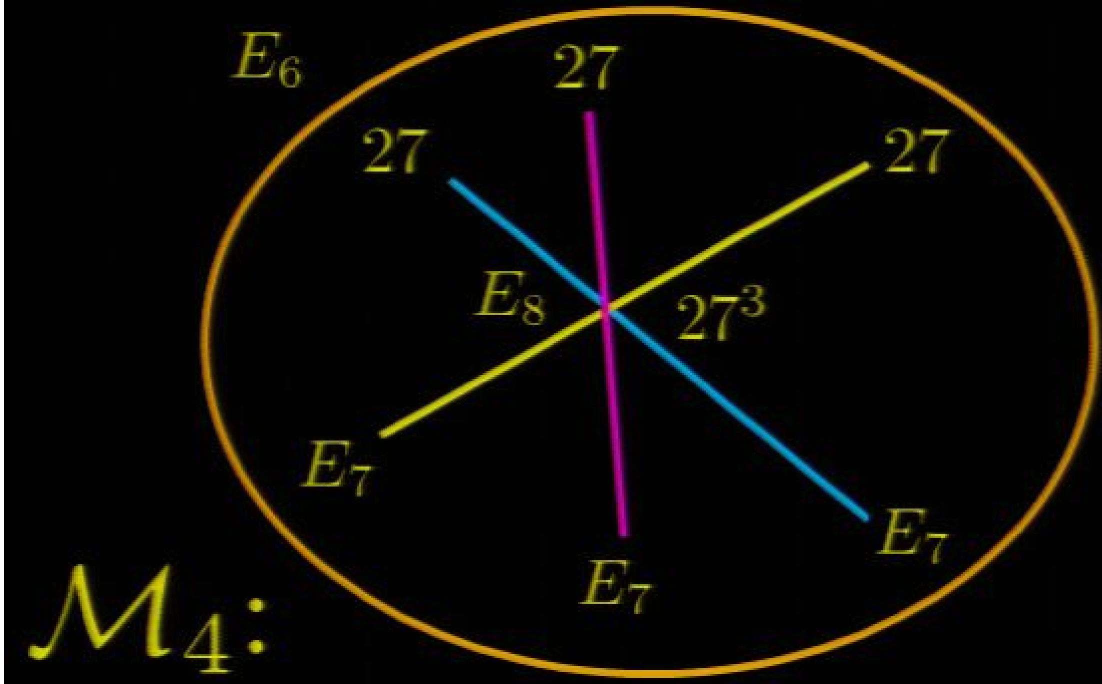
$(\overline{N}, M)$

$SU(N+M)$

$$ad_{SU(N+M)} \rightarrow ad_{SU(N)} + ad_{SU(M)} + \boxed{(N,\overline{M}) + (\overline{N},M)} + (1,1)$$

Higgsing By Geometry II

Example: E_6 7-brane wrapping $\mathcal{M}_4$



$$E_8 \rightarrow E_6 \times \overbrace{U(1) \times U(1)}^{SU(3)}$$

$$248 \rightarrow (27,3) + (\overline{27},\overline{3}) + ...$$

Getting Chiral Matter

6d Matter: $\mathbb{R}^{3,1}\times$ 

+ gauge field flux on Σ

$(\not{D}_{\mathbb{R}^{3,1}} + \not{D}_{\Sigma})\Psi_{6d} = 0$: Massless modes $\iff$ $\not{D}_{\Sigma}\Psi_{(0)} = 0$

\# Generations $= \frac{1}{2\pi}\int_{\Sigma} F$

Yukawas From Wave Functions

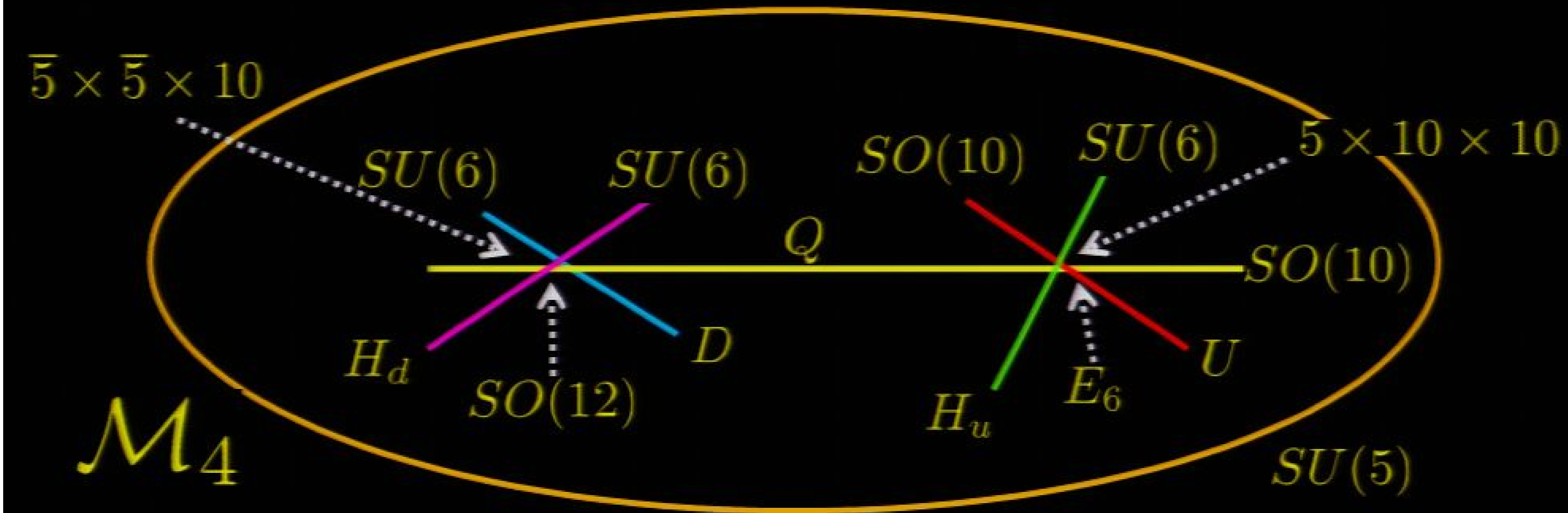
4d matter has a profile in the extra dimensions: Ψ_Q, Ψ_U,...

$$\not{D}_\Sigma \Psi_{matter} = 0$$

Example: $W \supset \lambda_{up}^{ij} Q^i U^j H_u$ with $\lambda_{up}^{ij} = \int \Psi_Q^i \Psi_U^j \Psi_{H_u}$

Quark Mixing

Mixing determined by local Ψ overlaps



Problem: $\Psi^{Q}_{near\ p_{down}} \neq \Psi^{Q}_{near\ p_{up}} \Rightarrow$ Misaligned mass eigenbases

$\Rightarrow$ CKM Matrix Not Hierarchical

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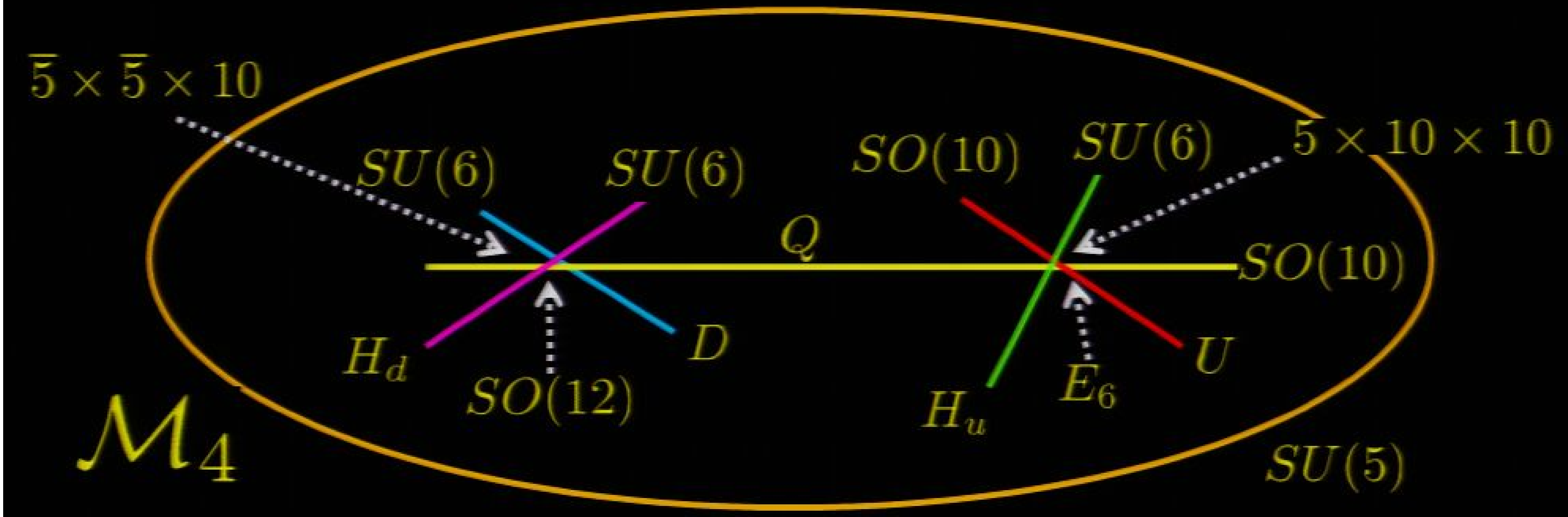
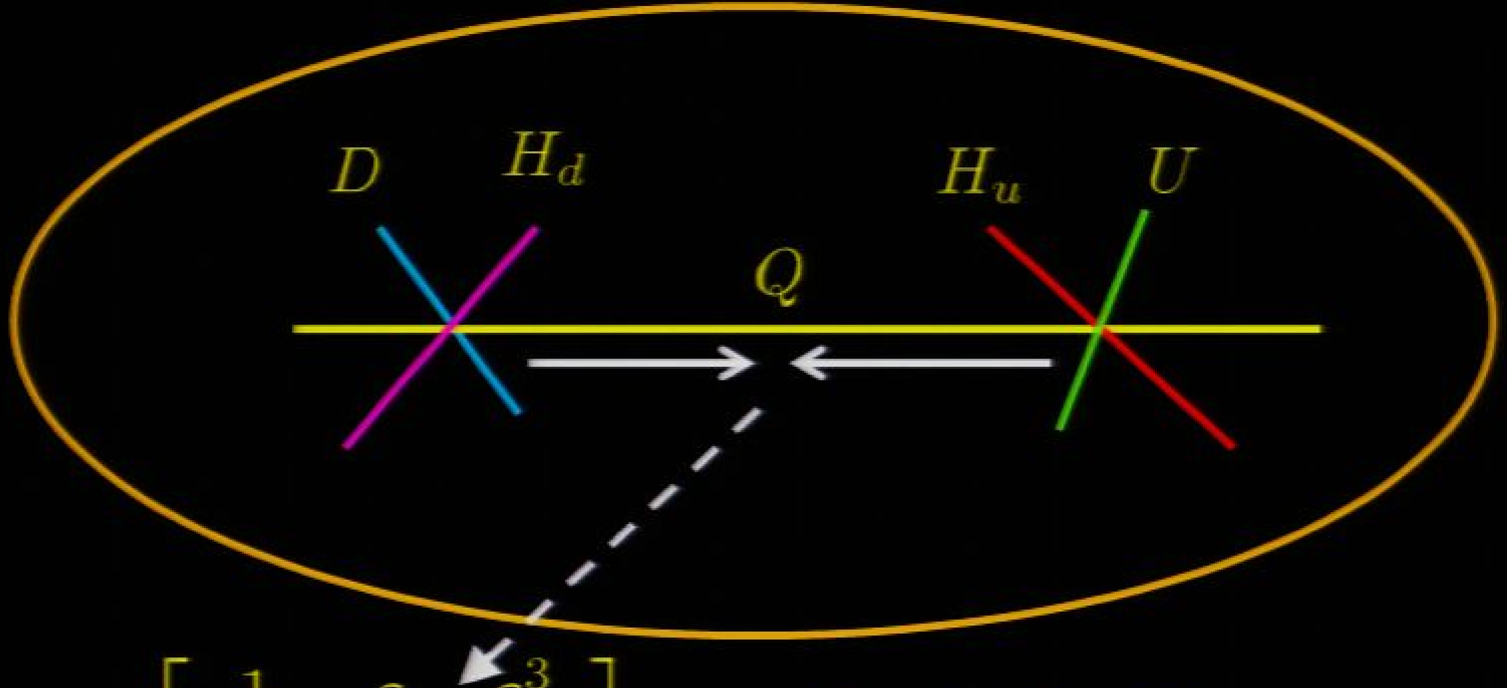


Problem: $\Psi^{Q}_{near\ p_{down}} \neq \Psi^{Q}_{near\ p_{up}} \Rightarrow$ Misaligned mass eigenbases

$\Rightarrow$ CKM Matrix Not Hierarchical

$p_{down} \to p_{up}$

Solution: $\Psi^{Q}_{near\ p_{down}} \to \Psi^{Q}_{near\ p_{up}}$

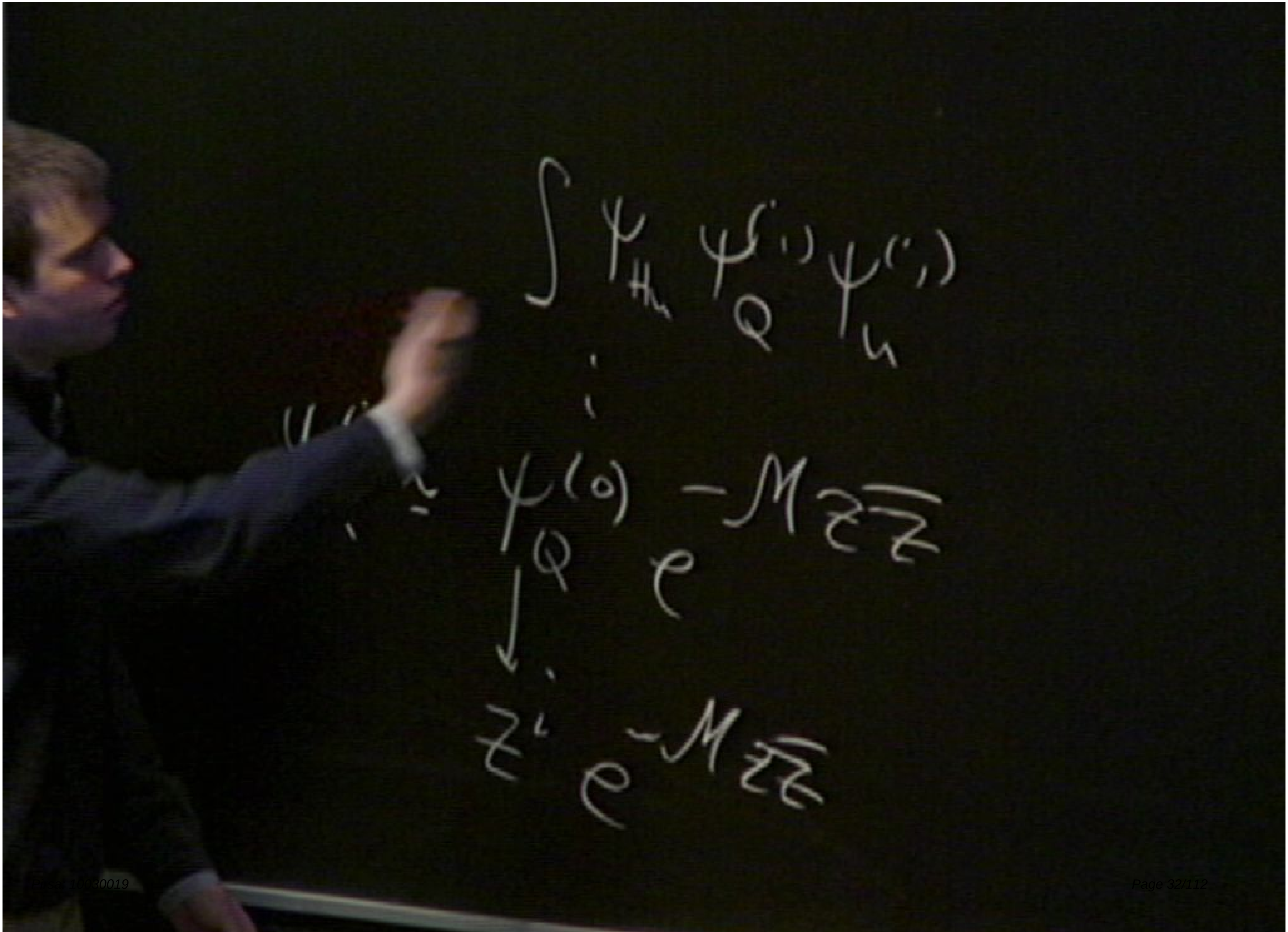


$$|V_{CKM}| \sim \begin{bmatrix} 1 & \varepsilon & \varepsilon^3 \\ \varepsilon & 1 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{bmatrix}$$

$$\begin{tikzcd} E_6 : 5_H 10_M 10_M \arrow[dr] & \\ & E_7 \\ SO(12) : \overline{5}_H \overline{5}_M 10_M \arrow[ur] & \end{tikzcd}$$

$\varepsilon \sim \sqrt{\alpha_{GUT}} \sim 0.2$

$$\int \psi_{th} \, \psi_{Q}^{(\cdot,\cdot)} \, \psi_{h}^{(\cdot,\cdot)}$$



$$\int \psi_{th}\, \psi_Q^{(1)}\, \psi_u^{(1)}$$

$$\psi_Q^{(0)}\; e^{-M z\bar{z}}$$

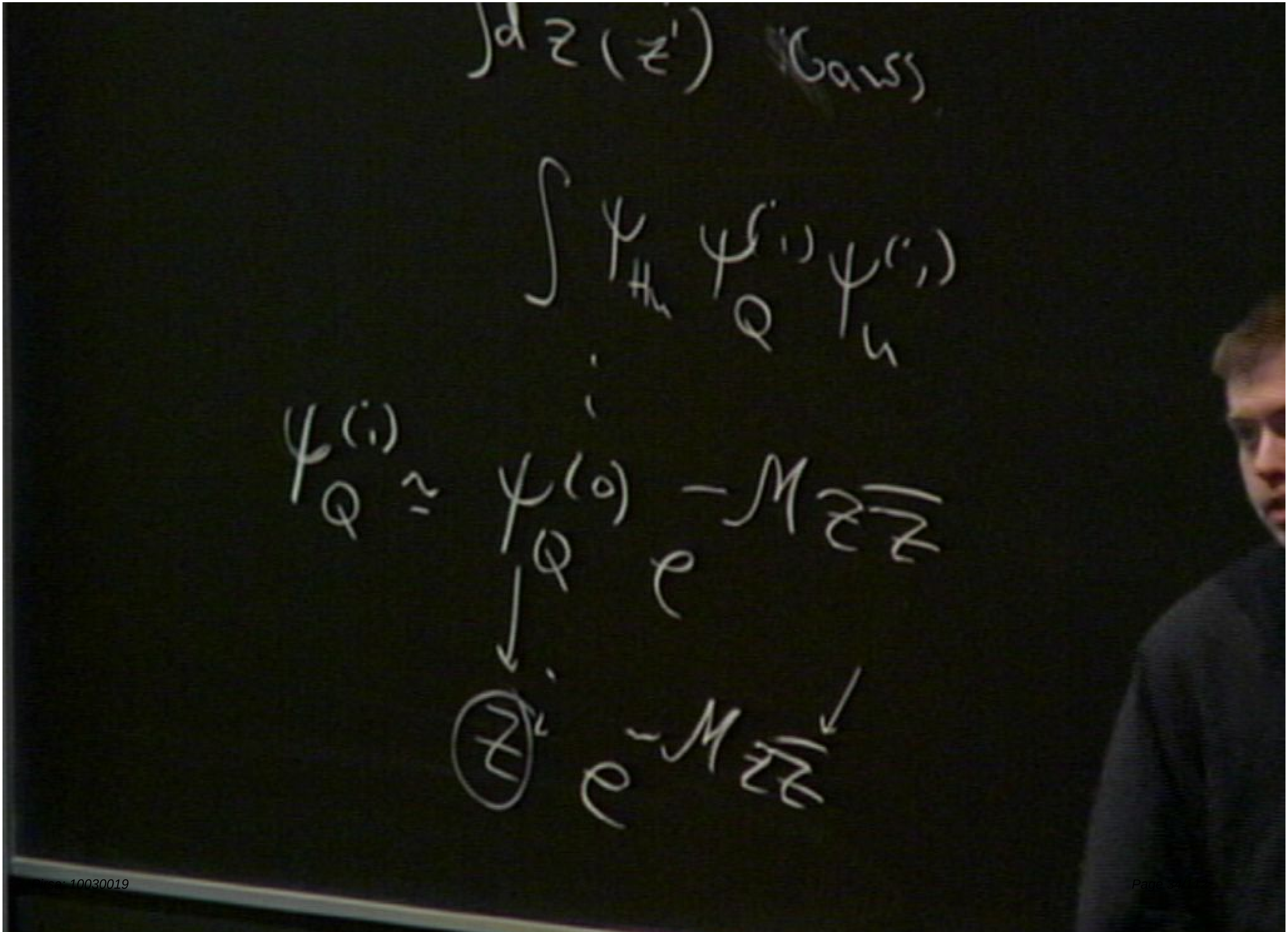
$$z^i\, e^{-M z\bar{z}}$$

$$\int \psi_{H_u} \psi_Q^{(i)} \psi_u^{(j)}$$

$$\psi_Q^{(i)} \simeq \psi_Q^{(0)} e^{-M z\bar{z}}$$

$$\Big\downarrow$$

$$z^i e^{-M z\bar{z}}$$



$$\int dz\,(z^i) \quad \text{Gauss}$$

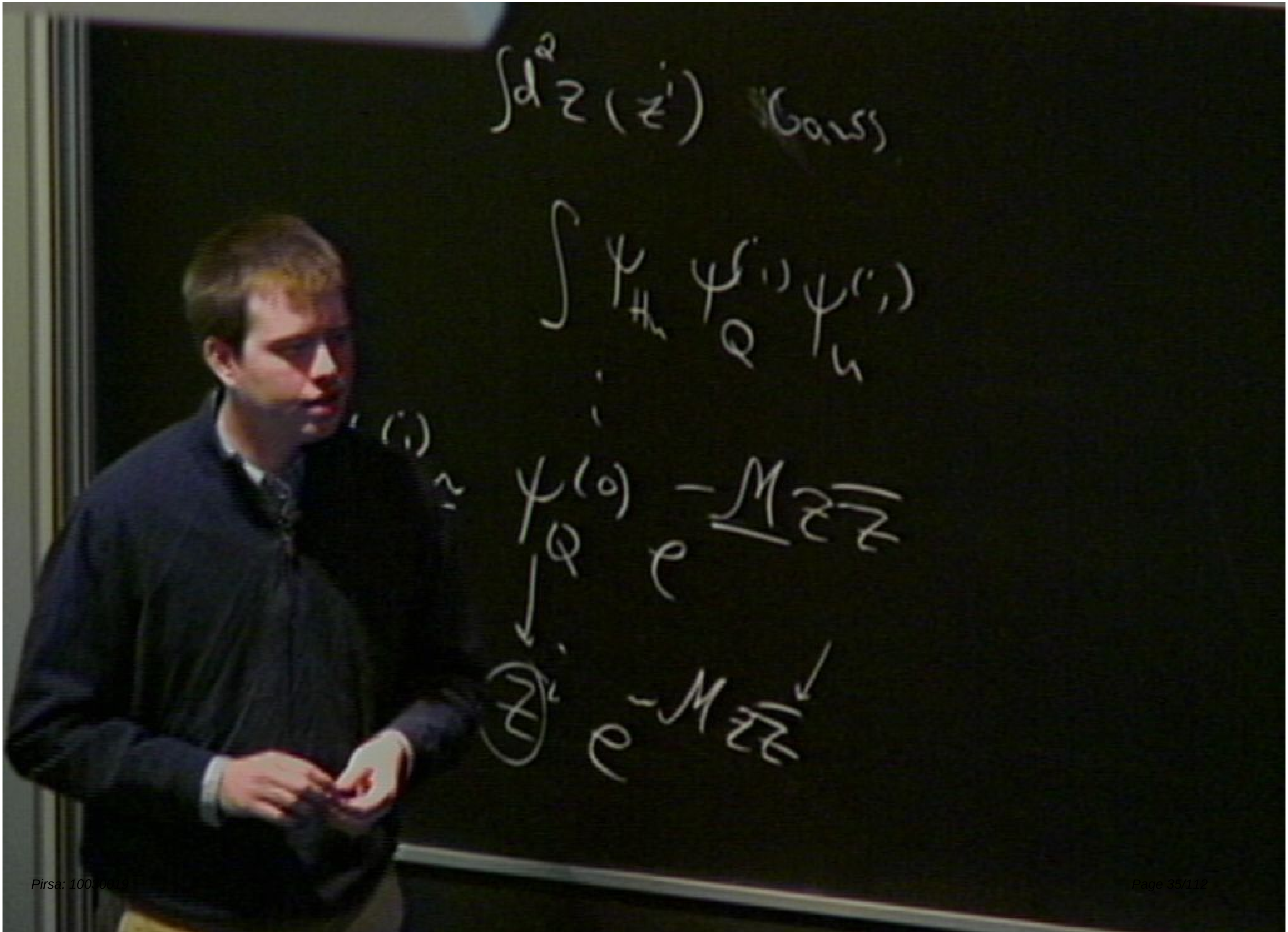
$$\int \psi_{th}\,\psi_Q^{(1)}\,\psi_h^{(1)}$$

