Title: LHC Olympics at CERN

Date: Mar 21, 2006 11:00 AM

URL: http://pirsa.org/06030016

Abstract:

LHC-

-CERN 25/26 July 2005

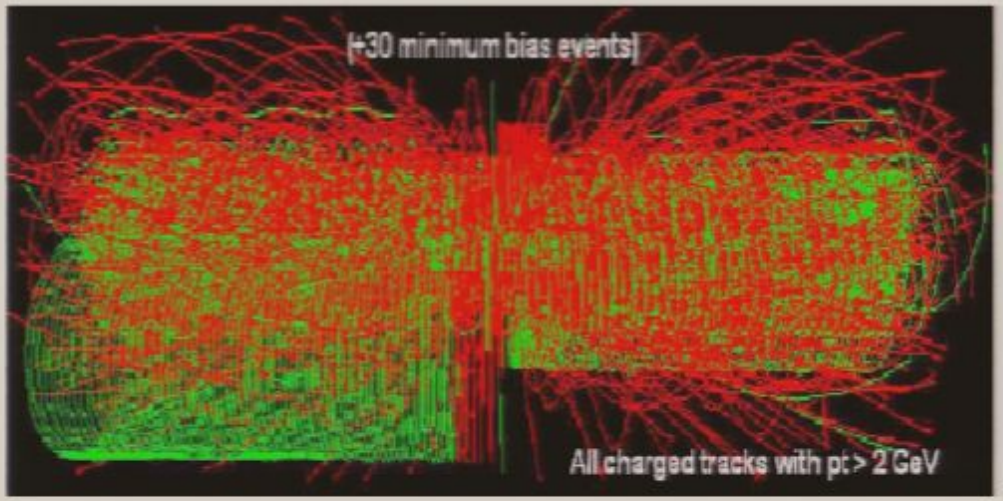
Information Letter

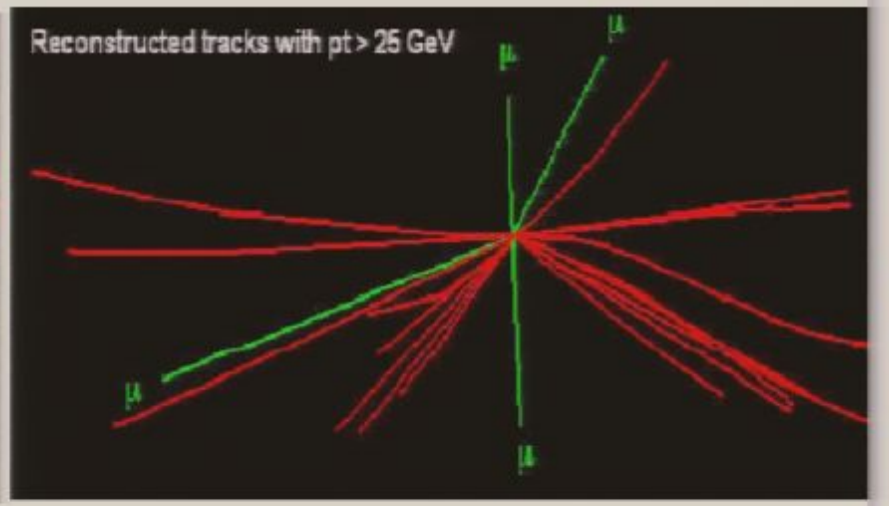
We are all eagerly awaiting data from the LHC that will point to how the electroweak symmetry is broken, perhaps confirm that superpartners exist, or more generally provide signals of physics beyond the Standard Model that can focus our attention and give us clues to the underlying theory.

Once there is a discovery there will be celebrations and champagne. Then what? Theorists and experimenters have increasingly begun to realize that we could be more prepared for finding and for learning to interpret the (hoped for) signals of physics beyond the Standard Model. Experimenters have already done some mock data challenges, but mostly in the context of very minimal mSUGRA models with limited connections to underlying theories, and with very special signatures. Theorists are less prepared. Some theorists and experimenters have been working on the very important studies of the SM signals that will be needed to recognize physics beyond the SM. Many theorists who are eager to have data pointing to how the SM will be extended have not yet developed the techniques to participate in the process of discovery, and it will take time to do that.

For simplicity let's assume supersymmetry is what is discovered to concretely discuss the issues - if it is something else there will be similar challenges. Experimenters report cross sections times decay branching ratios, and some kinematical distributions that are related to masses. In practice it may be possible to measure at most a few superpartner masses if any. How do we figure out the physics implications of the data? Is supersymmetry is broken, whether there is evidence for the 4D physics being determined by the existence of small extra dimensions, etc?

A "Primer" that non-experts can use to help connect a theory and "data" is accessible here in its minimal form. Please, have a look on the pdf-file or the the ps-file. We will keep upgrading it.





Organising Comittee

- Ignatios Antoniadis (CERN)
- Nima Arkani-Hamed (Harvard)
- Savas Dimopoulos (Stanford)
- Gordy Kane (Michigan)
- Joe Lykken (Fermilab)
- Steve Mrenna (Fermilab)
- Gary Shiu (Wisconsin)
- Herman Verlinde (Princeton)

For information/participation, please contact:

- Lhc.Olympics
- List of Participants
- Program
- CERN hostel
- Hotels in the area

Further Links

- CERN Homepage
- TH Homepage
- LHC News
- Atlas Homepage
- CMS Homepage

Preliminary Program of LHC_Olympics Workshop

CERN, TH Conference room
25 JULY TO 27 JULY 2005

Monday 25 July

Video Conference :

VRVS appointment in Mars Virtual Room that belongs to Planets/Universe community:

Start at 13:30 the 25 July 2005 Finish at 19:28 the 25 July 2005 Time displayed in Time Zone: GMT +2 summer (Bern/Switzerland)

Title: "LHC-Olympics"

9:30	**Gordy Kane**	Introduction and highlights of first LHC year
10:00	**Jesse Thaler**	From LHC signatures to models
10:30	***Coffee Break***	
11:00	**Discussion**	
12:00	***Lunch***	

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11:00	**Discussion**	
12:00	***Lunch***	
14:00	**Matt Strassler**	A model-independent approach to the LHC Olympics data
15:30	***Coffee Break***	
16:00		A collider physics primer for non-experts

Tuesday 26 July