$$\vdots$$

$$\psi_Q^{(1)} \simeq \psi_Q^{(0)}\, e^{-M z \bar{z}}$$

$$\downarrow$$

$$\boxed{\bar{z}}^{\,i}\, e^{-M z \bar{z}} \swarrow$$



$$\int d^2 z \, (z^i) \quad \text{Gauss}$$

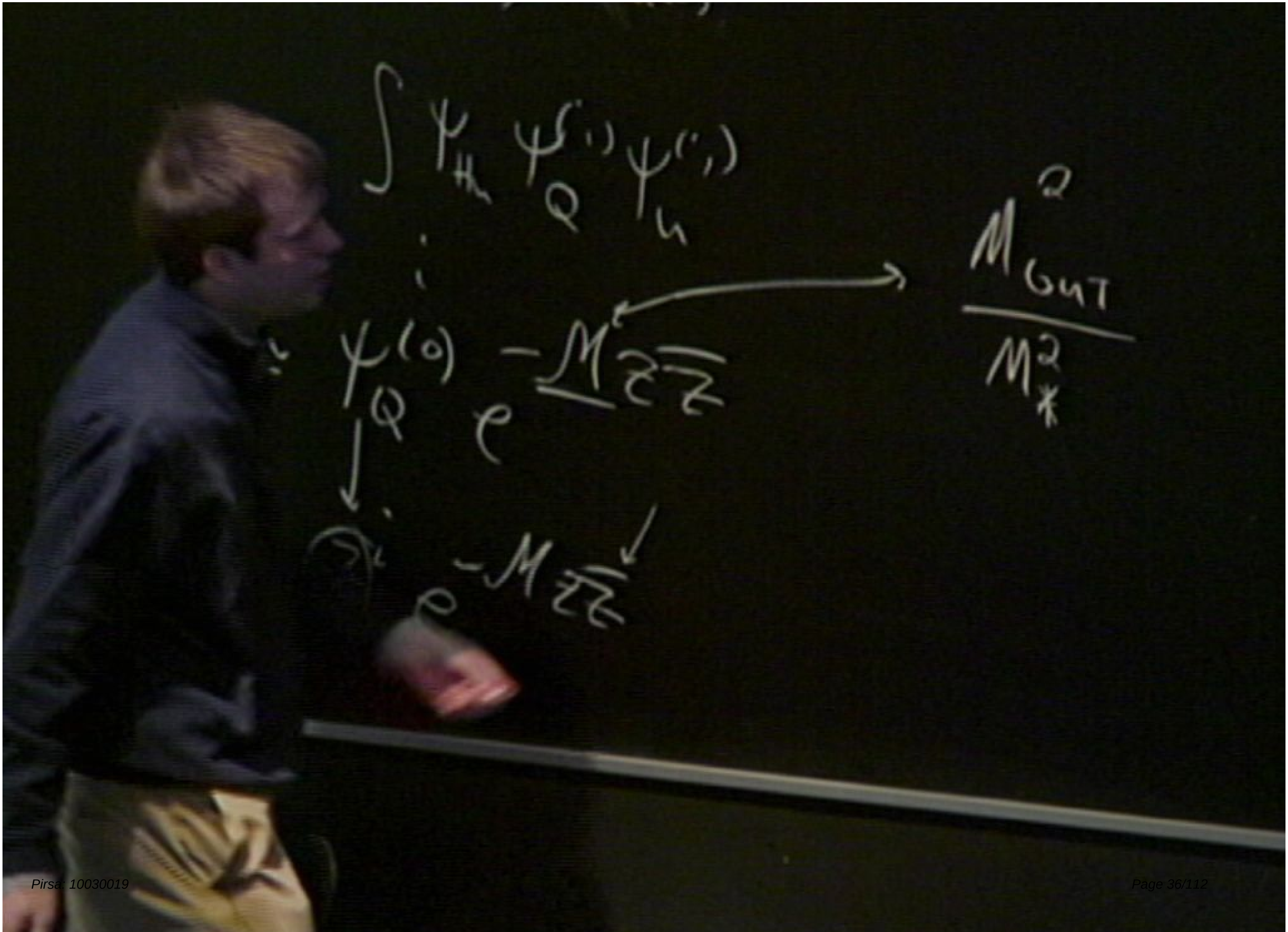
$$\int \psi_{th} \, \psi_Q^{(;)} \, \psi_h^{(;)}$$

$$\vdots$$

$$\psi_Q^{(0)} \, e^{-\underline{M} z \bar{z}}$$

$$\downarrow$$

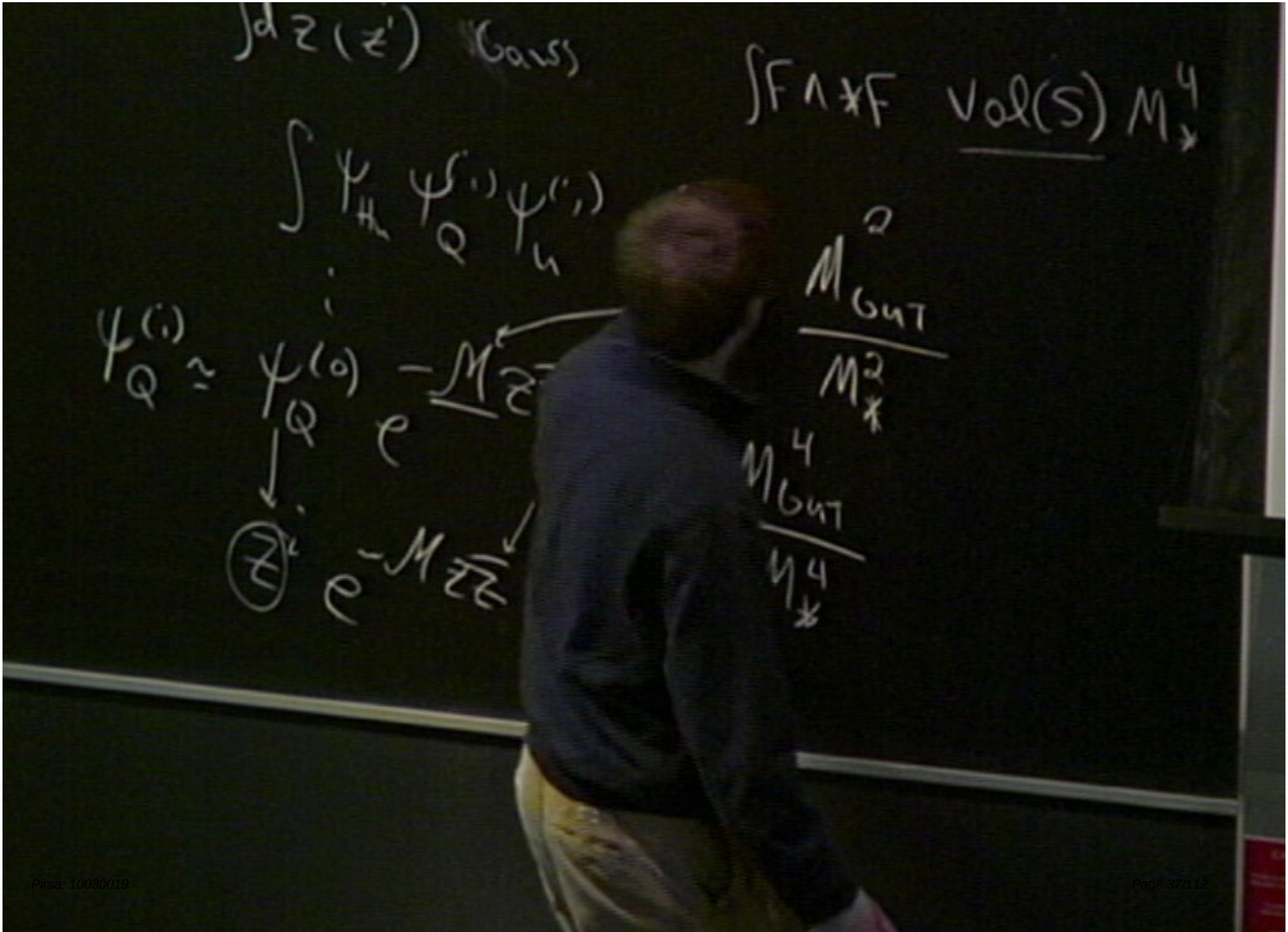
$$\boxed{z}^i \, e^{-M z \bar{z}}$$



$$\int \psi_{H_u}\, \psi_Q^{(\,)}\, \psi_u^{(\,)}$$

$$\psi_Q^{(0)} \sim e^{-\underline{M} z\bar{z}} \qquad \frac{M_{GUT}^2}{M_*^2}$$

$$\sim e^{-M z\bar{z}}$$



$\int dz\,(z')$ Gauss

$\int F\wedge *F \quad \underline{\mathrm{Vol}(S)}\, M_*^4$

$$\int \psi_{H_u}\,\psi_Q^{(1)}\,\psi_u^{(1)}$$

$\vdots$

$$\psi_Q^{(1)} \simeq \psi_Q^{(0)}\, e^{-\underline{M} z\bar{z}}$$

$\downarrow$

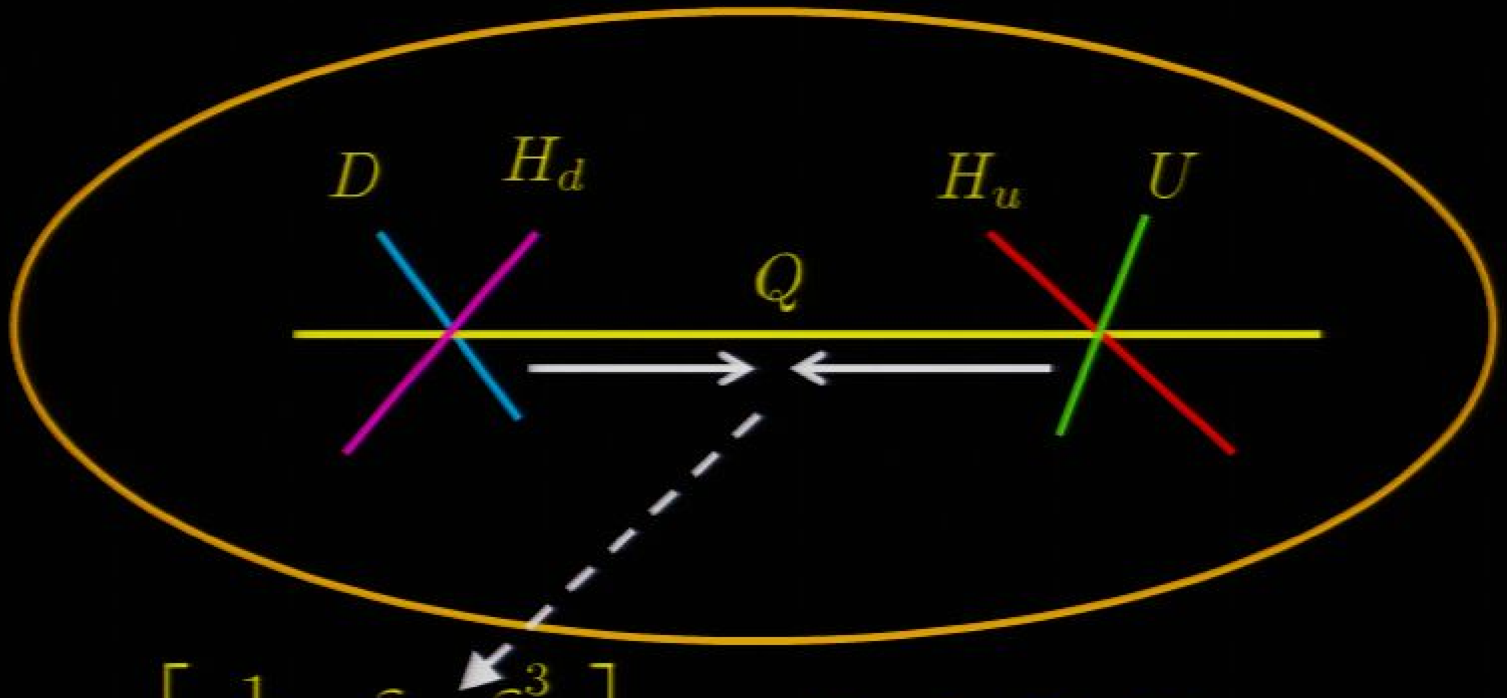
$$\enclose{circle}{z}^{i}\, e^{-M z\bar{z}}$$

$$\frac{M_{GUT}^2}{M_*^2}$$

$$\frac{M_{GUT}^4}{M_*^4}$$

$p_{down} \rightarrow p_{up}$

Solution: $\Psi^{Q}_{near\ p_{down}} \rightarrow \Psi^{Q}_{near\ p_{up}}$



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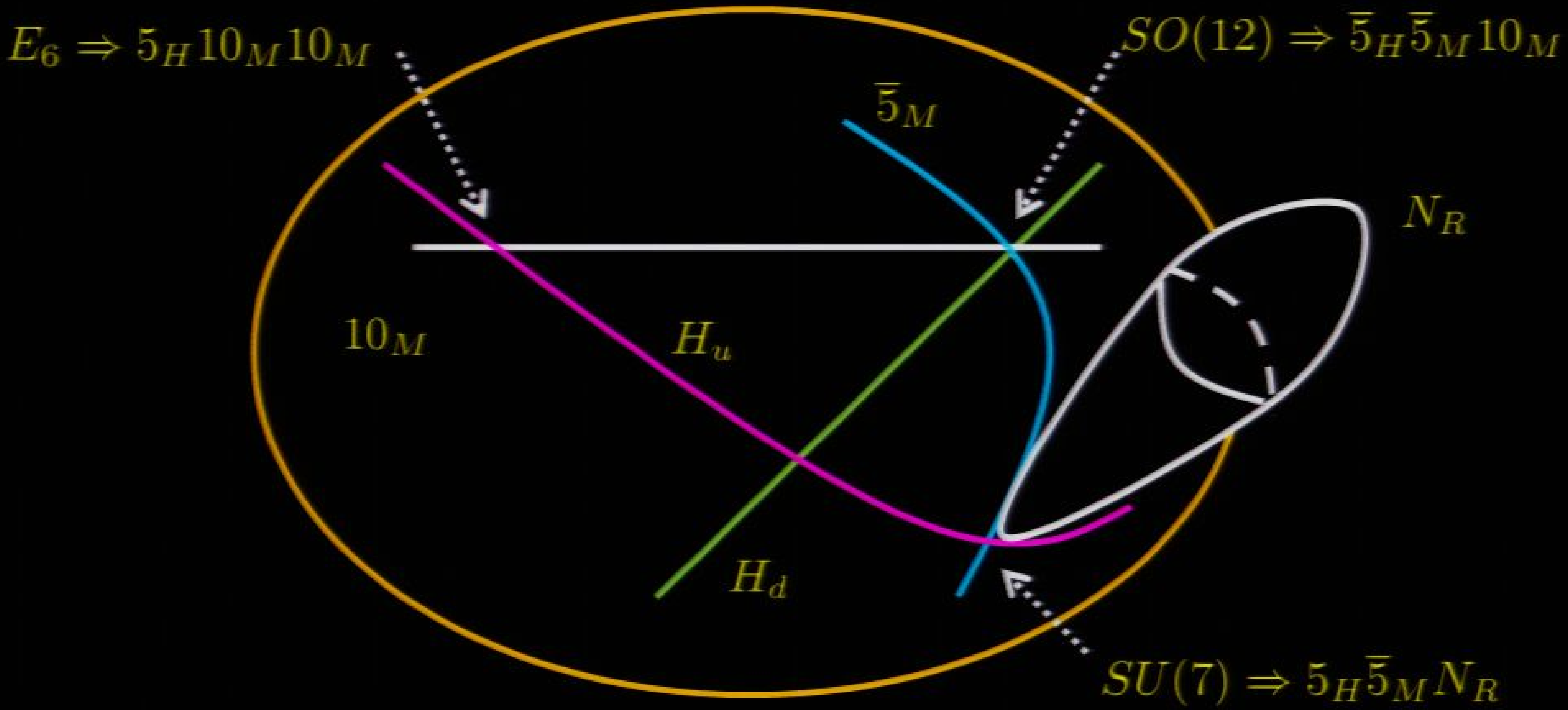
Point Unification



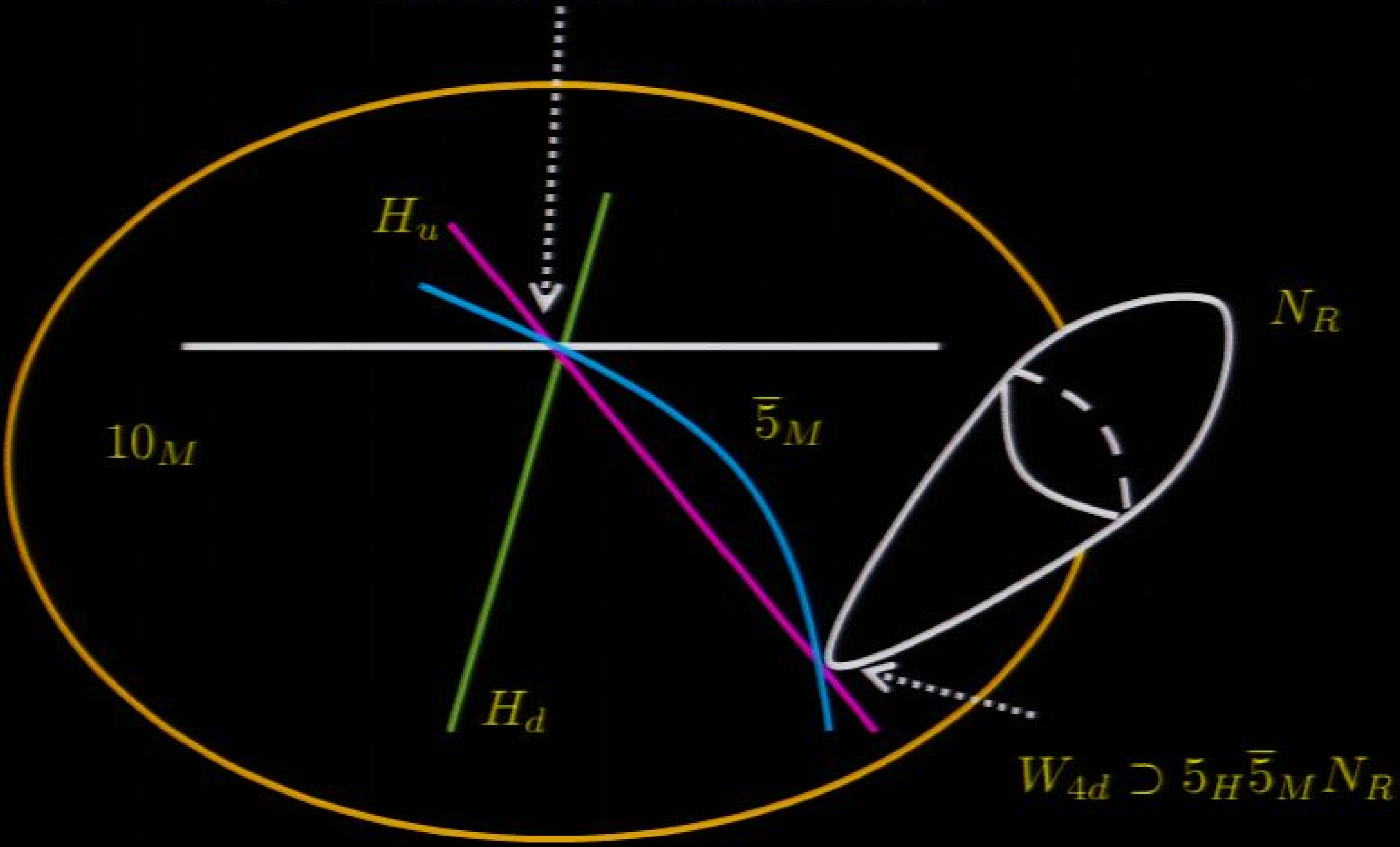
$E_6 \Rightarrow 5_H 10_M 10_M$

$SO(12) \Rightarrow \overline{5}_H \overline{5}_M 10_M$

$SU(7) \Rightarrow 5_H \overline{5}_M N_R$

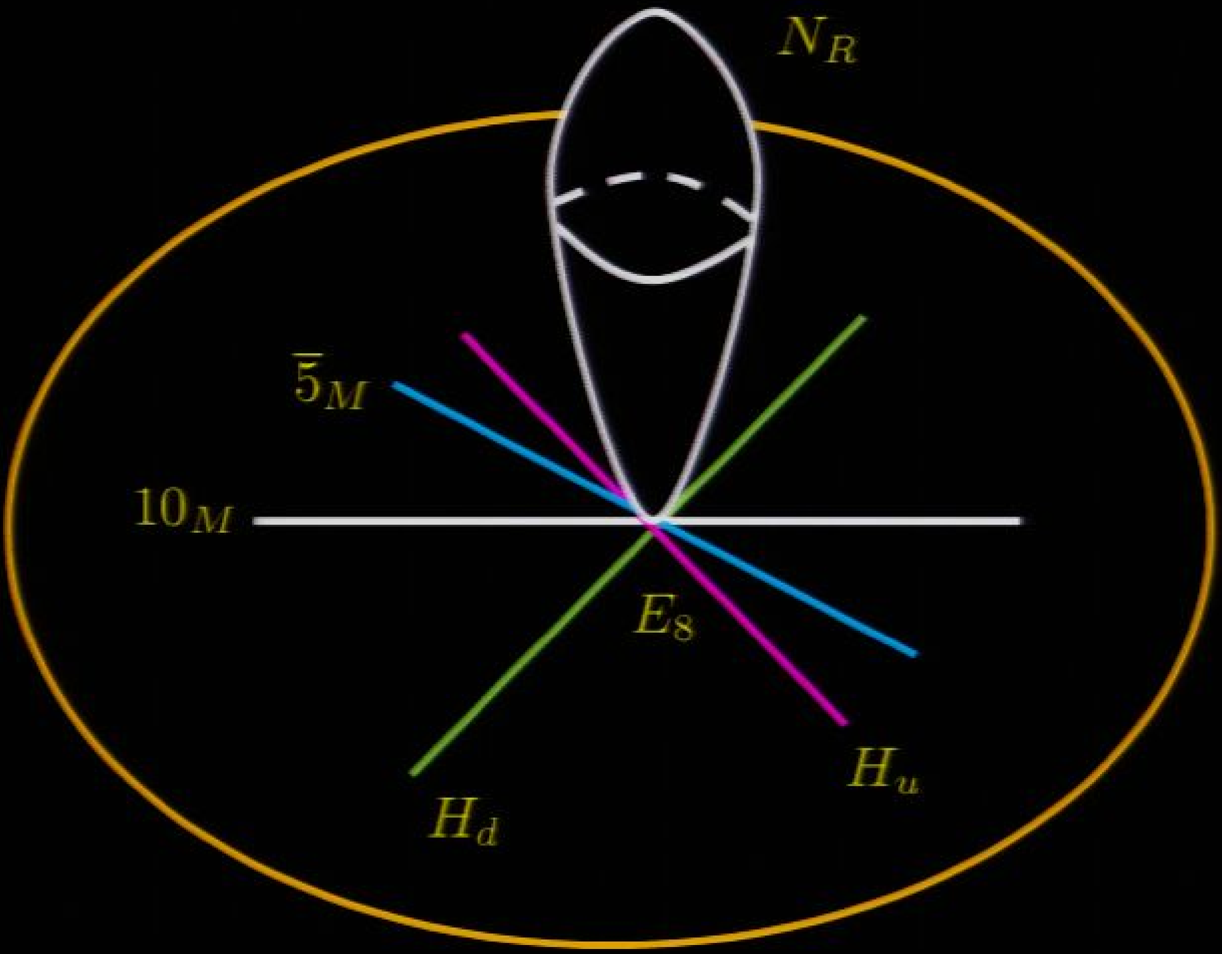
Point Unification

$E_7 \Rightarrow 5_H 10_M 10_M + \overline{5}_H \overline{5}_M 10_M$



$W_{4d} \supset 5_H \overline{5}_M N_R$

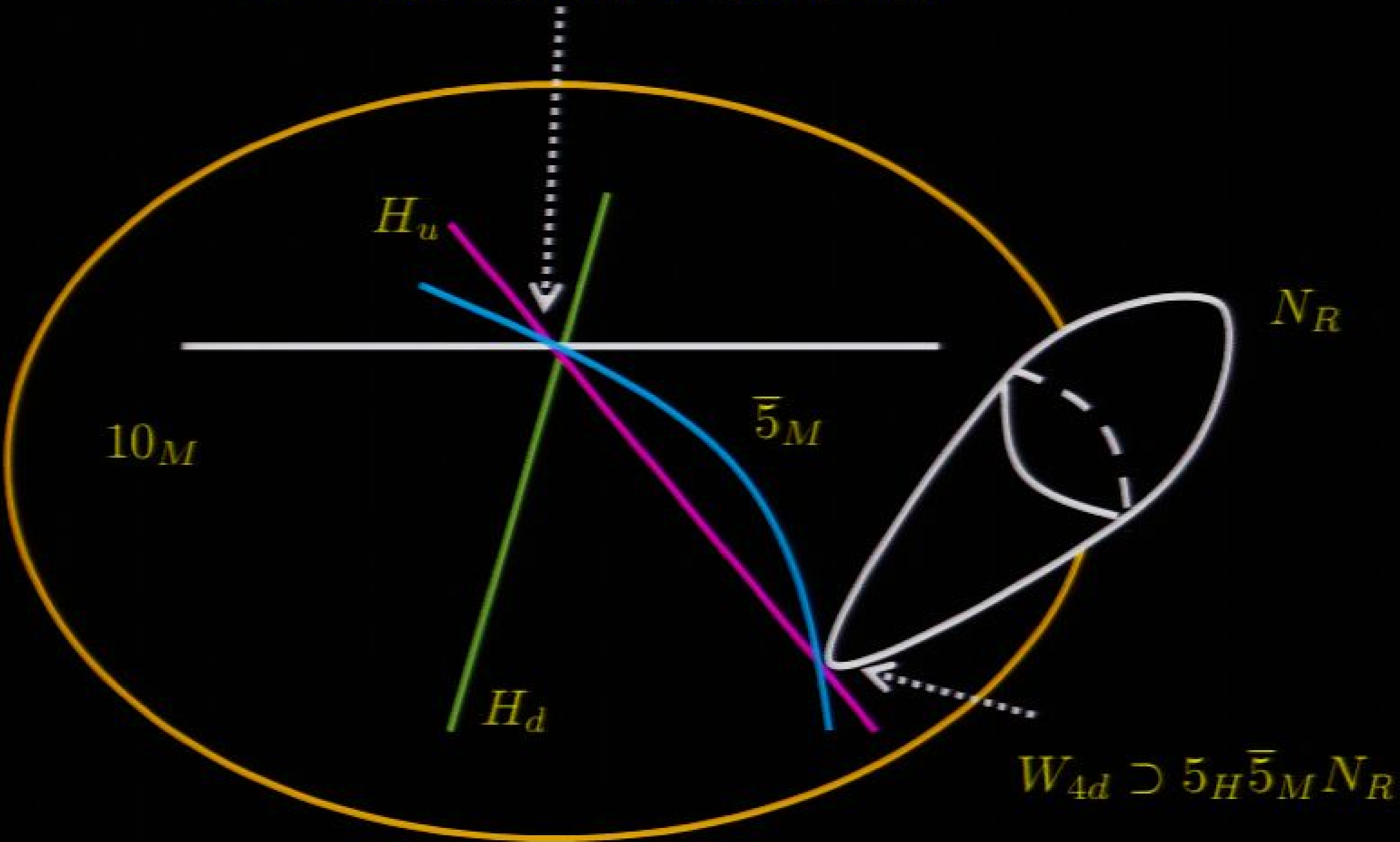
Point Unification



$\theta_{13}^{PMNS} < 0.2 \Rightarrow$ Unify quark and lepton interactions

Point Unification

$E_7 \Rightarrow 5_H 10_M 10_M + \bar{5}_H \bar{5}_M 10_M$



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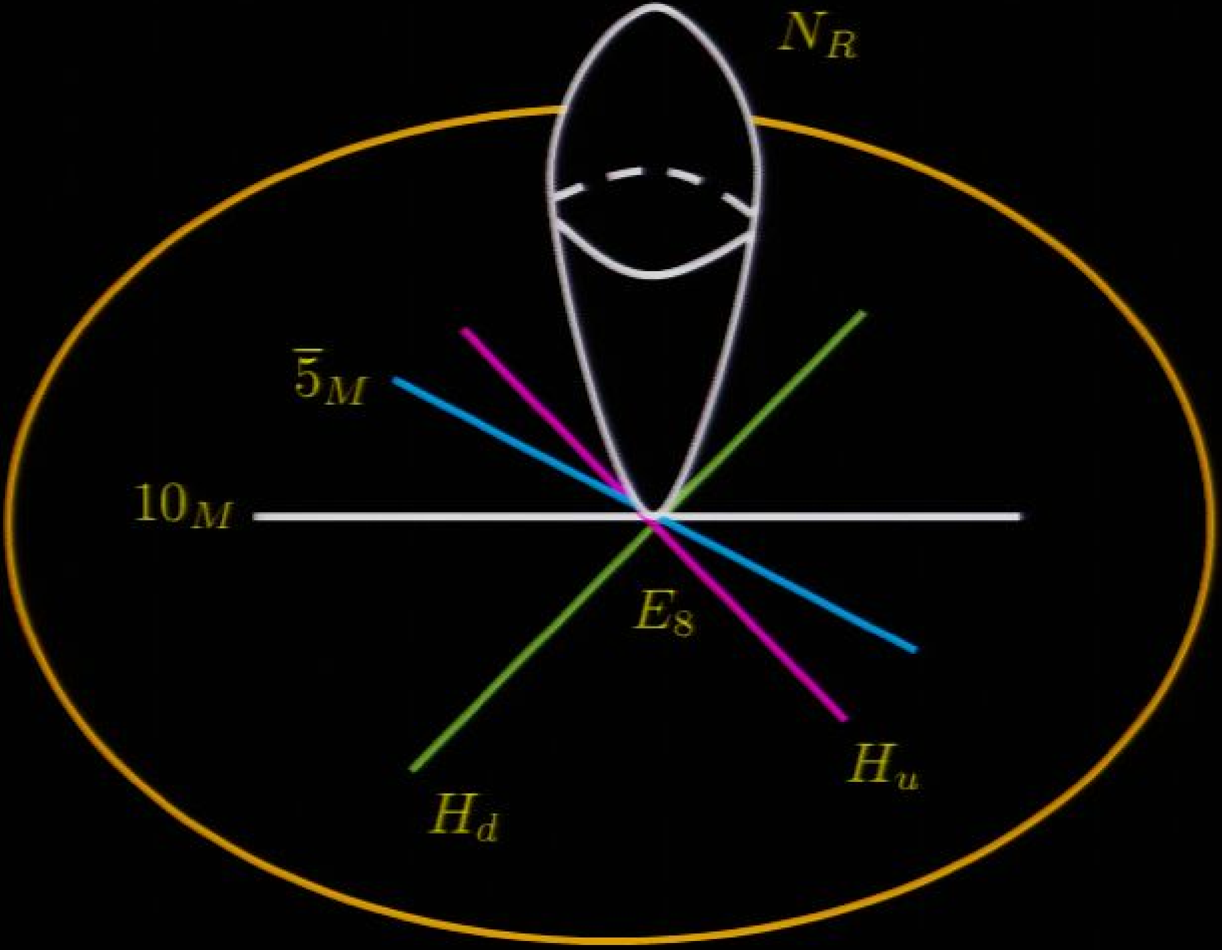


$\theta_{13}^{PMNS} < 0.2 \Rightarrow$ Unify quark and lepton interactions

E_8 Unification

E_8 Breaking gives us the GUT matter:

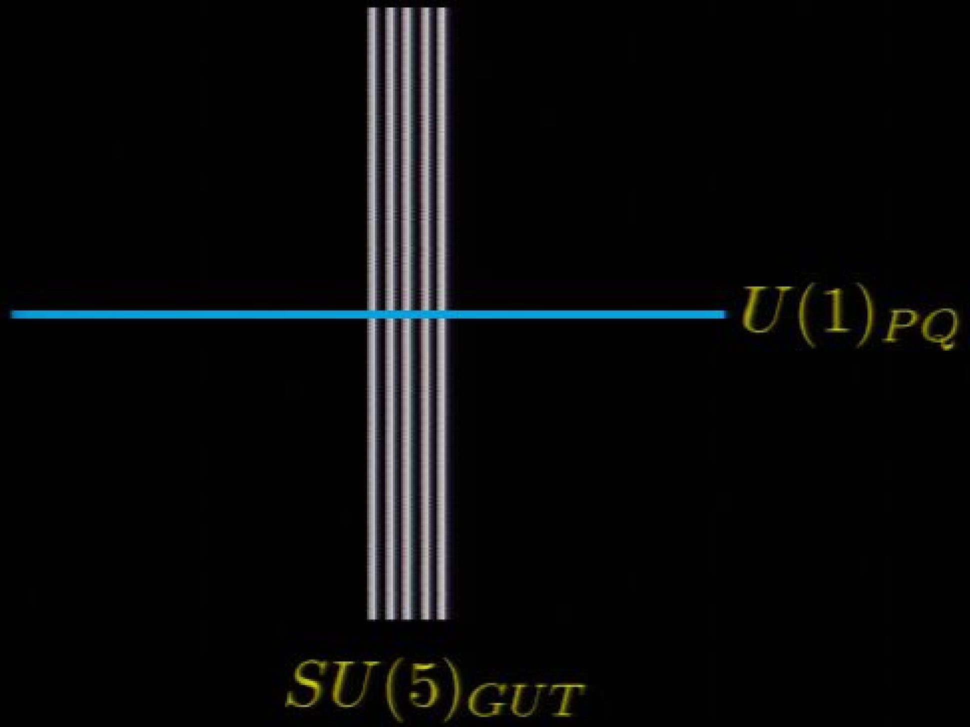
$$E_8 \rightarrow SU(5)_{GUT} \times SU(5)_{\perp}$$

$$248 \rightarrow (5_G, 10_{\perp}) + (\overline{5}_G, \overline{10}_{\perp}) + (10_G, \overline{5}_{\perp}) + (\overline{10}_G, 5_{\perp}) + adj$$

Viable breaking $\Rightarrow \quad E_8 \rightarrow SU(5)_{GUT} \times U(1)_{PQ}$

$U(1)_{PQ}$

In the six internal dimensions the picture is:



Note: MSSM matter charged under $U(1)_{PQ}$

E_8 Unification

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Viable breaking $\Rightarrow$ $E_8 \rightarrow SU(5)_{GUT} \times U(1)_{PQ}$

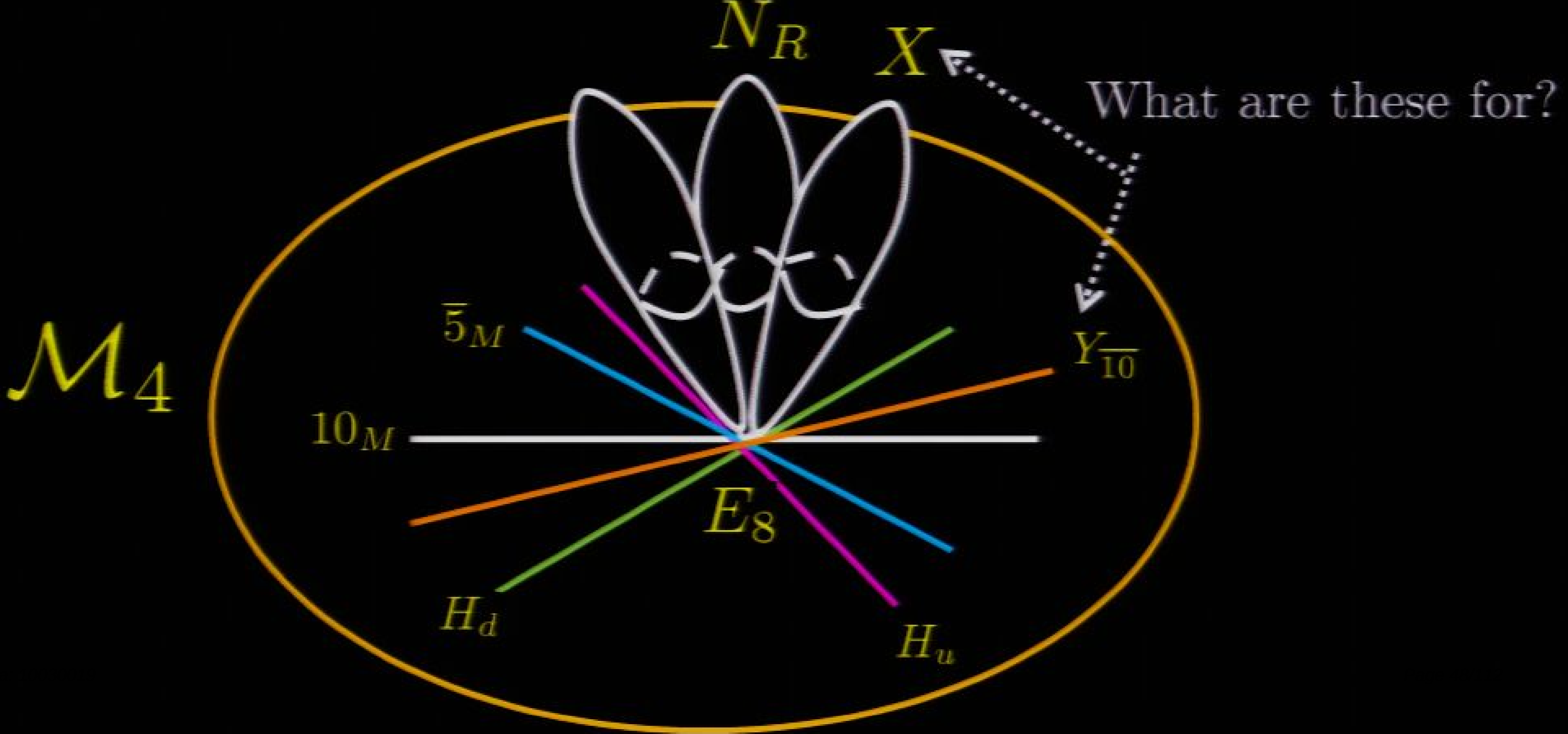
Roadmap

- F-theory GUTs
- ~~SUSY~~ and Stau NLSP

Extra Matter?

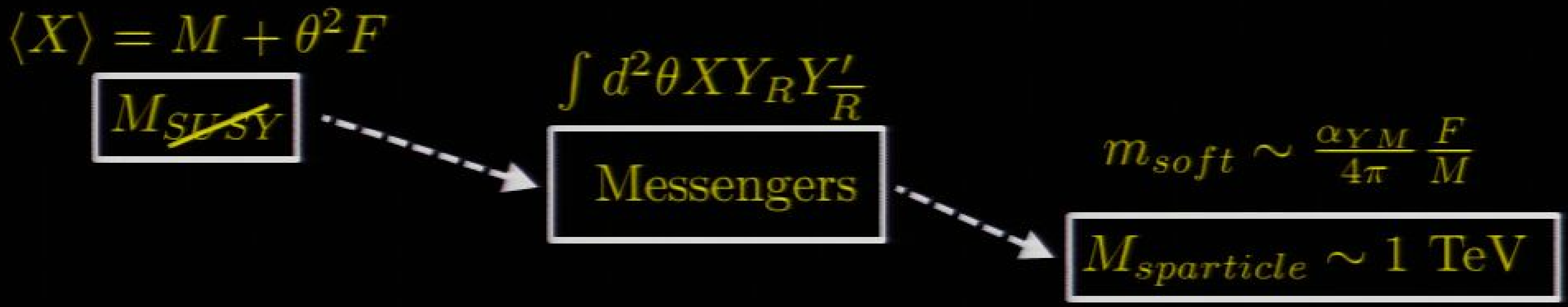
Remarkably, everything needed + a few extras

Barely fits inside E_8



$\cancel{\text{SUSY}}$ Mediation

min. gauge mediation review:



$\langle X \rangle = M + \theta^2 F$

$M_{\cancel{SUSY}}$

$\int d^2\theta X Y_R Y'_{\bar{R}}$

Messengers

$m_{soft} \sim \frac{\alpha_{YM}}{4\pi} \frac{F}{M}$

$M_{sparticle} \sim 1$ TeV

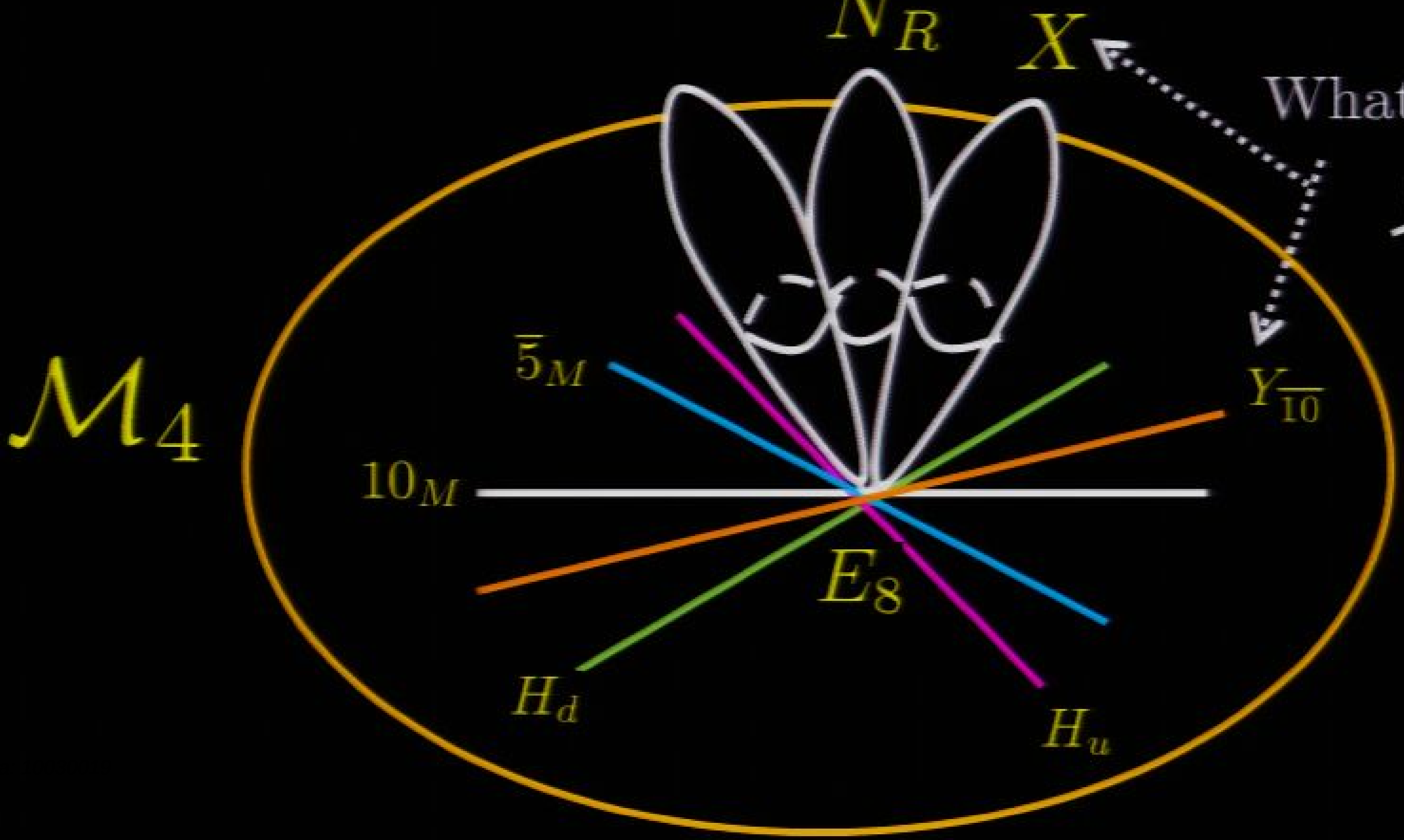
Messengers and X already part of the E_8 point

A Surprise: In nearly all cases messengers in $10 \oplus \overline{10}$

Extra Matter?

Remarkably, everything needed + a few extras

Barely fits inside E_8

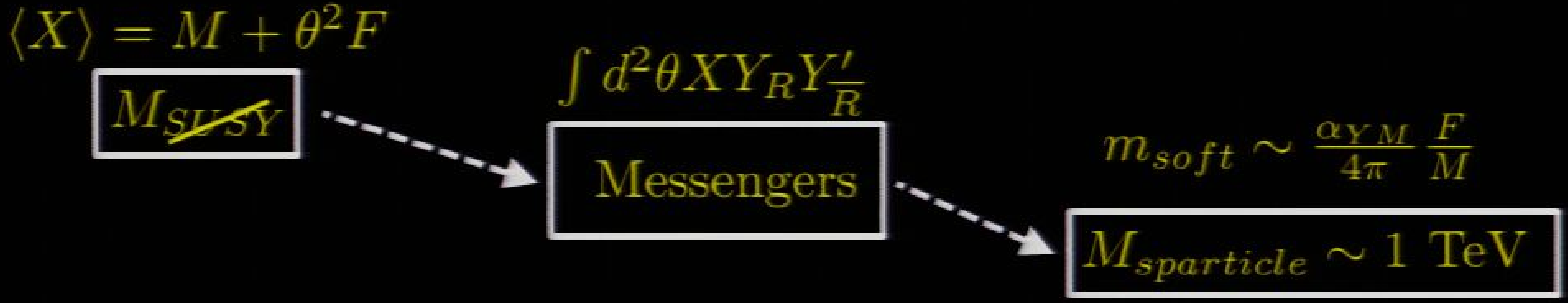


What are these for?

~~SUSY~~

~~SUSY~~ Mediation

min. gauge mediation review:



$\langle X\rangle = M + \theta^2 F$

$M_{\cancel{SUSY}}$

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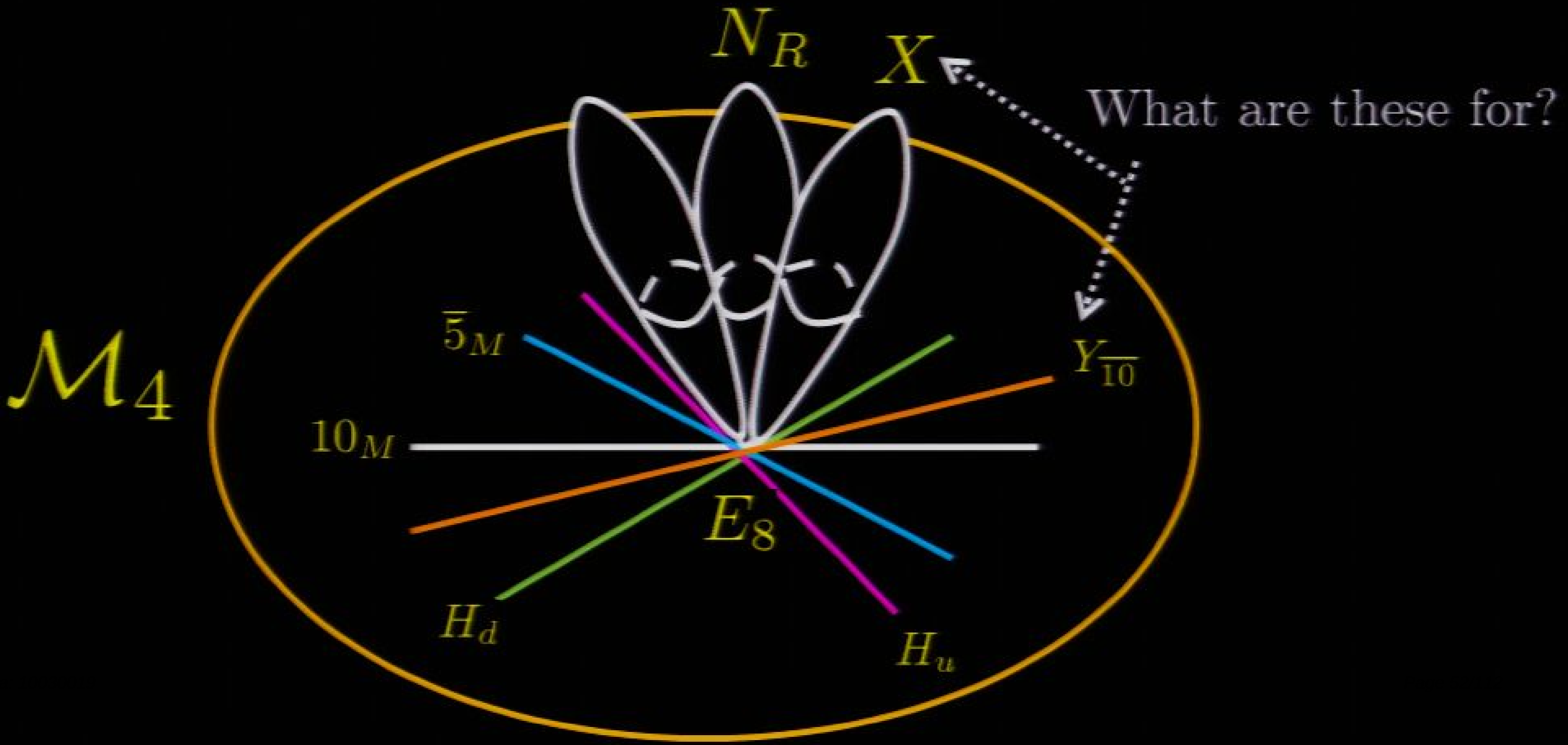

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From Standard Model Gauge Fields (minimal gauge mediation):

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$$m_{gaugino} \sim N_{10} \cdot \frac{\alpha}{4\pi}\Lambda$$

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$$m^2_{scalar} = m^2_{mGM} - q \cdot \frac{M^4_{\cancel{SUSY}}}{M^2_{U(1)}}$$

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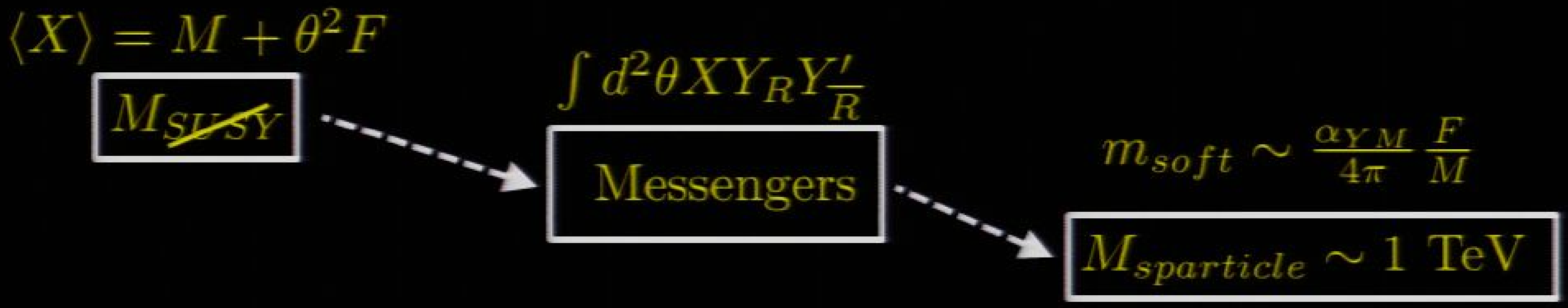

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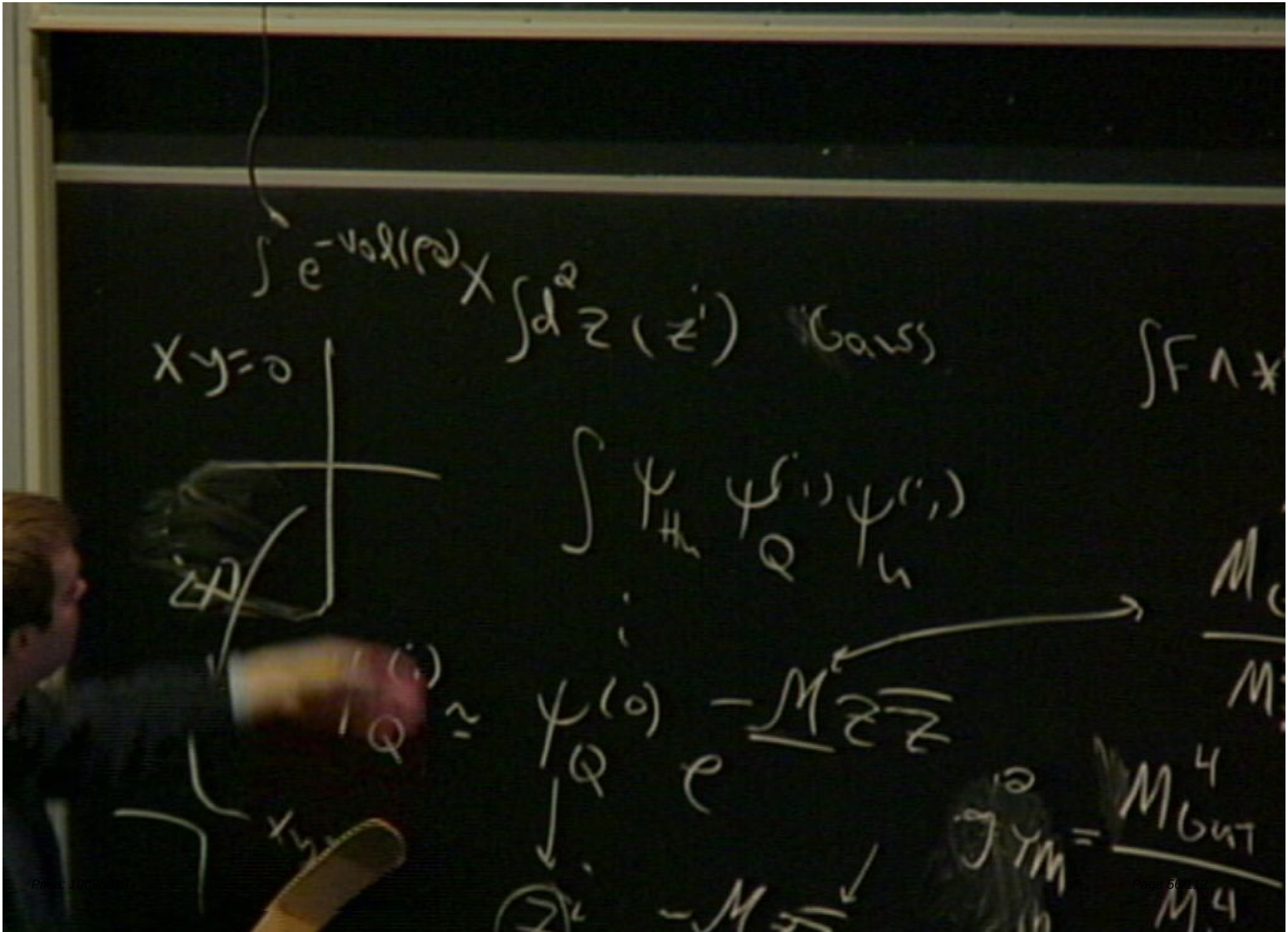
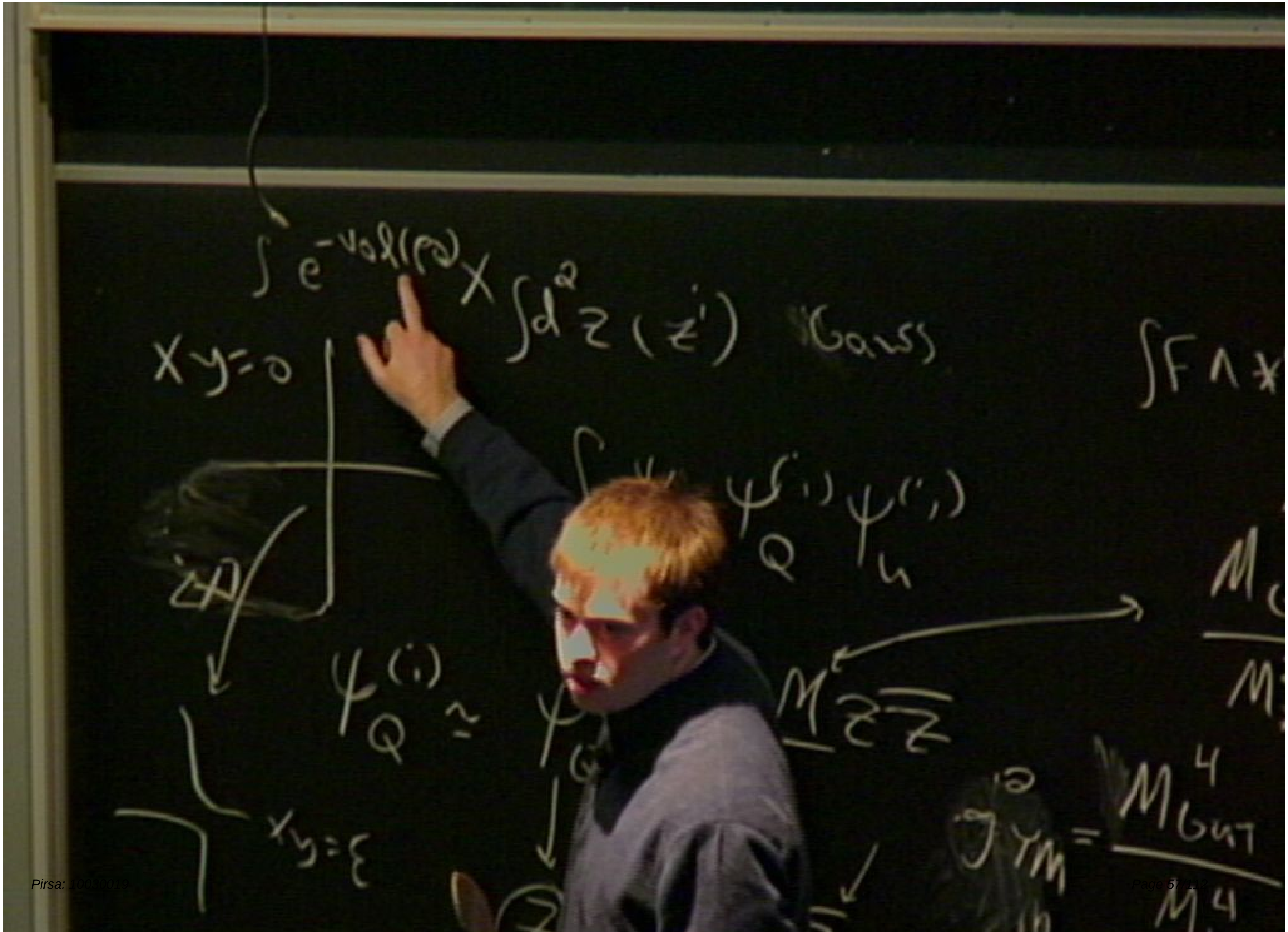
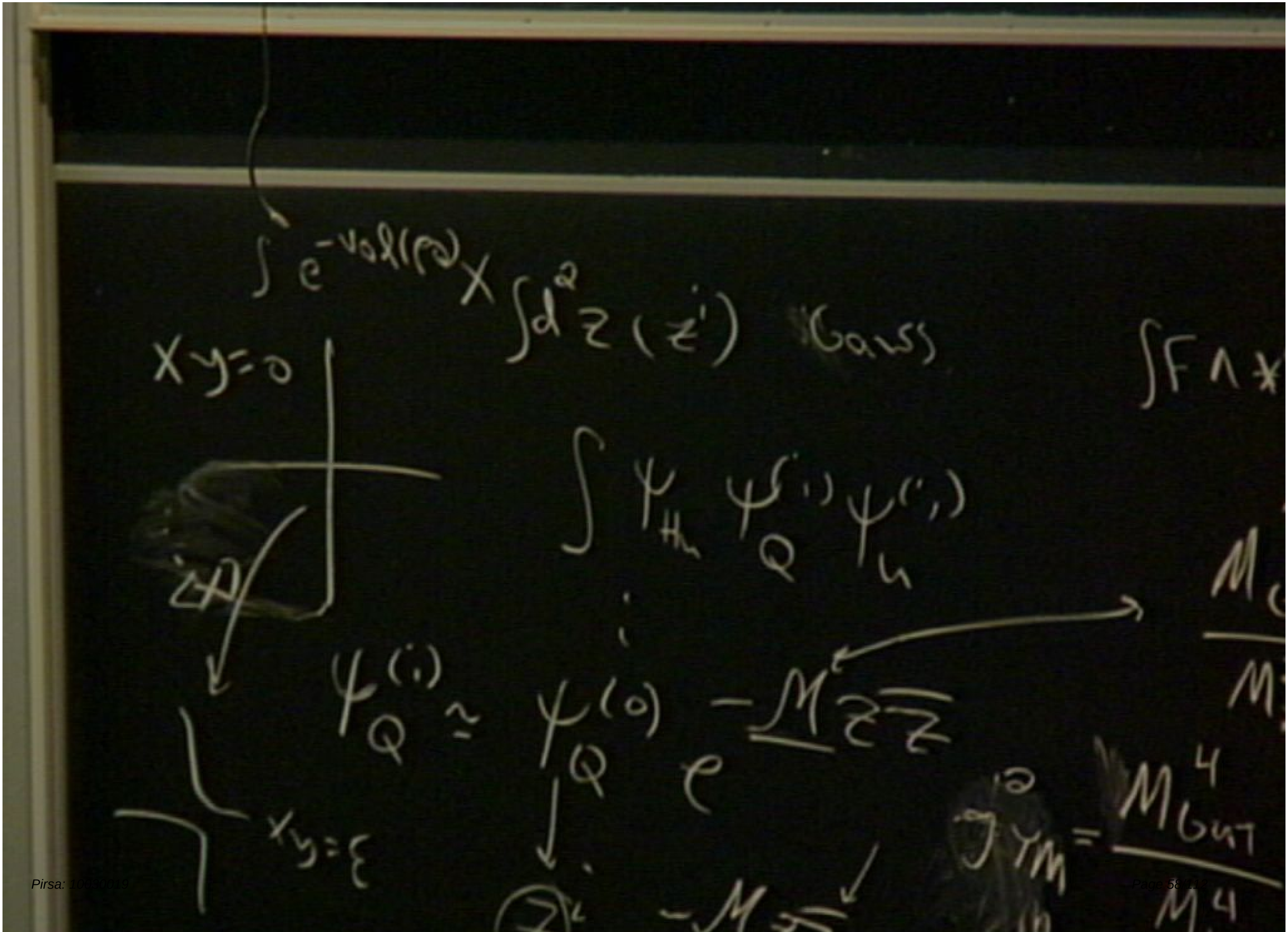

$\int e^{-\mathrm{vol}(\Sigma)} \times \int d^2 z\,(z^i)$ Gauss
$xy=0$
$\int F \wedge *$
$\int \psi_{H_u} \psi_Q^{(i)} \psi_u^{(j)}$
$\psi_Q^{(i)} \simeq \psi_Q^{(0)} e^{-M z\bar{z}}$
z^i
$-M z\bar{z}$
$\frac{M}{M}$
$g_{YM}^2 = \frac{M_{GUT}^4}{M_*^4}$


∫ e^{-vol(Σ)} × ∫ d²z (z')
Gauss
∫F∧*
xy=0
ψ_Q(·,·) ψ_u(·,·)
ψ_Q(·,·) ≃ ψ_u
M Z Z̄
xy=ε
g²_YM = M⁴_GUT / M⁴



$\int e^{-\mathrm{vol}(\Sigma)} \times \int d^2 z \, (z^i)$ Gauss

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$\int \psi_{H_u} \psi_Q^{(i,j)} \psi_u^{(i,j)}$

$\psi_Q^{(i,j)} \simeq \psi_Q^{(0)} e^{-\underline{M} z \bar{z}}$

$\frac{M}{M}$

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$xy = \varepsilon$

$(z)^i - M z\bar{z}$

S~~U~~SY

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Energy Scales

$\langle X \rangle = M + \theta^2 F$

$\sqrt{F} =$ ~~SUSY~~ scale

$M =$ Global $U(1)_{PQ}$ symm. breaking scale $= f_{axion}$

μ term from: $\int d^4\theta \frac{X^\dagger H_u H_d}{\Lambda_{UV}} \dashrightarrow F \sim 10^{17}\ \mathrm{GeV}^2$

$m_{soft} \sim \frac{\alpha_{YM}}{4\pi}\frac{F}{M} \sim 0.1 - 1\ \mathrm{TeV} \dashrightarrow M \sim 10^{12}\ \mathrm{GeV}$

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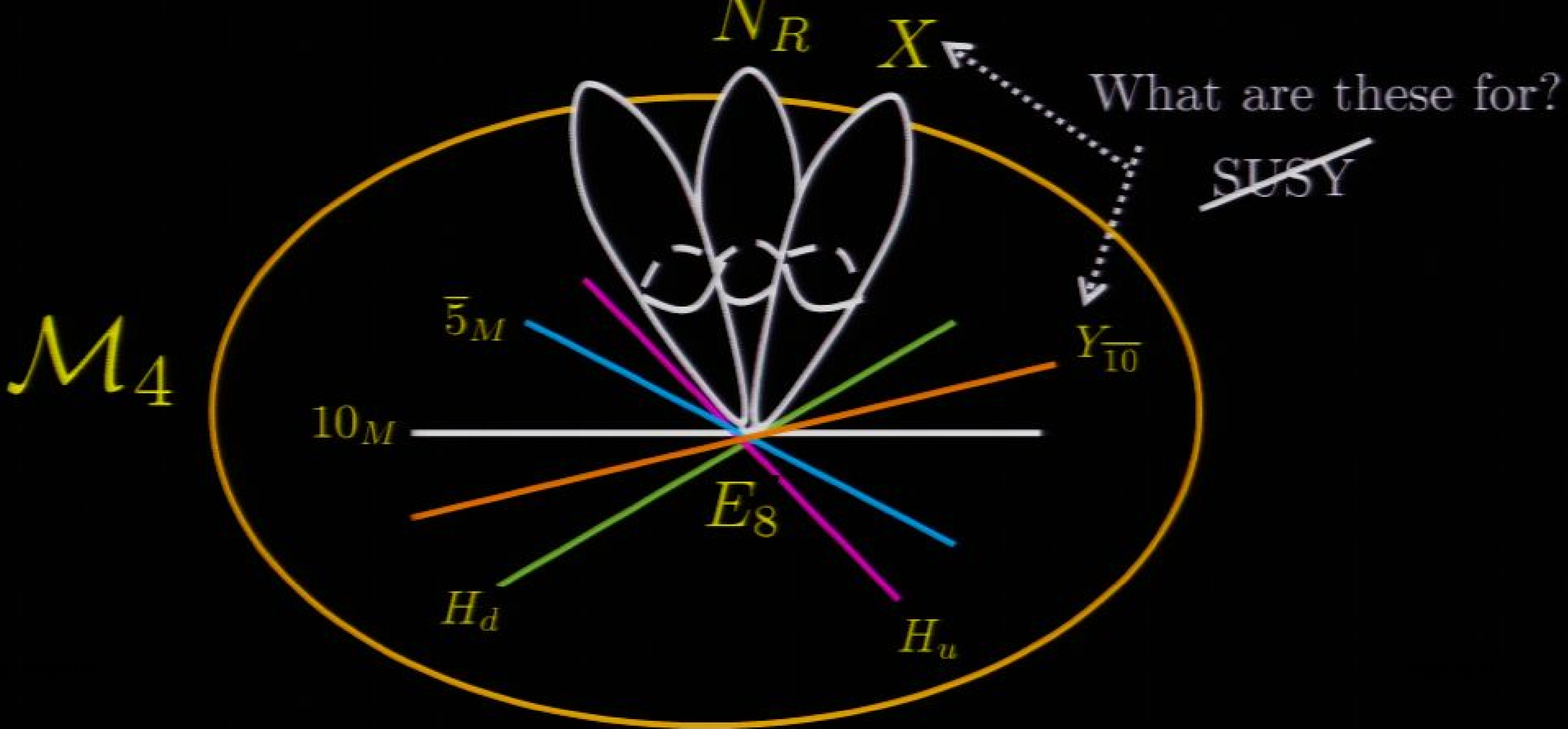

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F-GUT Parameters

Two Continuous Parameters:

$$\Lambda \equiv \frac{F}{M} \sim 100 \text{ TeV}$$

$$\Delta_{PQ} \sim O(100) \text{ GeV}$$

One Discrete Parameter: $N_{10} = 1$ or 2

Fixed Parameters:

$$M_{mess} \sim 10^{12} \text{ GeV}$$

$$\tan\beta = \frac{v_u}{v_d} \sim 20 - 30$$

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The LSP

LSP = Gravitino: $m_{Gravitino} \sim \frac{M^2_{\cancel{SUSY}}}{M_{pl}} \sim 10 - 100$ MeV

NLSP decays to Gravitino: $\Gamma(\widetilde{\psi} \rightarrow \widetilde{G} + \psi) \sim \frac{m^5_{NLSP}}{M^4_{\cancel{SUSY}}}$

$\Rightarrow$ NLSP is quasi-stable: $\tau_{NLSP} \sim 1$ second to an hour

The NLSP

Typical Candidates: Stau $\widetilde{\tau}_1$ and Bino-like $\widetilde{\chi}_1^0$

Note: $\widetilde{\tau}_1$ = scalar and $\widetilde{\chi}_1^0$ = gaugino

Messengers: $\frac{m_{scalar}}{m_{gaugino}} \propto \frac{1}{\sqrt{\#\text{ of messengers}}}$

Δ_{PQ} Lowers all scalar masses: $m^2_{soft} = m^2_{mGM} - q\Delta^2_{PQ}$

$\Rightarrow$ NLSP = Stau though Bino is possible when $N_{10} < 2$

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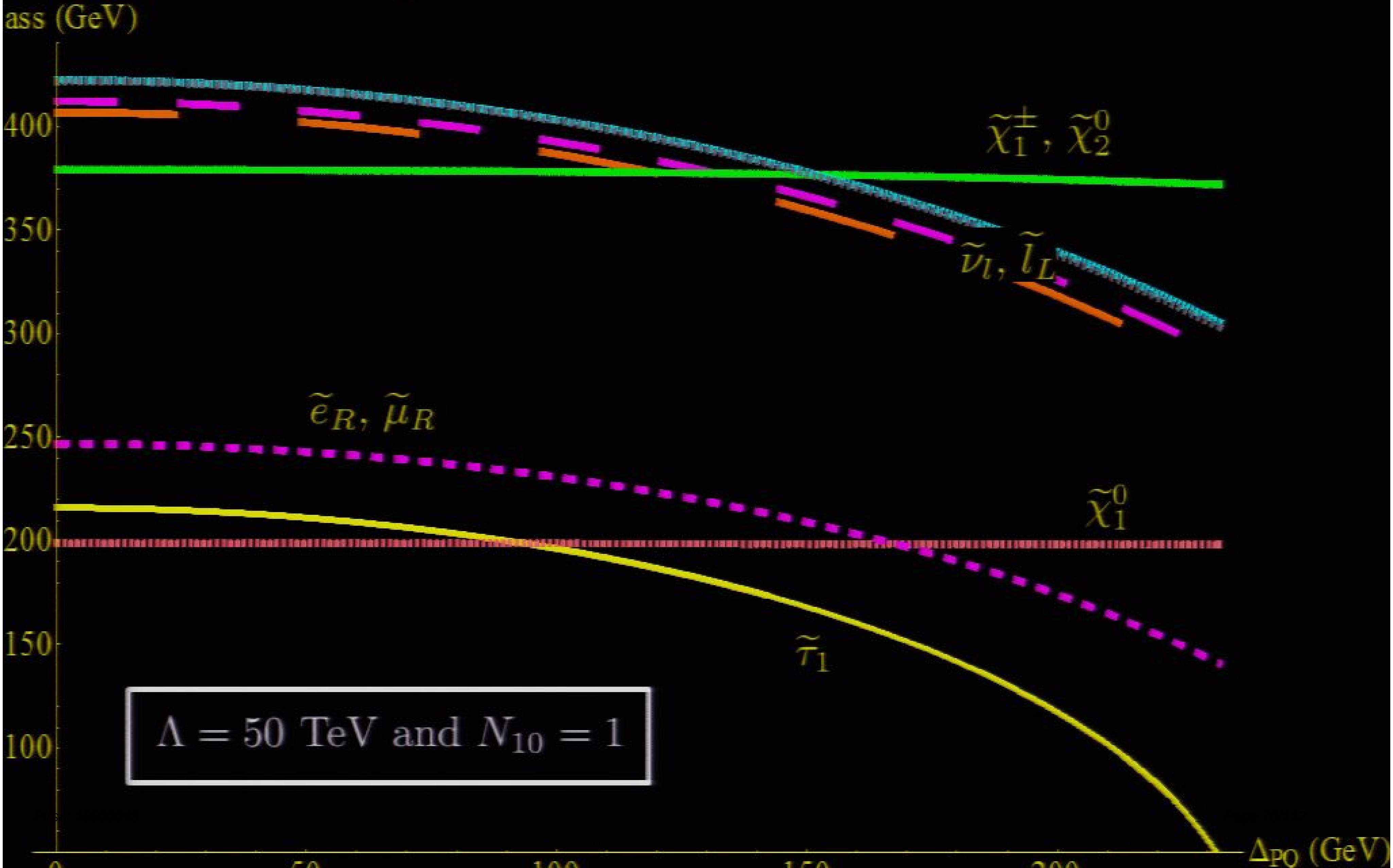
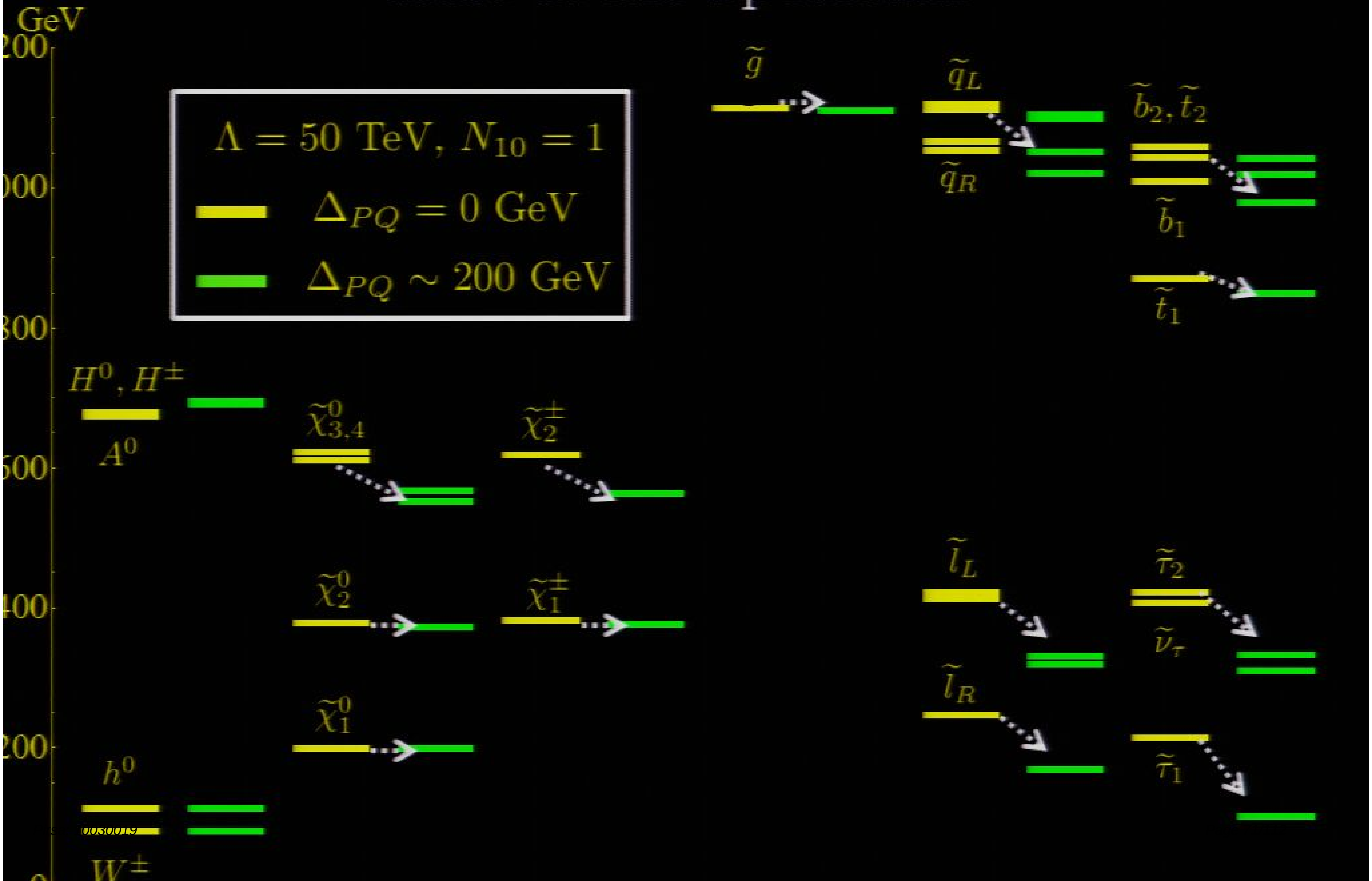
Δ_{PQ} and Slepton Mass



Rest of the Spectrum



Differences From Other Models

Although a deformation of mGMSB, it is a narrow and less studied region of parameter space.

Compare with:
minimal gauge mediation – mGMSB
minimal supergravity – mSUGRA

	low scale mGMSB	F-GUT	mSUGRA
$M_{\cancel{SUSY}}$	10^5 GeV	$10^8 - 10^9$ GeV	10^{11} GeV
LSP	Gravitino	Gravitino	$\widetilde{\chi}_1^0$
NLSP	Short-Lived $\widetilde{\chi}_1^0$	Long-Lived $\widetilde{\tau}_1$	Short-Lived $\widetilde{\tau}_1$
signature	2 High p_T Photons + Missing E_T	Charged Track	Missing E_T

Roadmap

- ~~SUSY~~ and Stau NLSP
- Stau Search

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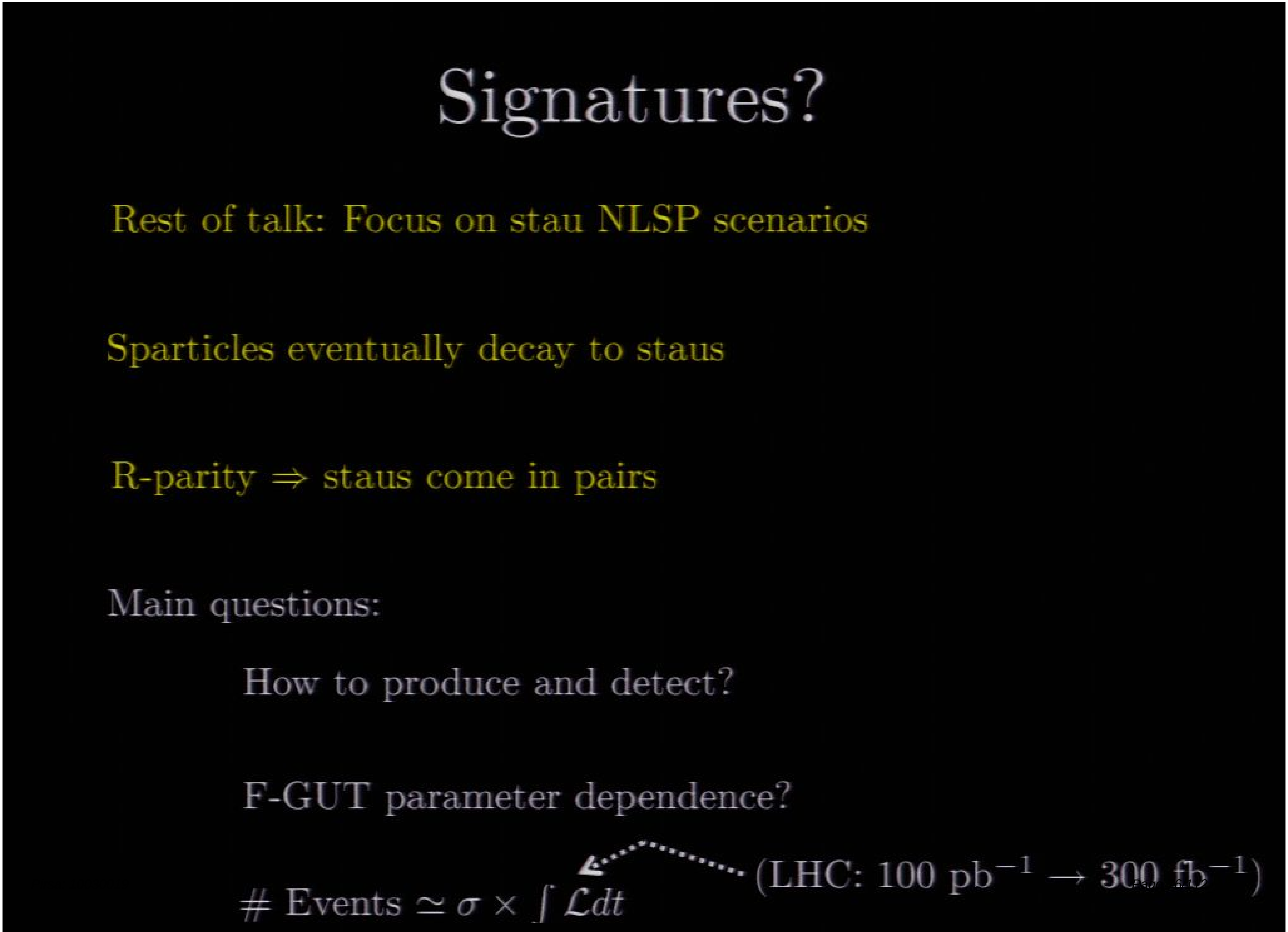


Signatures?

Rest of talk: Focus on stau NLSP scenarios

Sparticles eventually decay to staus

R-parity ⇒ staus come in pairs

Main questions:

- How to produce and detect?
- F-GUT parameter dependence?

\# Events $\simeq \sigma \times \int \mathcal{L} dt$ (LHC: $100\ \text{pb}^{-1} \rightarrow 300\ \text{fb}^{-1}$)

Simulation

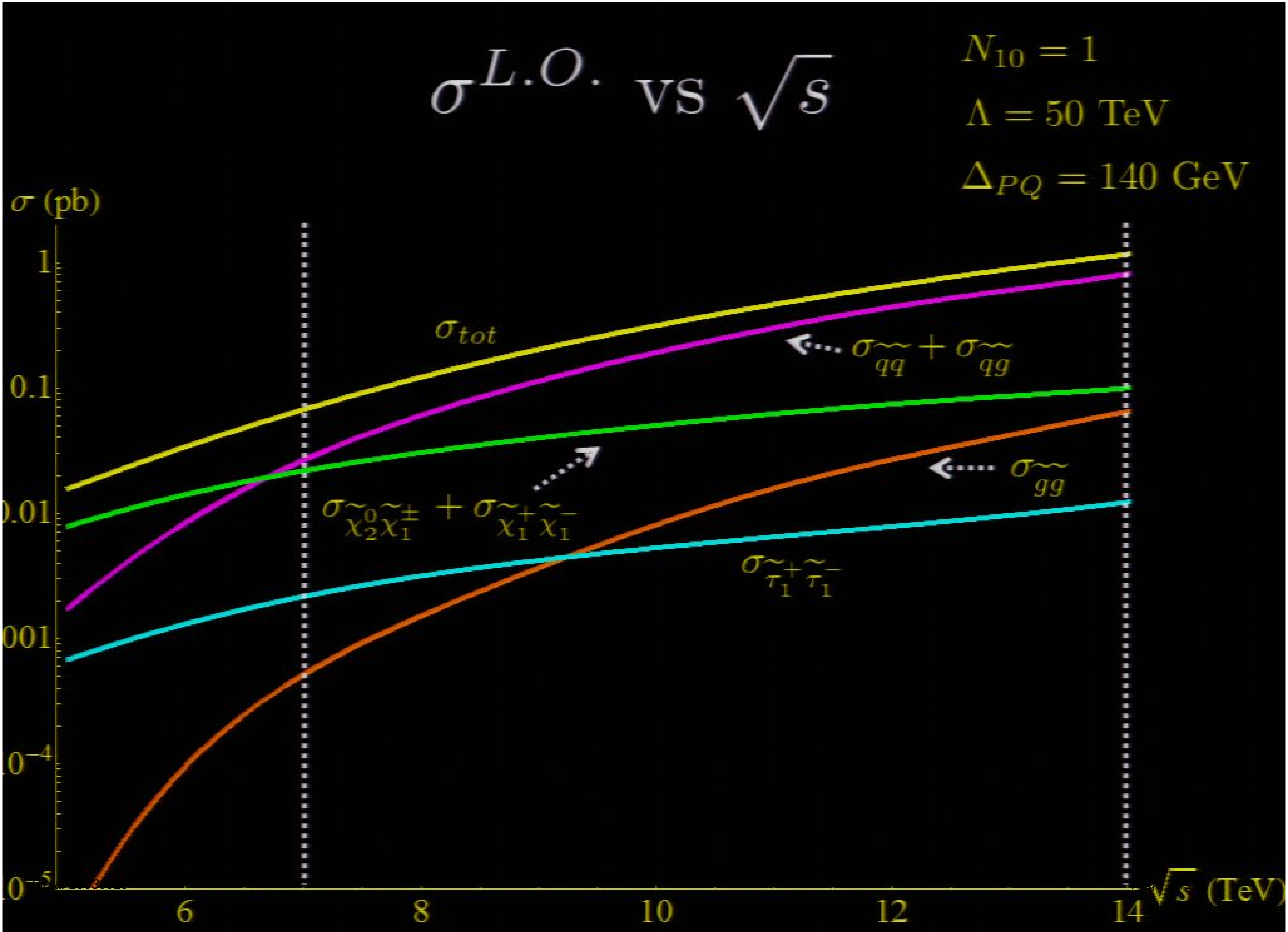
Simulate 10,000 SUSY events in `PYTHIA` at $\sqrt{s} = 7$ and 14 TeV

based on parton-level objects

Leptons:
- $p_T > 10$ GeV and $|\eta| < 2.5$
- $E_T < 5$ GeV in cone with $\Delta R < 0.4$

Tau Jets: $P_T > 20$ GeV, $|\eta| < 2.5$ with efficiency $\varepsilon_\tau = 0.5$

Also crudely mimic stau momentum and velocity smearing

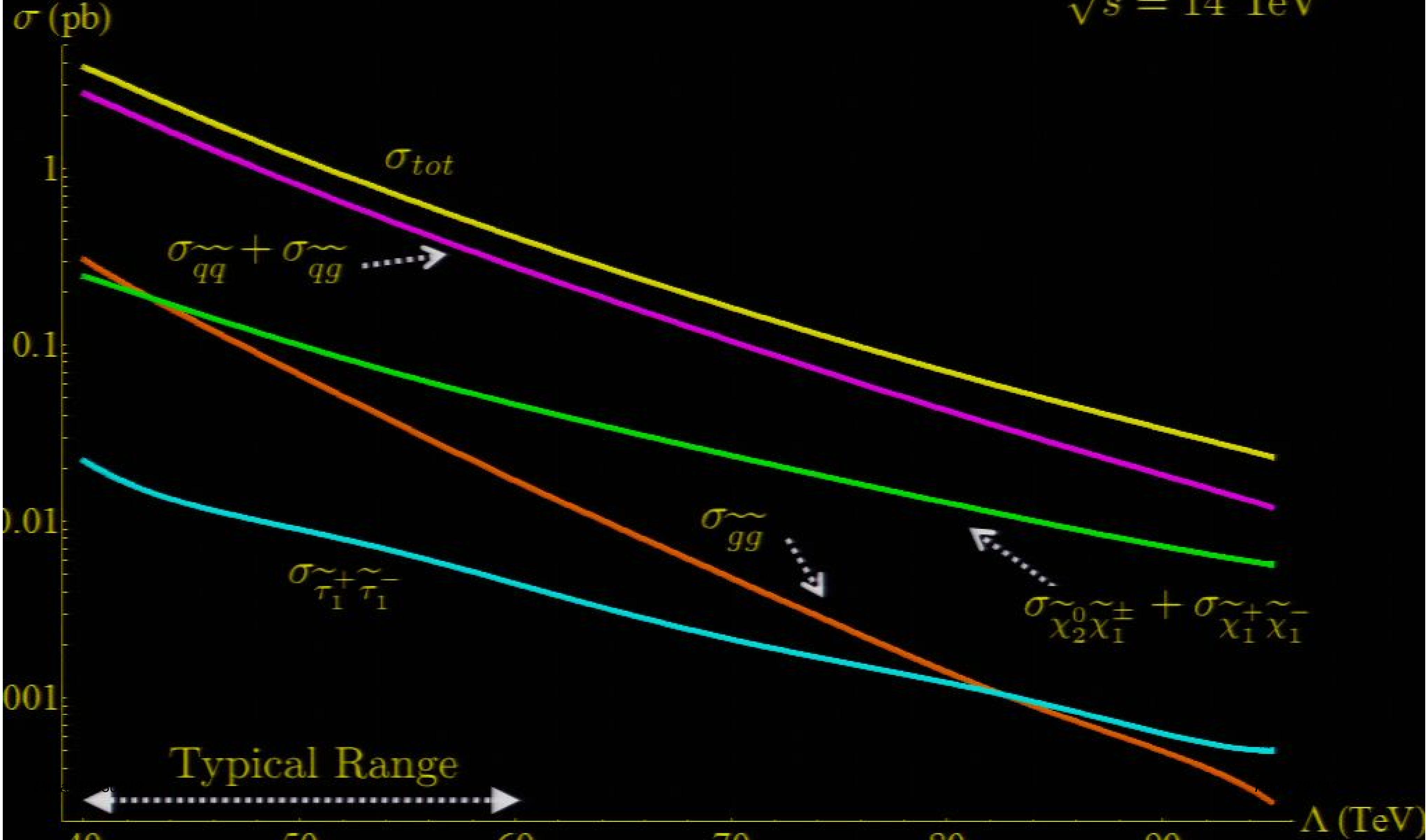

$\sigma^{L.O.}$ vs $\sqrt{s}$
$N_{10} = 1$
$\Lambda = 50$ TeV
$\Delta_{PQ} = 140$ GeV
σ (pb)
1
0.1
0.01
001
10^{-4}
10^{-5}
6
8
10
12
14
$\sqrt{s}$ (TeV)
σ_{tot}
$\sigma_{\tilde{q}\tilde{q}} + \sigma_{\tilde{q}\tilde{g}}$
$\sigma_{\tilde{g}\tilde{g}}$
$\sigma_{\tilde{\chi}_2^0\tilde{\chi}_1^\pm} + \sigma_{\tilde{\chi}_1^+\tilde{\chi}_1^-}$
$\sigma_{\tilde{\tau}_1^+\tilde{\tau}_1^-}$

$\sigma^{L.O.}$ vs Λ

$N_{10} = 1$

$\Delta_{PQ} = 140$ GeV

$\sqrt{s} = 14$ TeV



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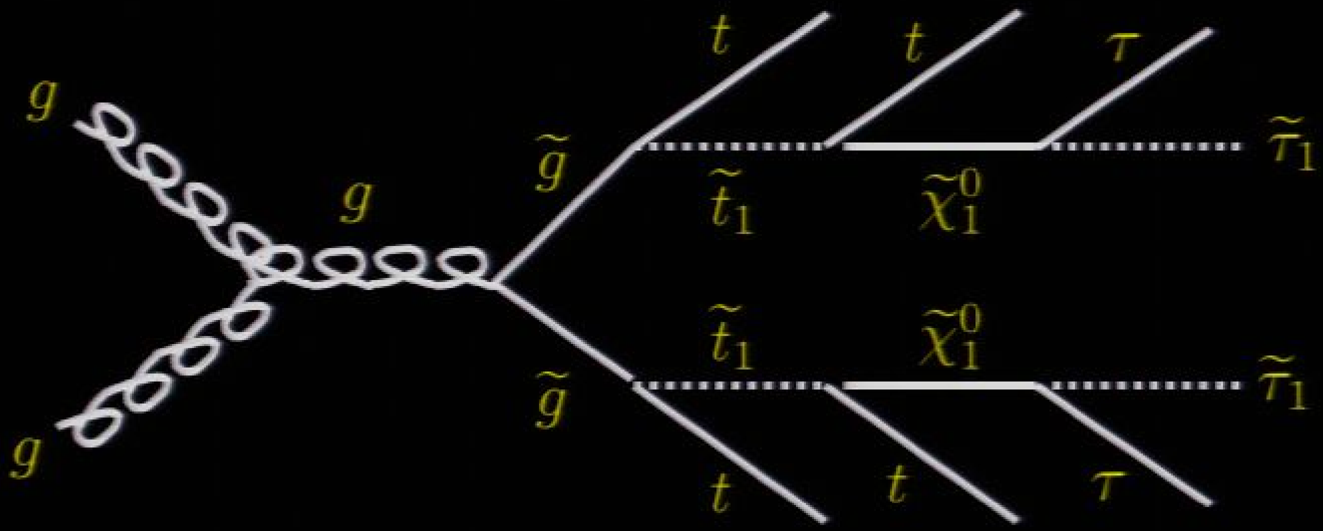
(LHC: $100\ \mathrm{pb}^{-1} \rightarrow 300\ \mathrm{fb}^{-1}$)

$$\#\ \text{Events} \simeq \sigma \times \int \mathcal{L} dt$$

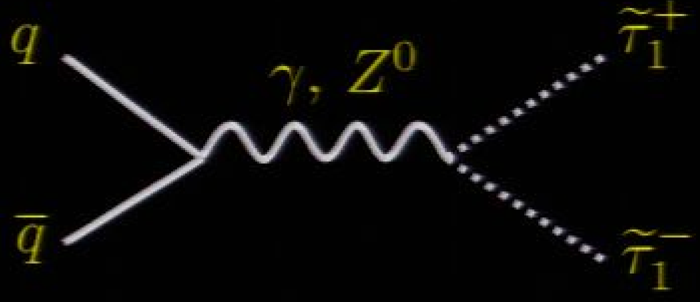
Generating Staus at the LHC

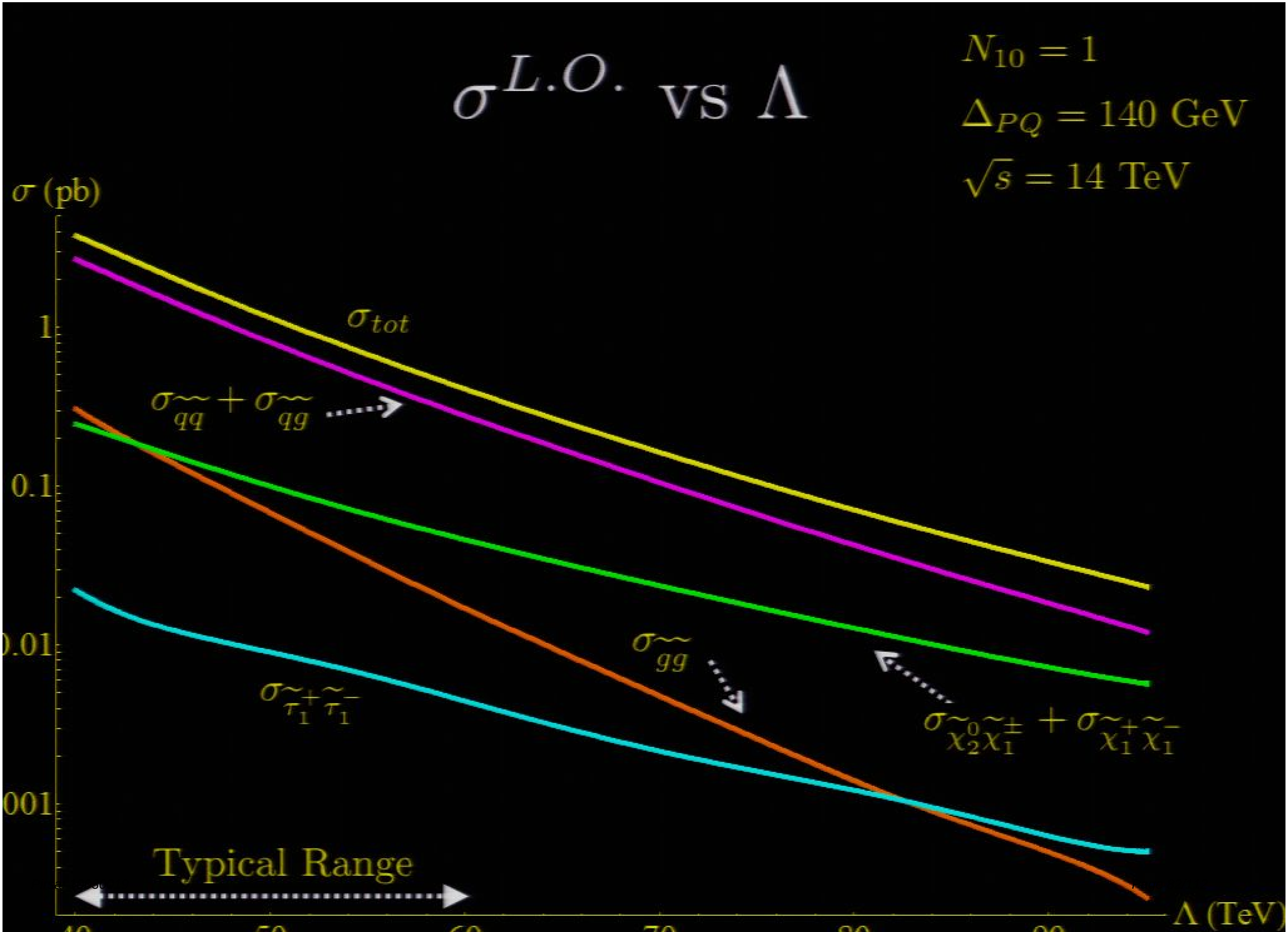
Every SUSY process ends with $\widetilde{\tau}_1$'s, for example:

Cascade Decays:



Pair Production (Drell-Yan):




$\sigma^{L.O.}$ vs Λ
$N_{10} = 1$
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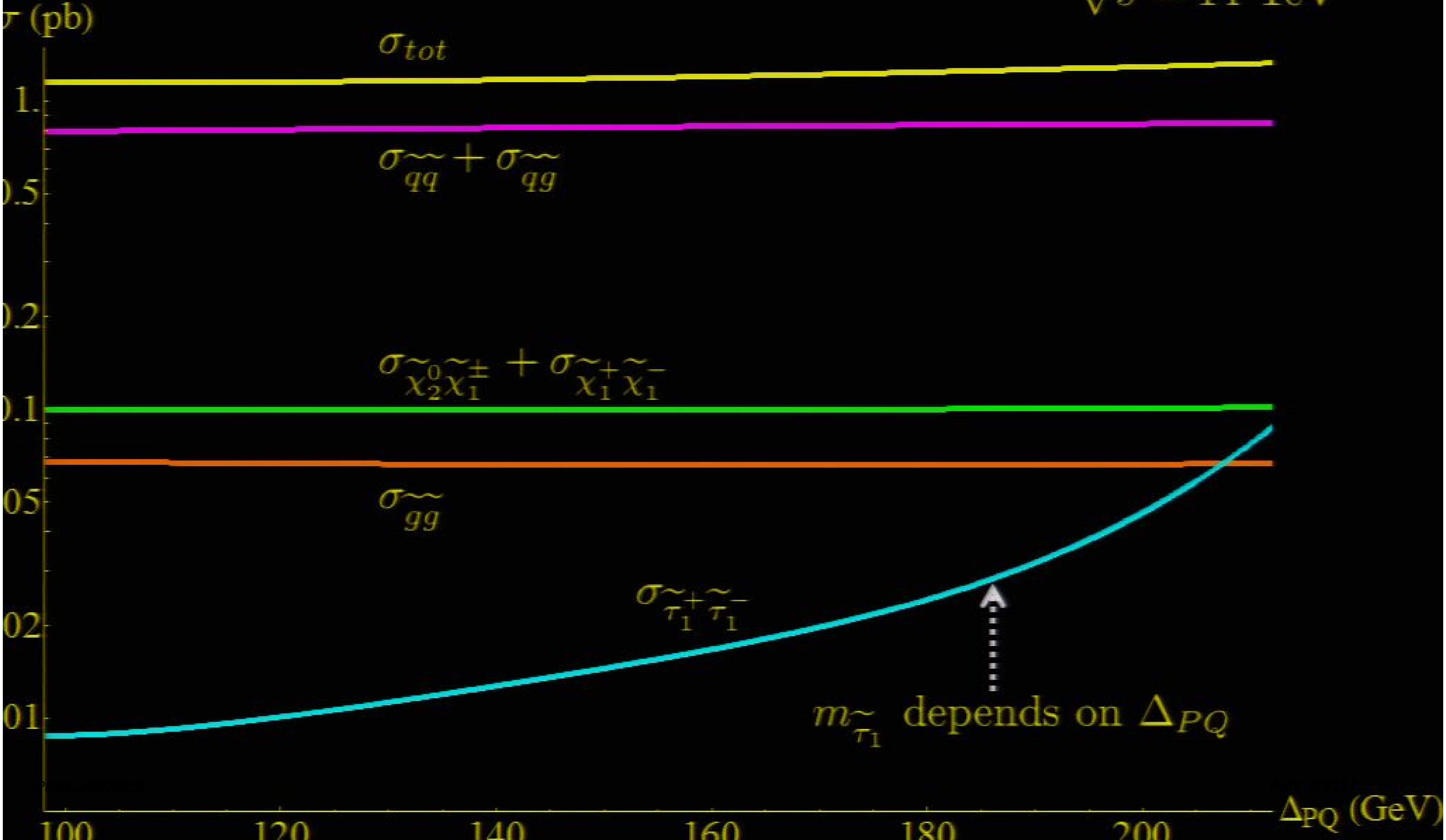
$\sqrt{s} = 14$ TeV
σ (pb)
1
0.1
0.01
001
σ_{tot}
$\sigma_{\tilde{q}\tilde{q}} + \sigma_{\tilde{q}\tilde{g}}$
$\sigma_{\tilde{g}\tilde{g}}$
$\sigma_{\tilde{\tau}_1^+\tilde{\tau}_1^-}$
$\sigma_{\tilde{\chi}_2^0\tilde{\chi}_1^\pm} + \sigma_{\tilde{\chi}_1^+\tilde{\chi}_1^-}$
Typical Range
Λ (TeV)

$\sigma^{L.O.}$ vs Δ_{PQ}

$N_{10} = 1$
$\Lambda = 50$ TeV
$\sqrt{s} = 14$ TeV



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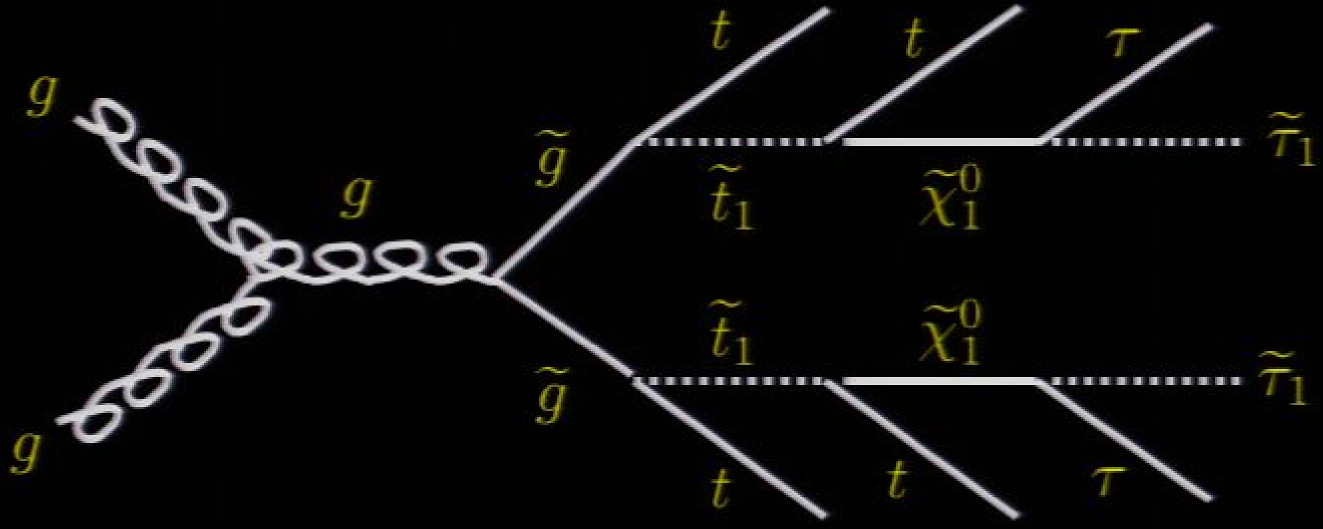

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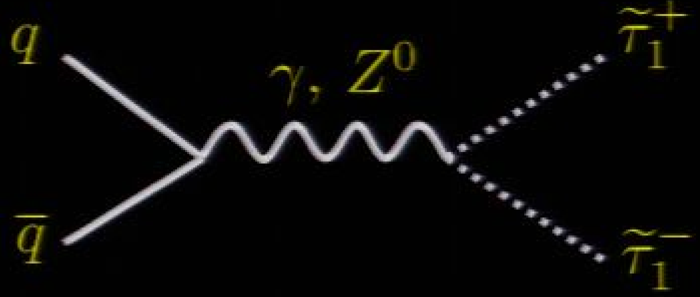
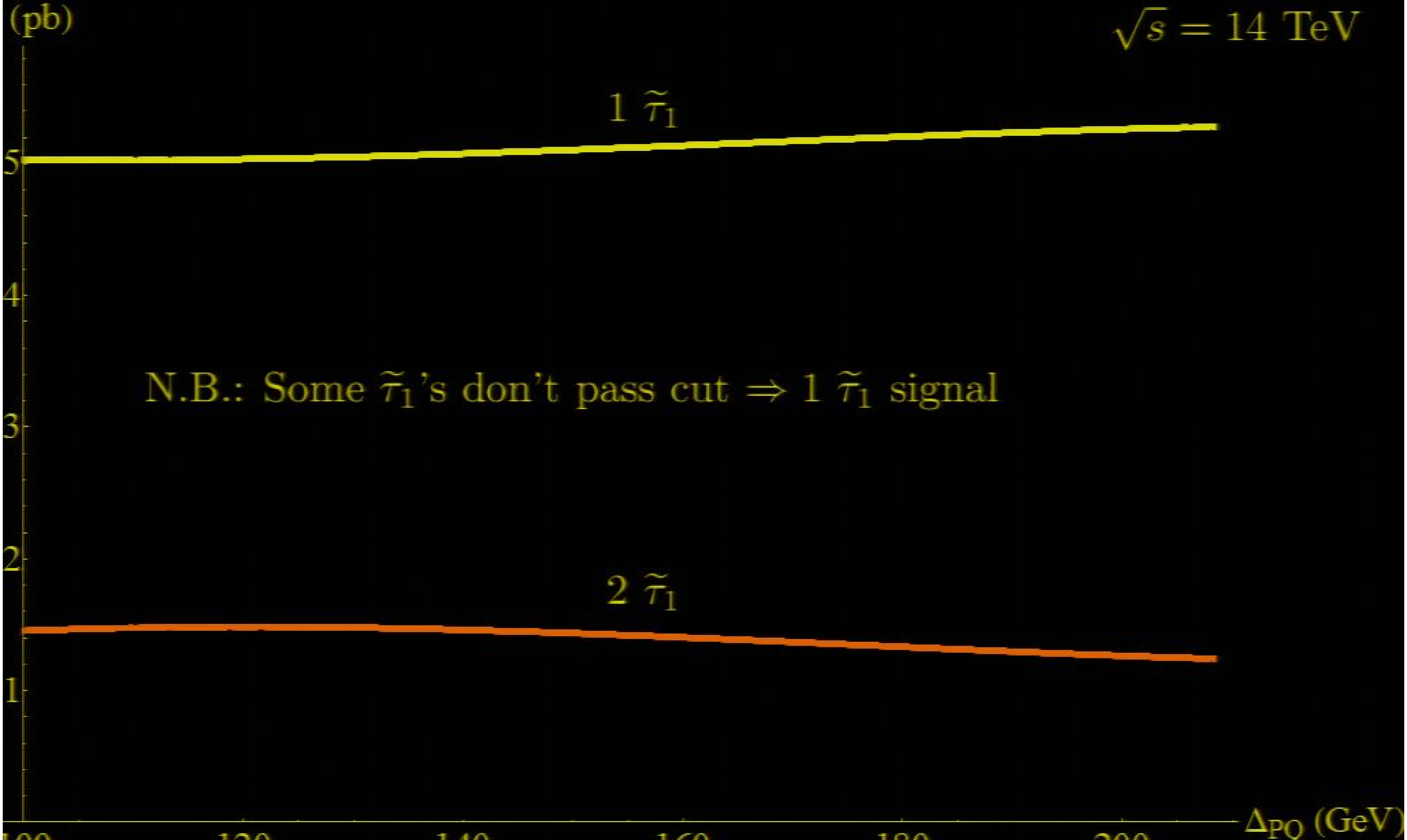


Inclusive $\widetilde{\tau}_1$'s

$N_{10} = 1$

$\Lambda = 50$ TeV

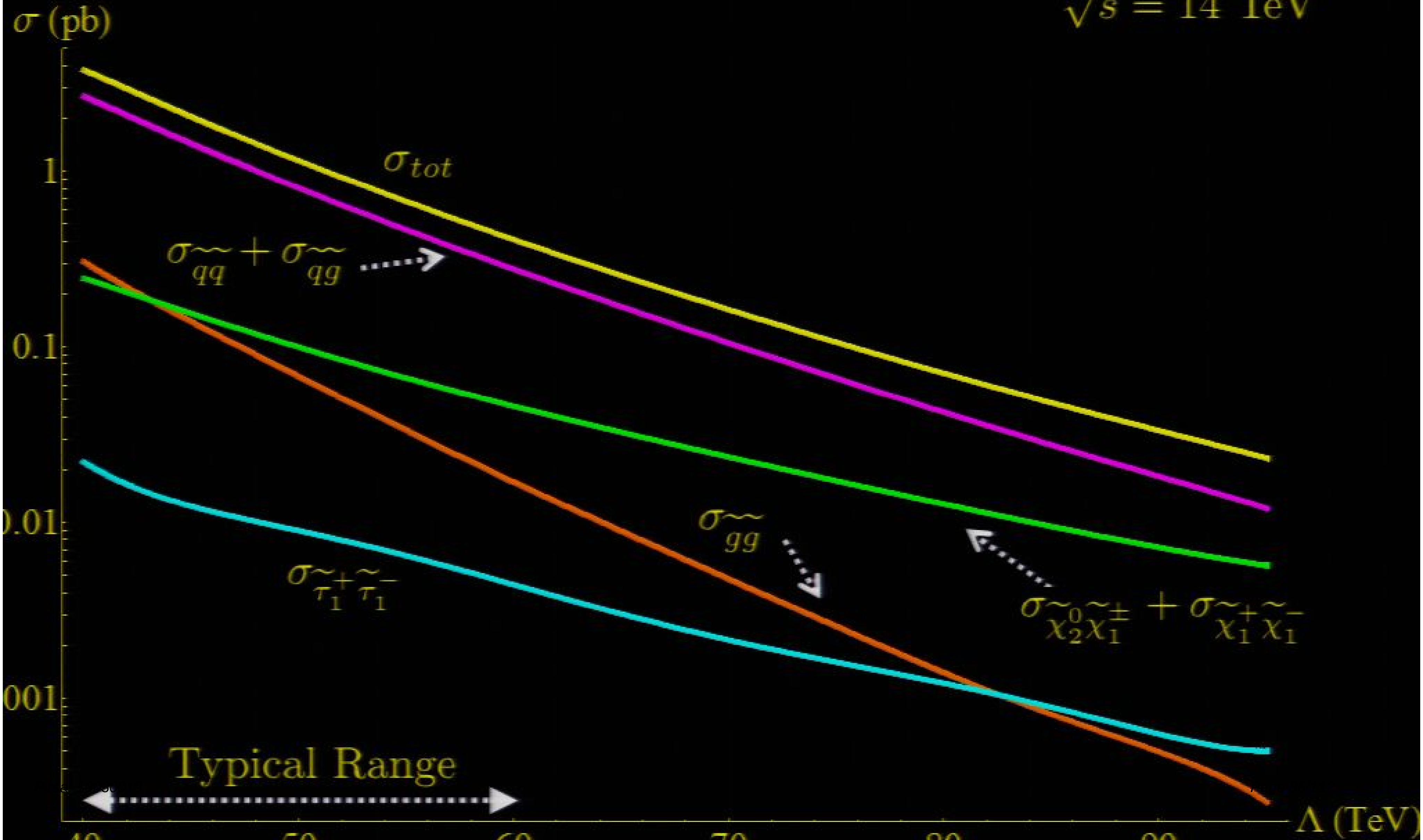
$\sqrt{s} = 14$ TeV



N.B.: Some $\widetilde{\tau}_1$'s don't pass cut $\Rightarrow$ 1 $\widetilde{\tau}_1$ signal

$\sigma^{L.O.}$ vs Λ

$N_{10} = 1$
$\Delta_{PQ} = 140$ GeV
$\sqrt{s} = 14$ TeV



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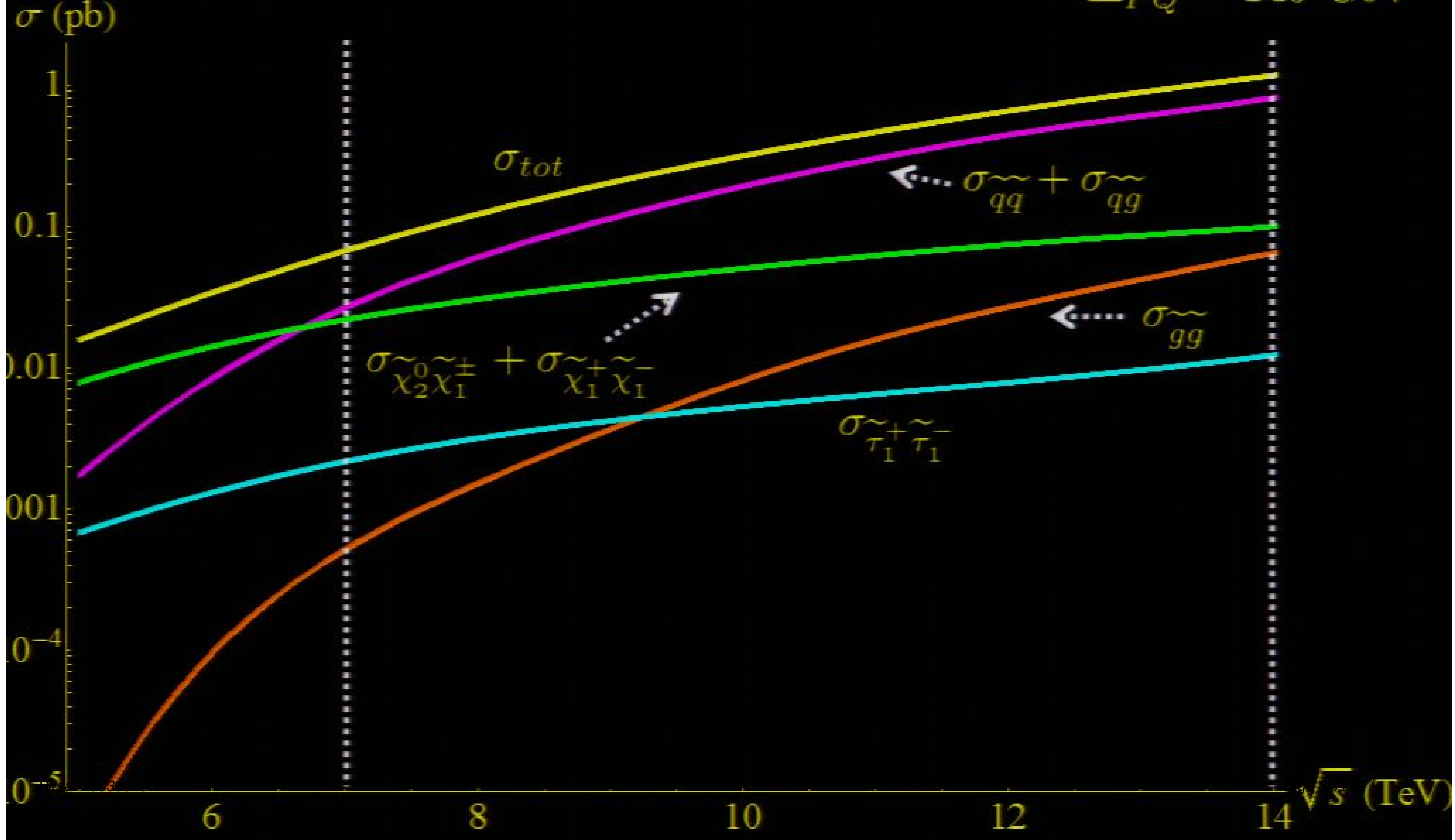

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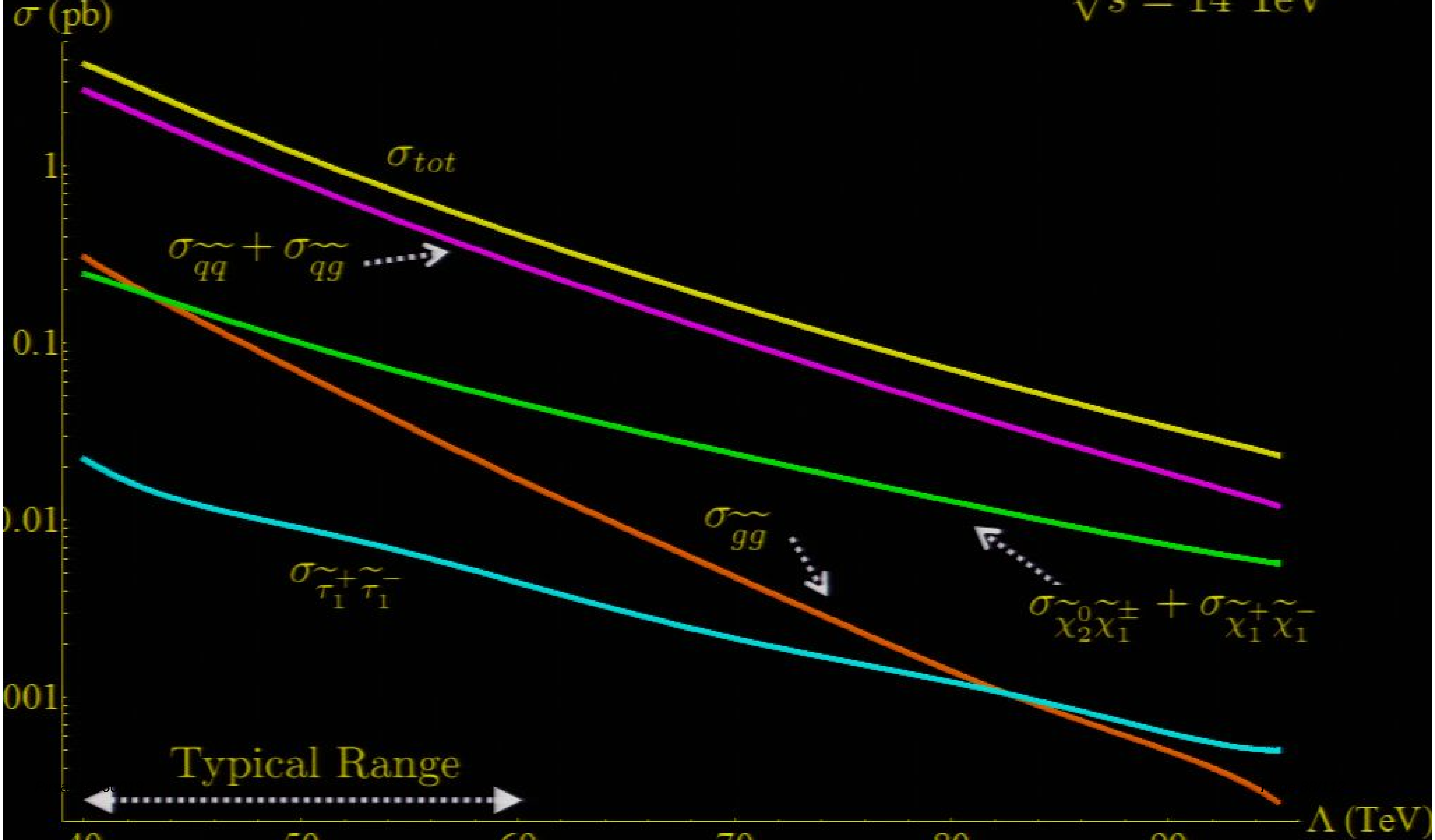

$\sigma^{L.O.}$ vs Δ_{PQ}

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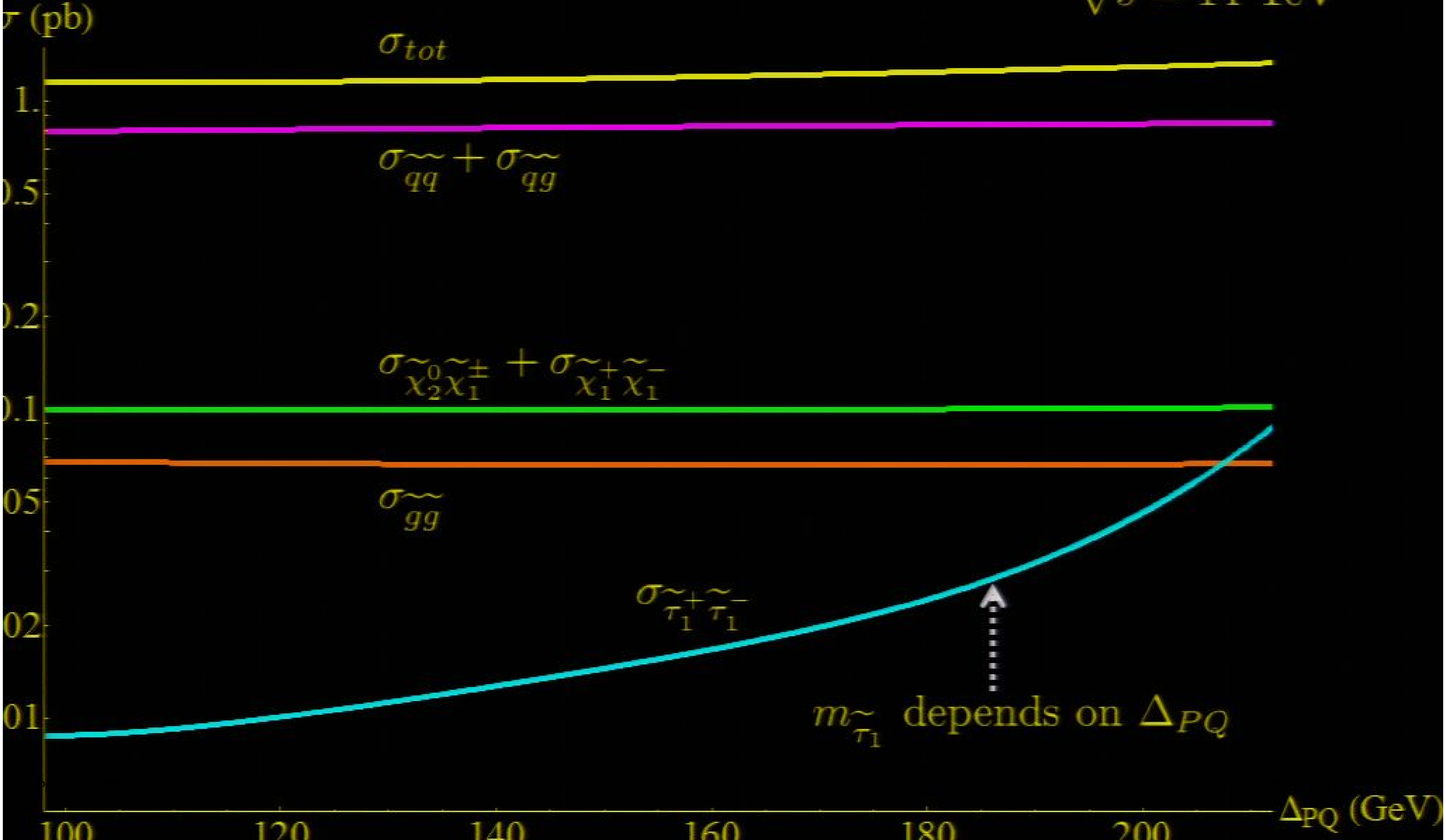
$\Lambda = 50$ TeV

$\sqrt{s} = 14$ TeV



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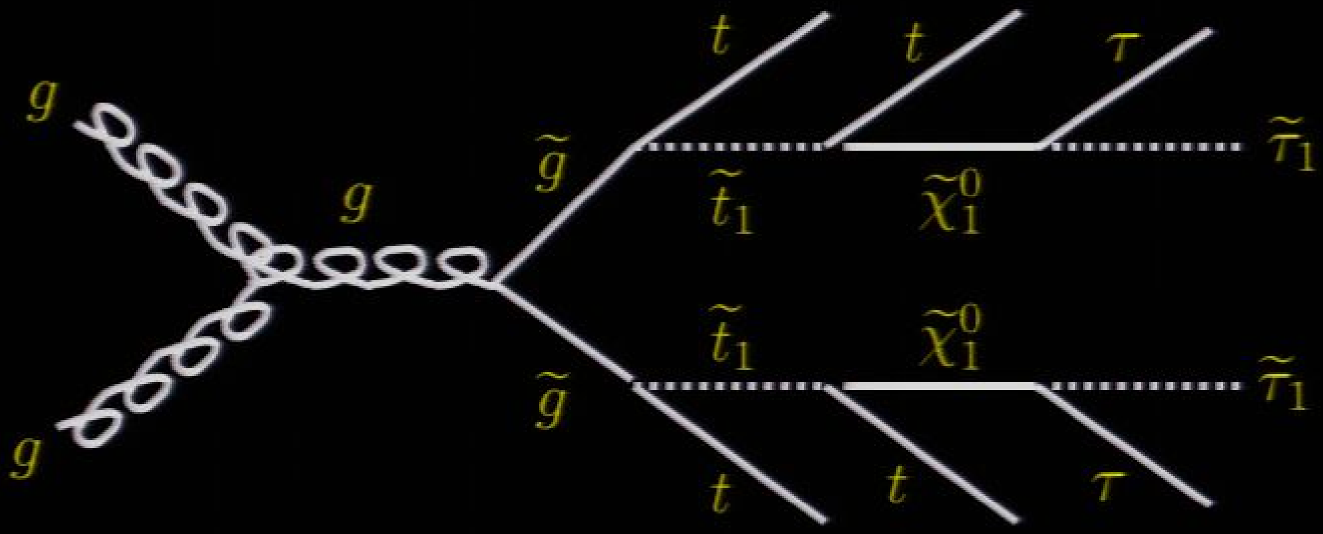

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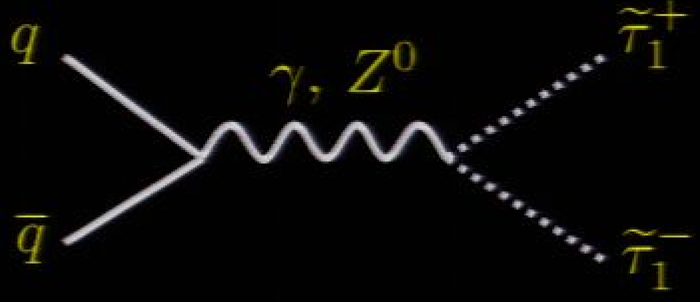


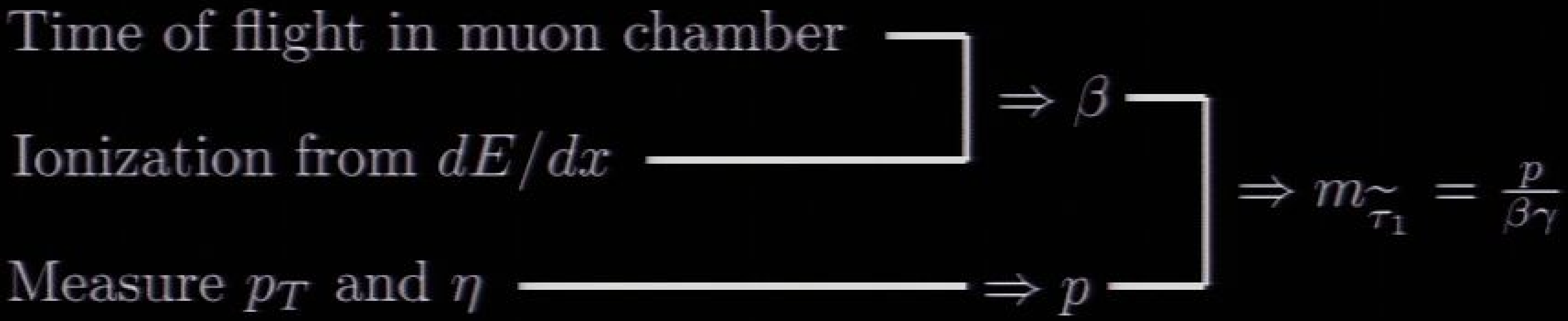
Finding Staus

Staus are heavy, charged and quasi-stable i.e. “heavy muon”

Low Standard Model Background

c.f. Martin Wells ’97,
Hinchliffe Paige ’98,
Ambrosiano et al. ’00
Ellis et al. ’06, Ibe Kitano ’07
ATLAS TDR, CMS TDR,...

Stau tracks:



Time of flight in muon chamber

Ionization from dE/dx

$\Rightarrow \beta$

Measure p_T and η

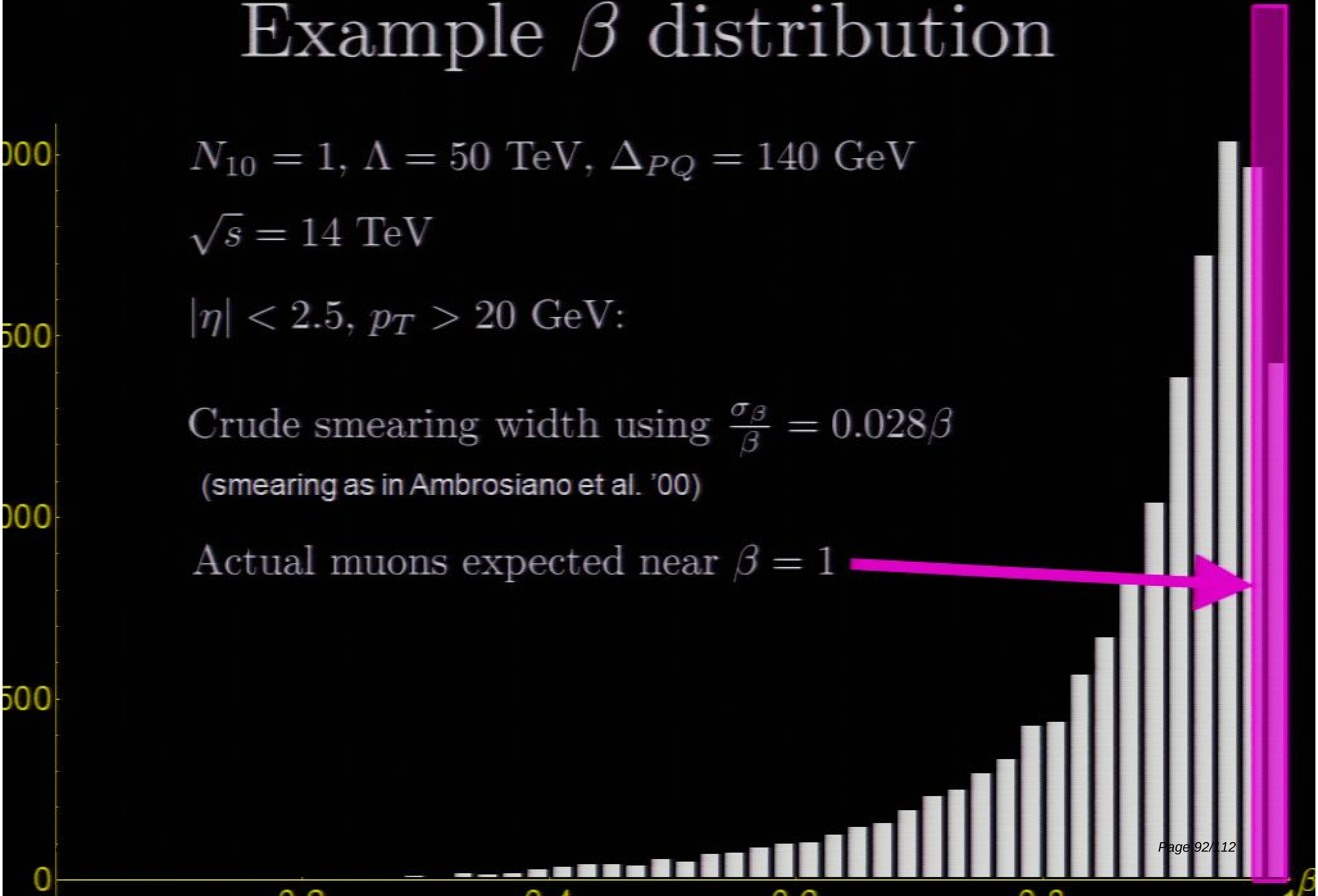
$\Rightarrow p$

$\Rightarrow m_{\tilde{\tau}_1} = \frac{p}{\beta\gamma}$

We shall identify stau as:

$$p_T > 20 \text{ GeV}, |\eta| < 2.5 \text{ and } 0.67 < \beta < 0.91 \lesssim \beta_{muon}$$

Example β distribution



$N_{10} = 1$, $\Lambda = 50$ TeV, $\Delta_{PQ} = 140$ GeV

$\sqrt{s} = 14$ TeV

$|\eta| < 2.5$, $p_T > 20$ GeV:

Crude smearing width using $\frac{\sigma_\beta}{\beta} = 0.028\beta$

(smearing as in Ambrosiano et al. '00)

Actual muons expected near $\beta = 1$

Inclusive Channels

All events with 1 or 2 $\widetilde{\tau}_1$'s

$p_T > 20$ GeV, $|\eta| < 2.5$ and $0.67 < \beta < 0.91$

(c.f. Ambrosiano et al. '00)

At least 1 hadronic jet, $p_T > 50$ GeV

Reduces SM Background

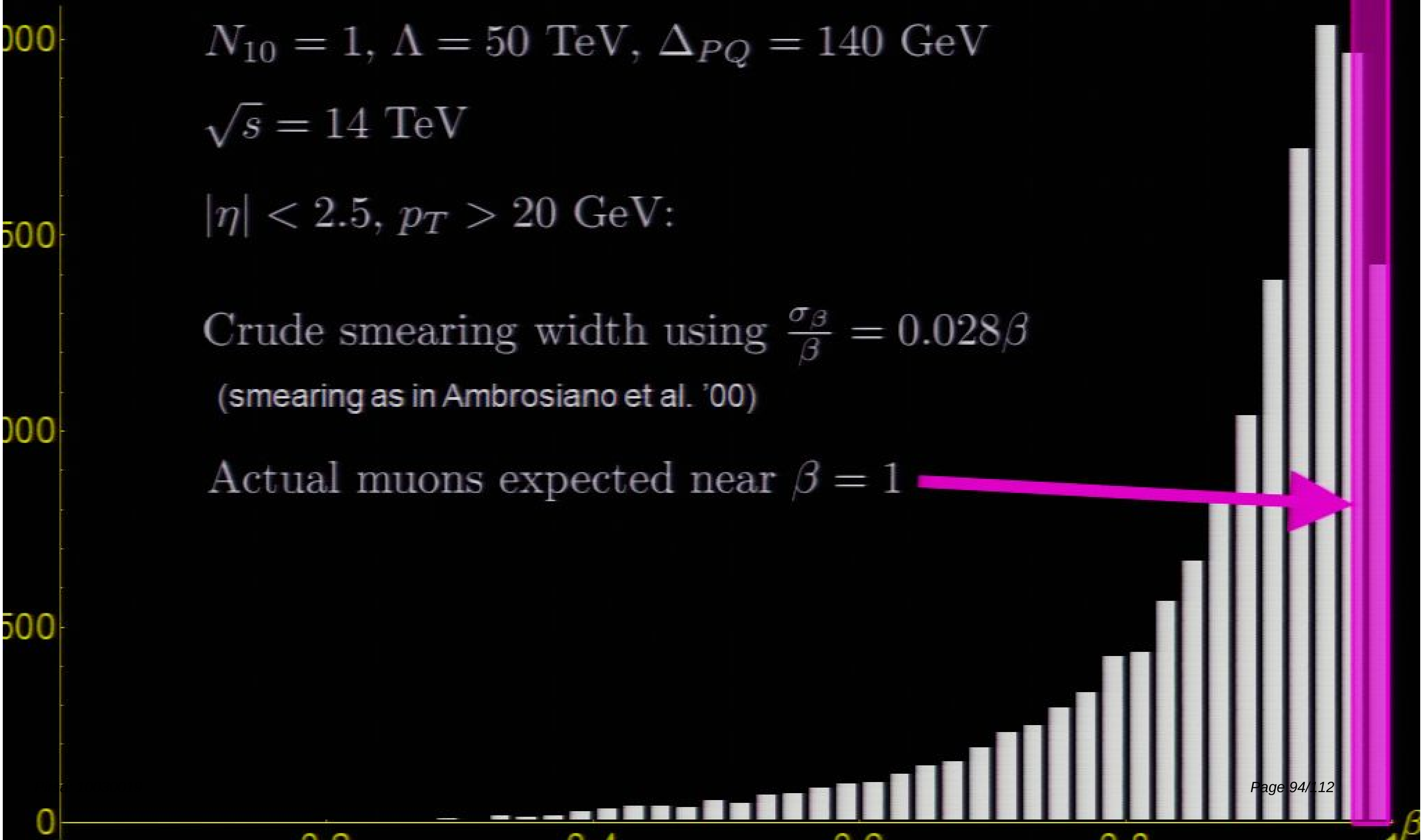
$\sigma^{SM}_{BKG} < 1$ fb

And $E_T^{miss} > 50$ GeV (trigger)

$m_{eff} \equiv \sum p_T^{jet,i} + \sum p_T^{\mu,i} > 800$ GeV

$\sigma_{1\widetilde{\tau}_1} + \sigma_{2\widetilde{\tau}_1} \sim O(1)$ pb (decreases as Λ increases)

Example β distribution



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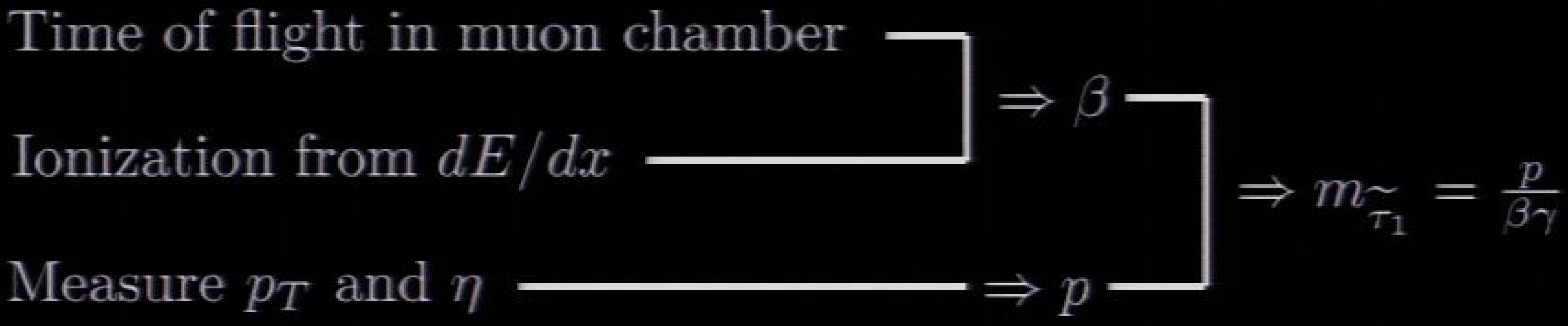
c.f. Martin Wells ’97,
Hinchliffe Paige ’98,
Ambrosiano et al. ’00
Ellis et al. ’06, Ibe Kitano ’07
ATLAS TDR, CMS TDR,...

Stau tracks:



Time of flight in muon chamber

Ionization from dE/dx

$\Rightarrow \beta$

Measure p_T and η

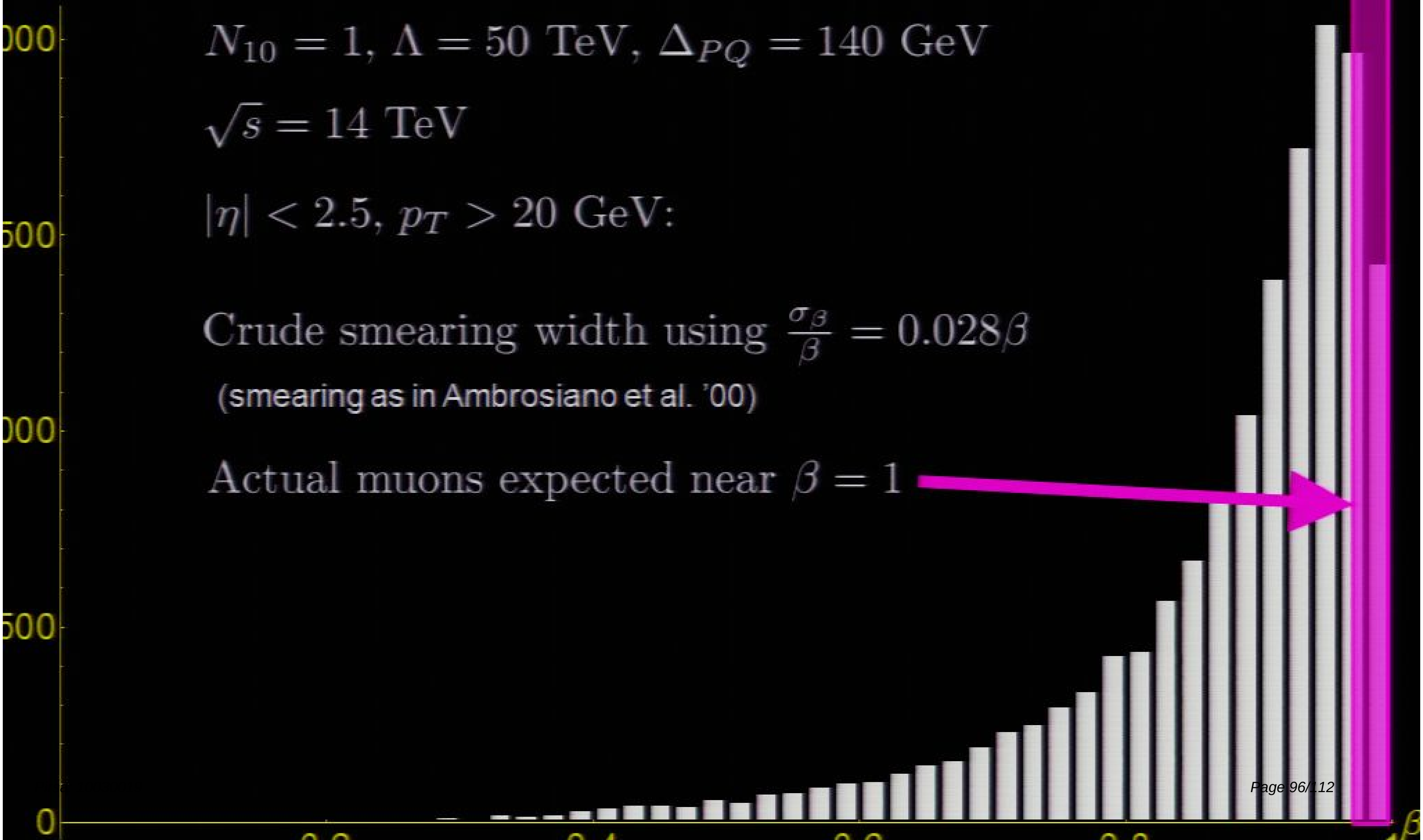
$\Rightarrow p$

$\Rightarrow m_{\tilde{\tau}_1} = \frac{p}{\beta\gamma}$

We shall identify stau as:

$$p_T > 20 \text{ GeV}, \ |\eta| < 2.5 \text{ and } 0.67 < \beta < 0.91 \lesssim \beta_{muon}$$

Example β distribution



$N_{10} = 1$, $\Lambda = 50$ TeV, $\Delta_{PQ} = 140$ GeV

$\sqrt{s} = 14$ TeV

$|\eta| < 2.5$, $p_T > 20$ GeV:

Crude smearing width using $\frac{\sigma_\beta}{\beta} = 0.028\beta$

(smearing as in Ambrosiano et al. '00)

Actual muons expected near $\beta = 1$

Inclusive Channels

All events with 1 or 2 $\widetilde{\tau}_1$'s

$p_T > 20$ GeV, $|\eta| < 2.5$ and $0.67 < \beta < 0.91$

(c.f. Ambrosiano et al. '00)

At least 1 hadronic jet, $p_T > 50$ GeV

Reduces SM Background

And $E_T^{miss} > 50$ GeV (trigger)

$\sigma^{SM}_{BKG} < 1$ fb

$m_{eff} \equiv \sum p_T^{jet,i} + \sum p_T^{\mu,i} > 800$ GeV

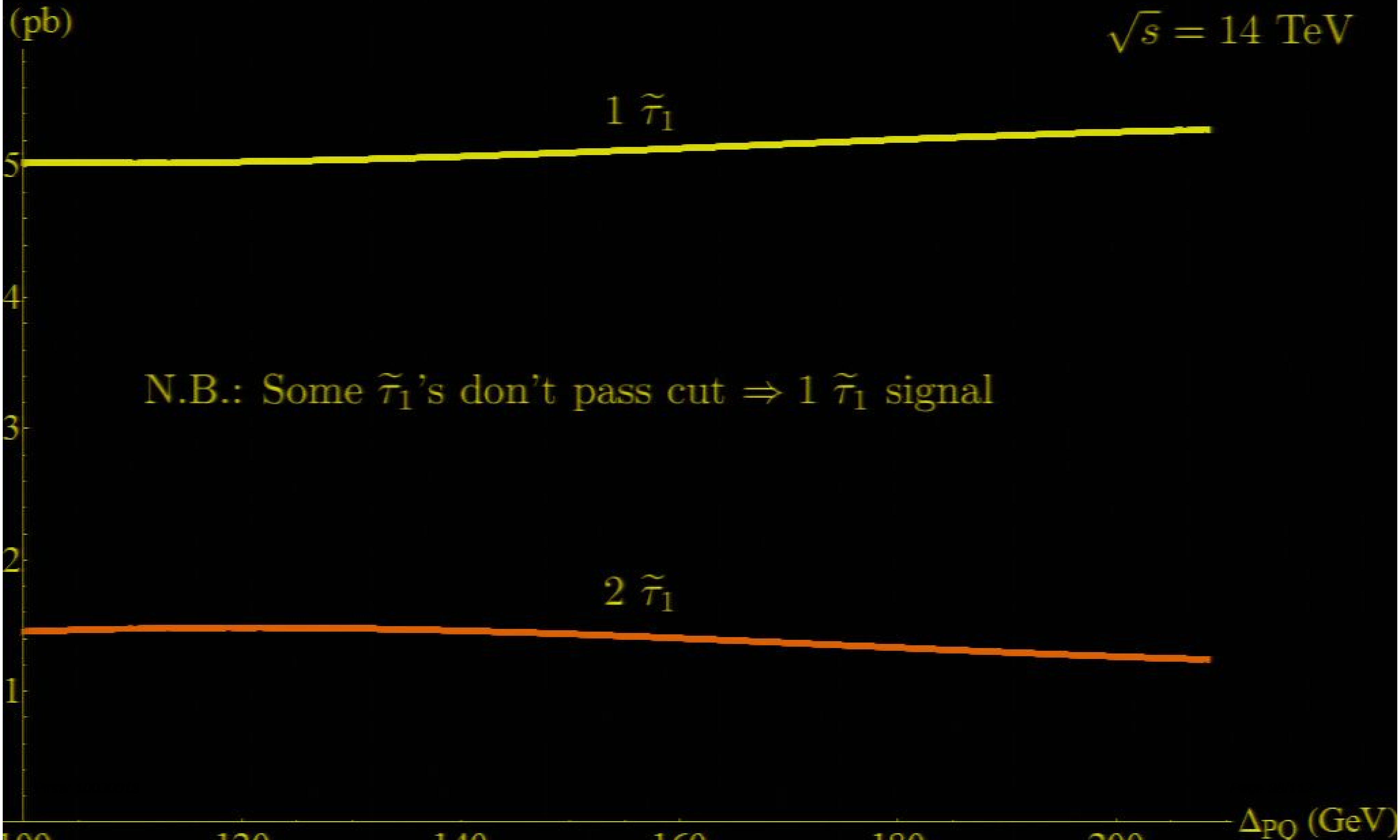
$\sigma_{1\widetilde{\tau}_1} + \sigma_{2\widetilde{\tau}_1} \sim O(1)$ pb (decreases as Λ increases)

Inclusive $\widetilde{\tau}_1$'s

$N_{10} = 1$

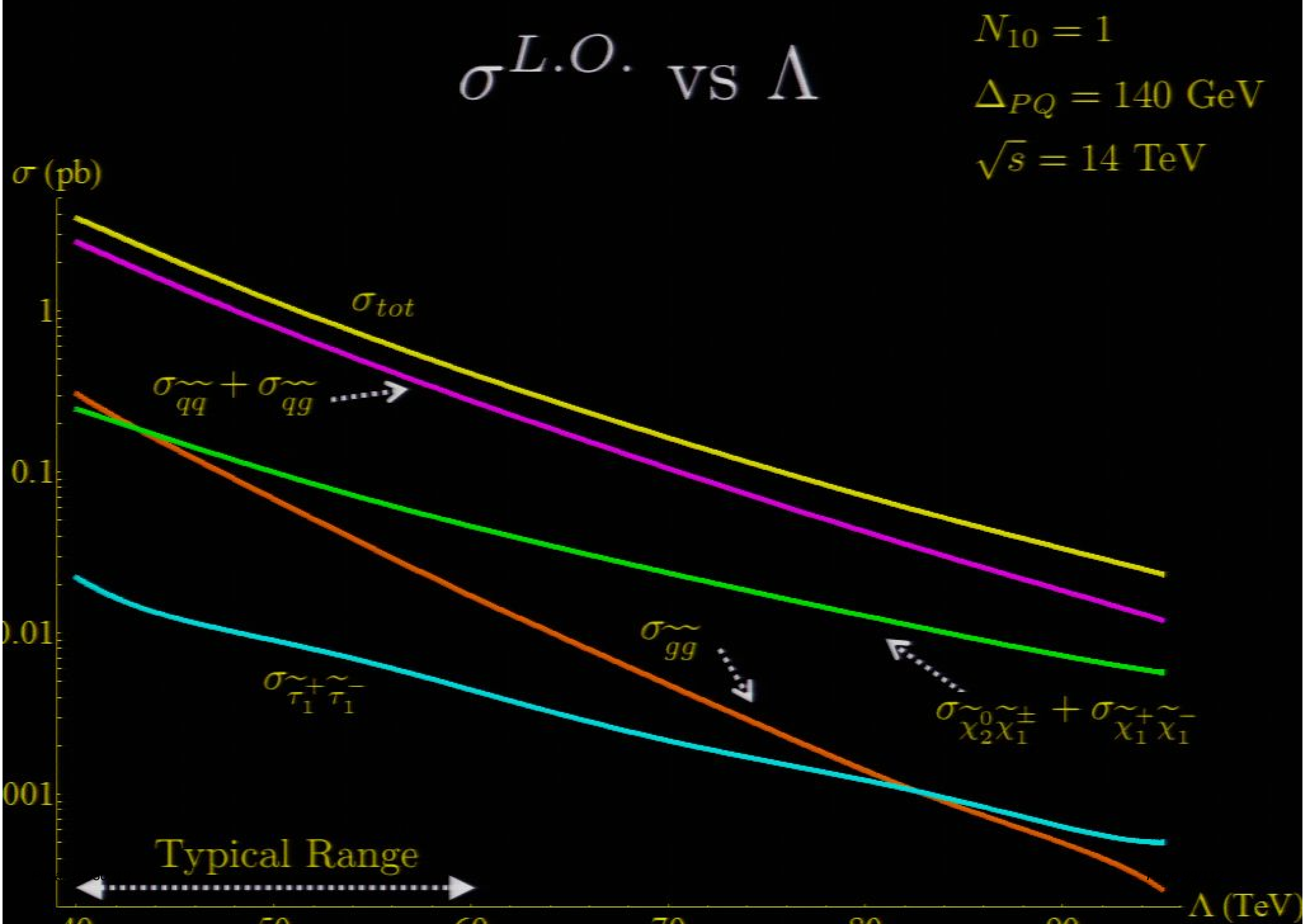
$\Lambda = 50$ TeV

$\sqrt{s} = 14$ TeV



N.B.: Some $\widetilde{\tau}_1$'s don't pass cut ⇒ 1 $\widetilde{\tau}_1$ signal

$\sigma^{L.O.}$ vs Λ



Inclusive $\widetilde{\tau}_1$'s

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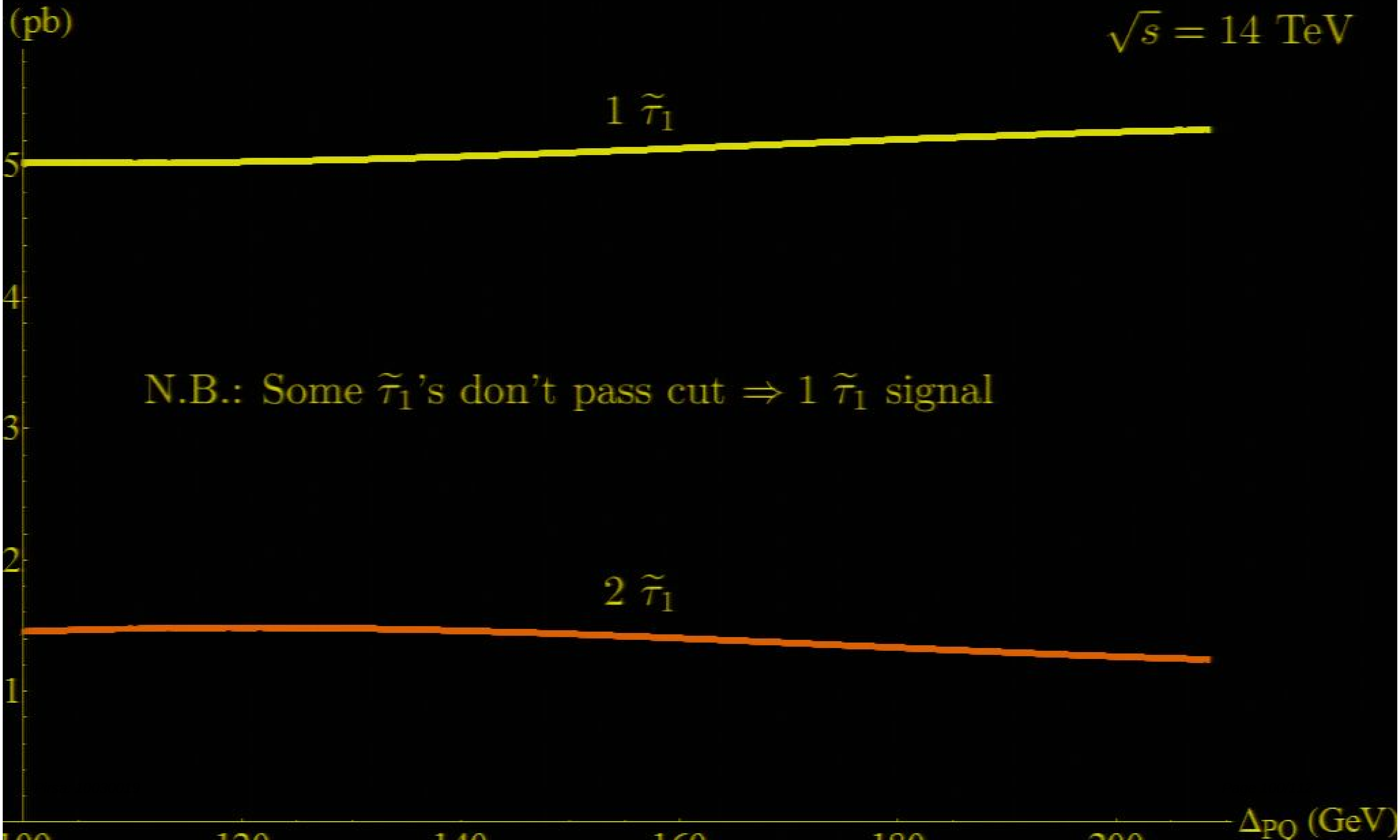


N.B.: Some $\widetilde{\tau}_1$'s don't pass cut $\Rightarrow 1\ \widetilde{\tau}_1$ signal

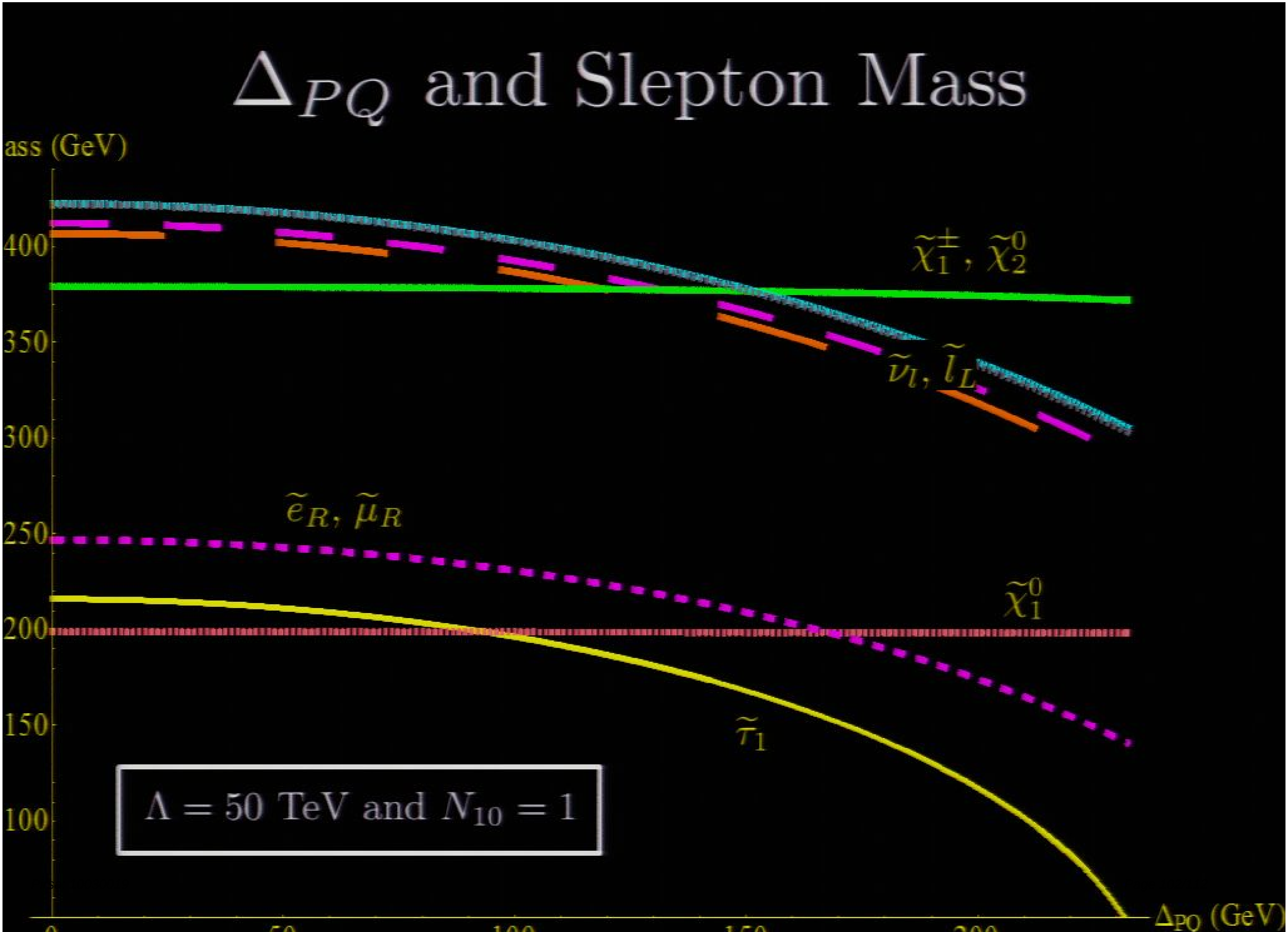
Exclusive Channels

Exclusive channels depend on Δ_{PQ}:

$\widetilde{\tau}_1^+ + \widetilde{\tau}_1^-$ and nothing else

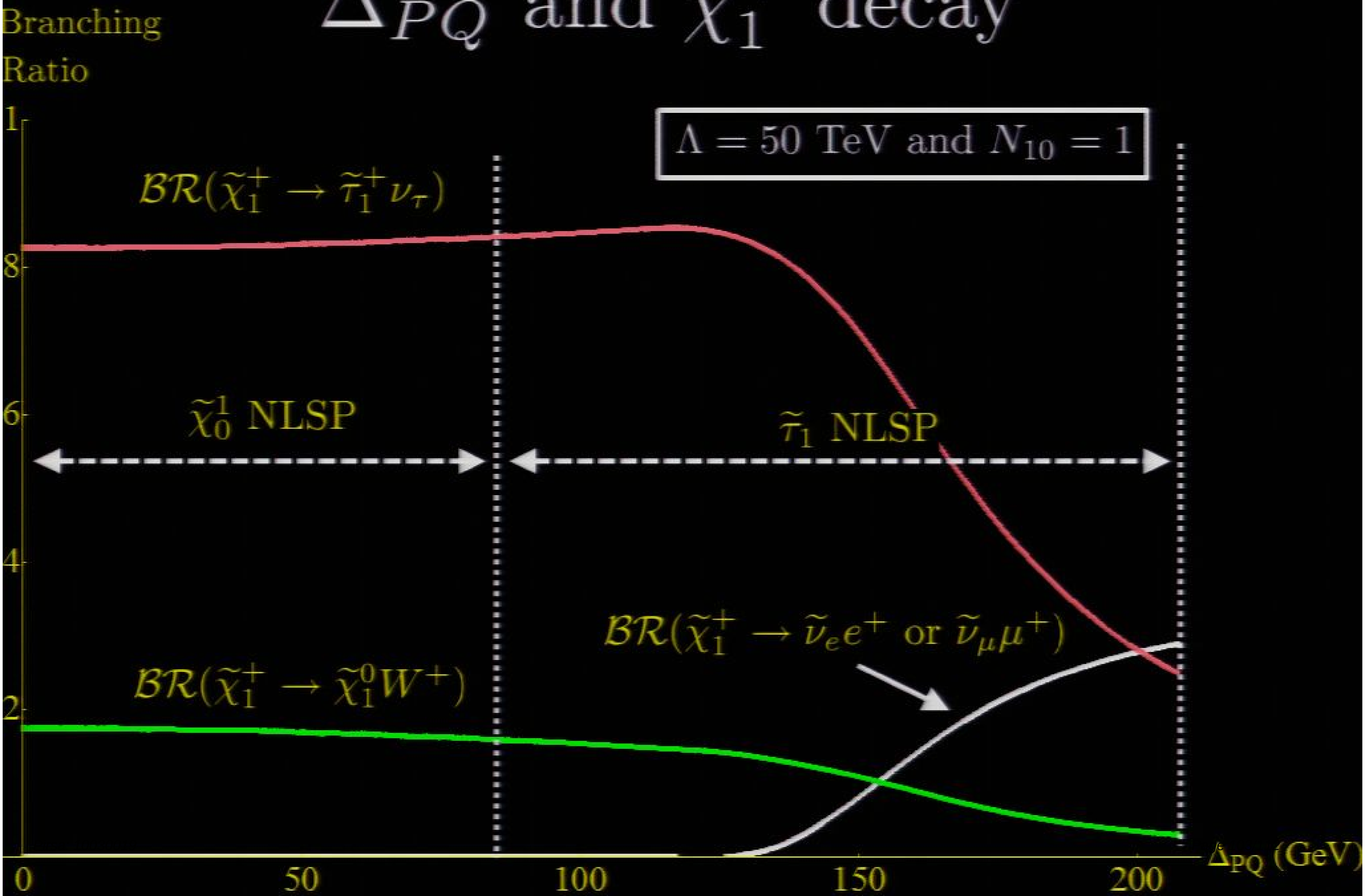
$\boxed{2\widetilde{\tau}_1 + \text{leptons}}$ ← Focus on this for talk

Multi-“lepton” events with 2 hard “leptons” ($p_T > 100$ GeV)



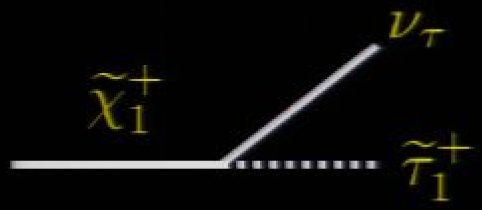
Δ_{PQ} and Slepton Mass

Δ_{PQ} and $\widetilde{\chi}_1^+$ decay

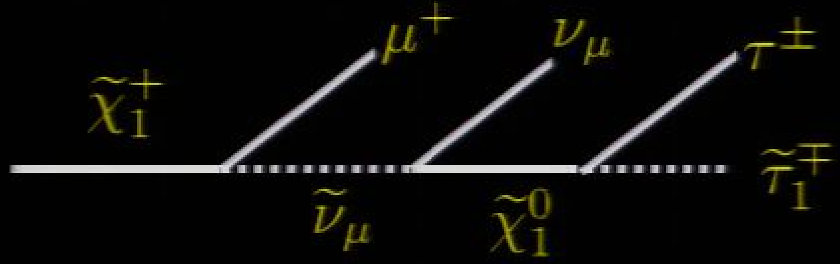


Example: $2\tilde{\tau}_1$+ Leptons

At low Δ_{PQ}: $m_{\tilde{\nu}} > m_{\tilde{\chi}_1^+} \Rightarrow$

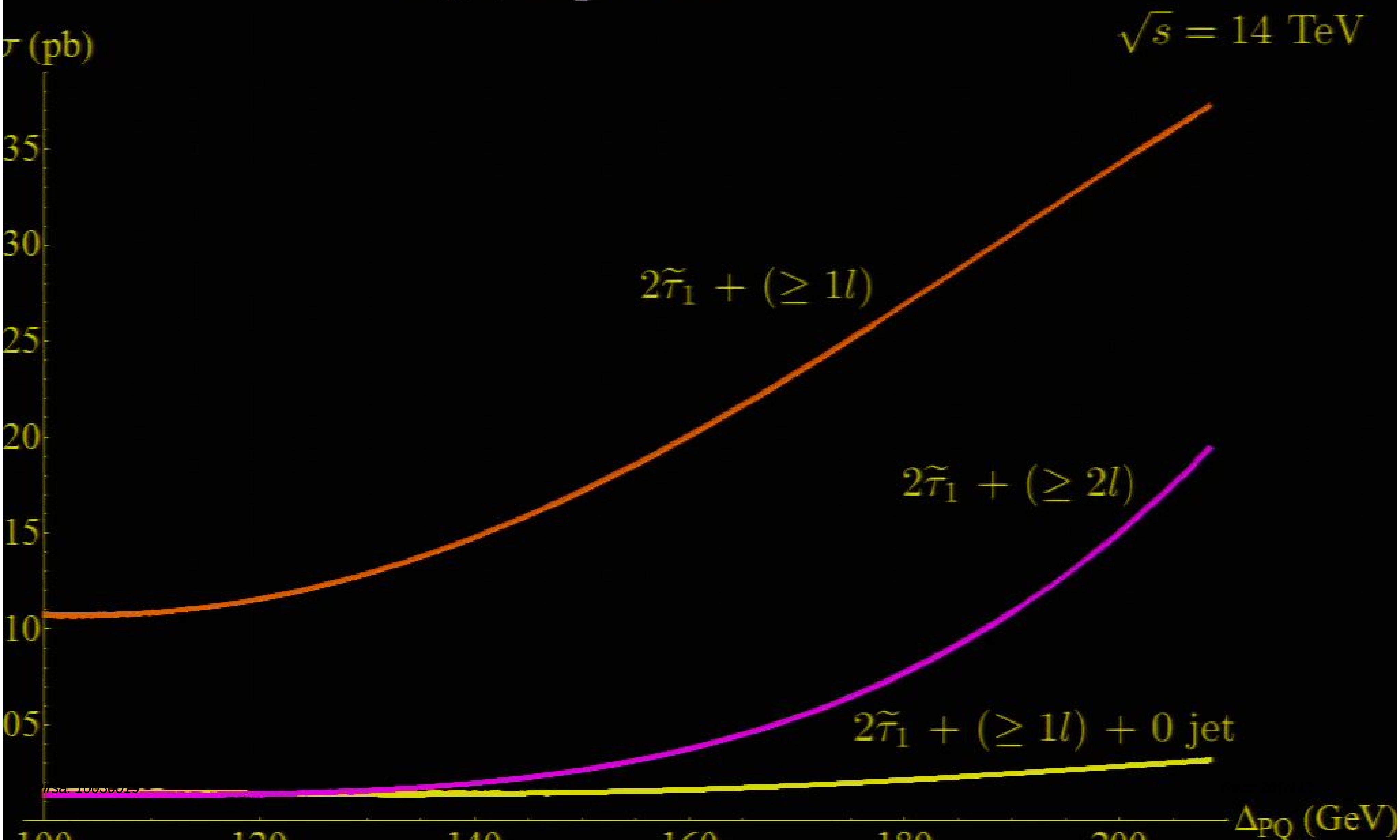


At moderate Δ_{PQ}: $m_{\tilde{\nu}} < m_{\tilde{\chi}_1^+} \Rightarrow$



$\sigma_{2\tilde{\tau}_1+\text{leptons}}(\Delta_{PQ})$ increases with Δ_{PQ}

$\sigma_{2\widetilde{\tau}_1+\mathrm{leptons}}$ vs Δ_{PQ}



Uses For Staus I

Mass Reconstruction:

Hinchliffe Paige '98 Ellis et al. '06
Ibe Kitano '07 Ito Kitano Moroi '09

β and $p \Rightarrow m_{\widetilde{\tau}_1} = \frac{p}{\beta\gamma}$

Once $p_\mu(\widetilde{\tau}_1)$'s known, reconstruct masses up the decay chain

≤ 2 GeV for non-colored

With 30 fb^{-1}, precision of:

~ 4 GeV for 1^{st} and 2^{nd} gen $\widetilde{q}$

Ellis et al. '06

Uses For Staus II

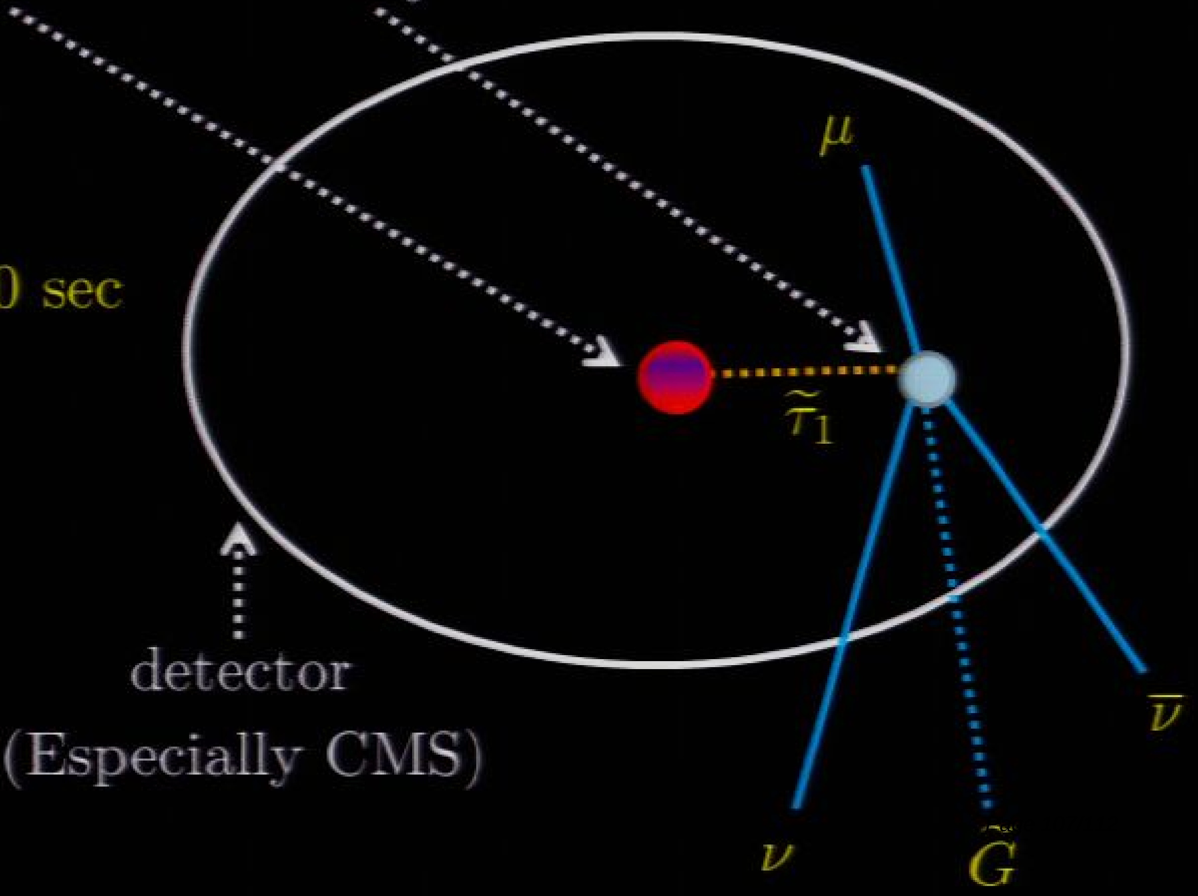
Stopped Staus ⇒ Measure Lifetime ⇒ $M_{\cancel{SUSY}}$: $\Gamma^{-1}_{\tilde{\tau}_1} \sim \frac{M^4_{\cancel{SUSY}}}{m^5}$

Requires correlating production with decay

Most studied: $\Gamma^{-1}_{\tilde{\tau}_1} \gtrsim 1$ day

May be possible: $\Gamma^{-1}_{\tilde{\tau}_1} \sim 100$ sec

(not well studied)



detector

(Especially CMS)

Buchmuller et al. '04
Feng and Smith '04
De Roeck et al. '05
Hamaguchi et al. '04, '06, '09

Stopped Staus

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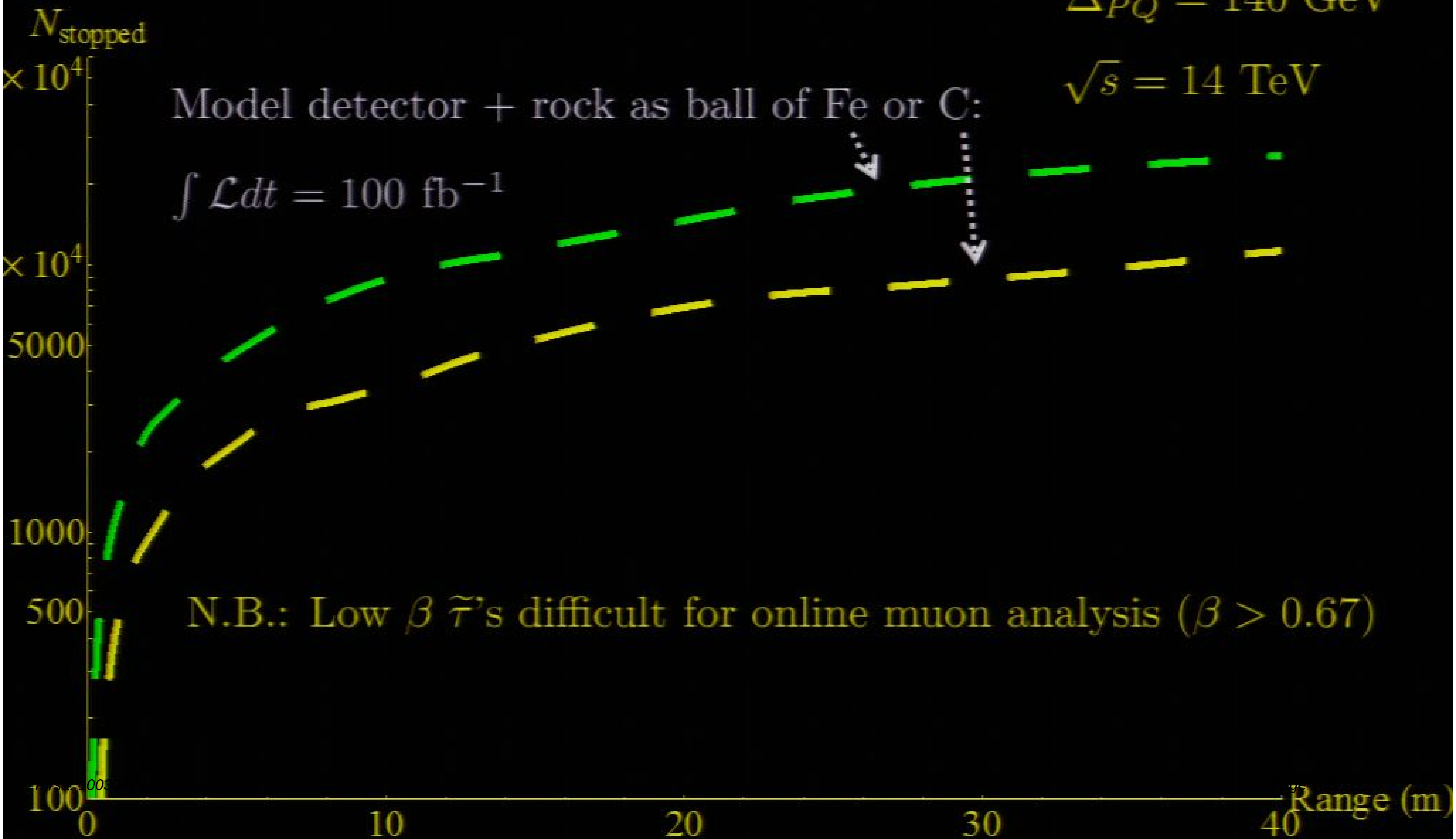
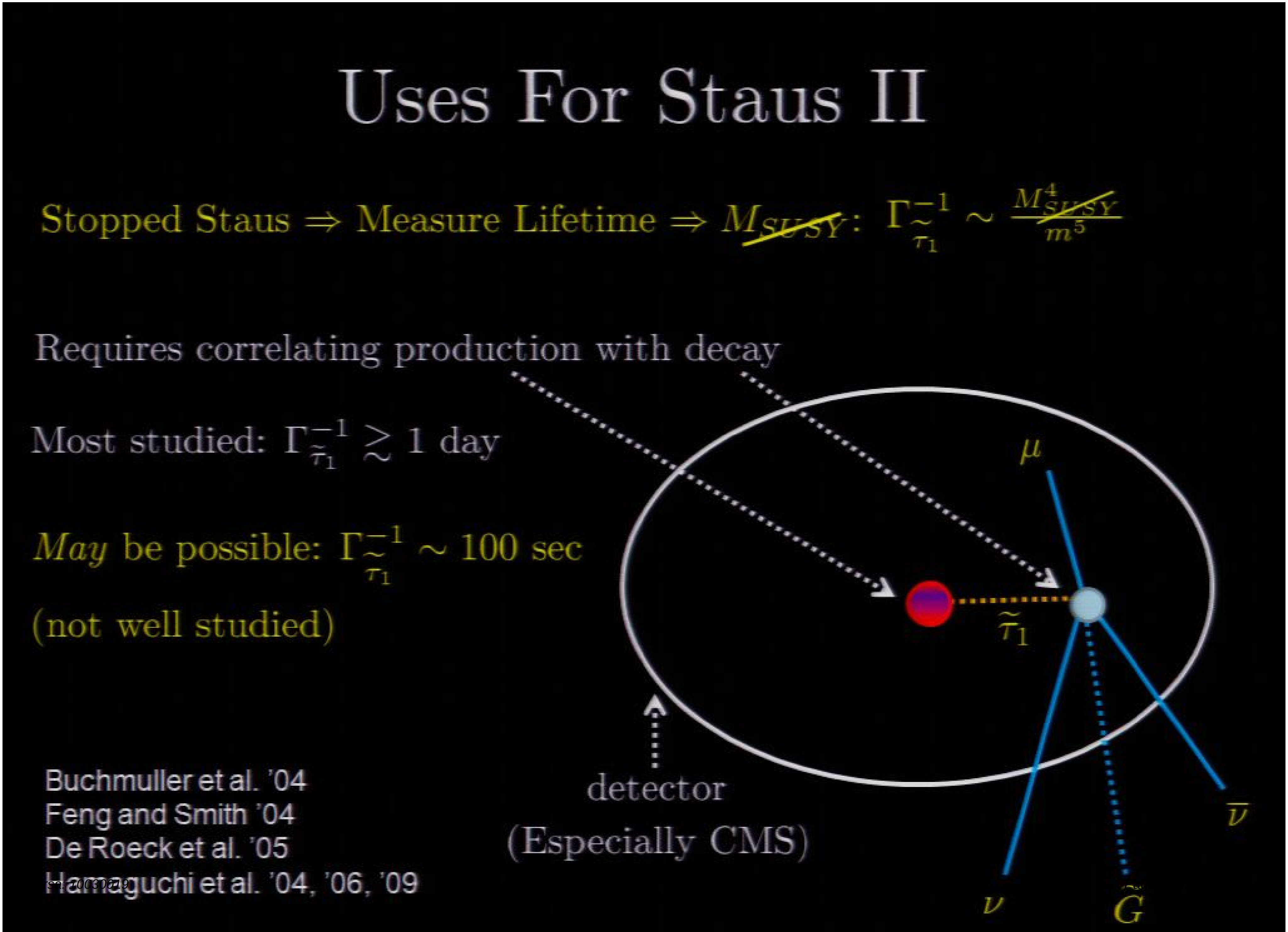


Model detector + rock as ball of Fe or C:

$\int \mathcal{L} dt = 100\ \mathrm{fb}^{-1}$

N.B.: Low β $\tilde{\tau}$'s difficult for online muon analysis ($\beta > 0.67$)



Uses For Staus II

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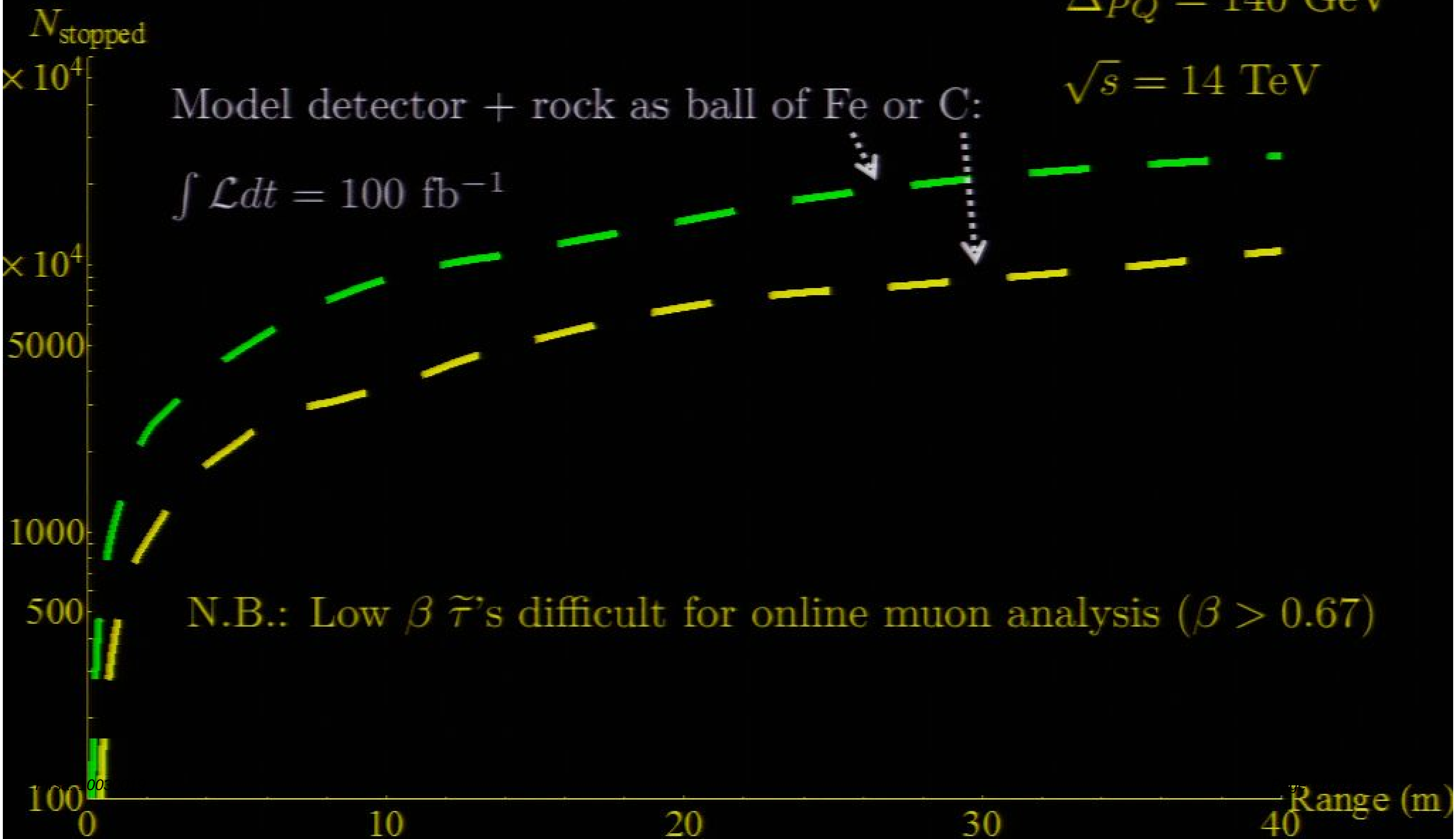

Model detector + rock as ball of Fe or C:

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Conclusions

- E_8 and ~~SUSY~~
- Stau NLSP
- LHC Signatures
- ¿Stopped Staus and $M_{\cancel{SUSY}}$?

End of slide show, click to exit.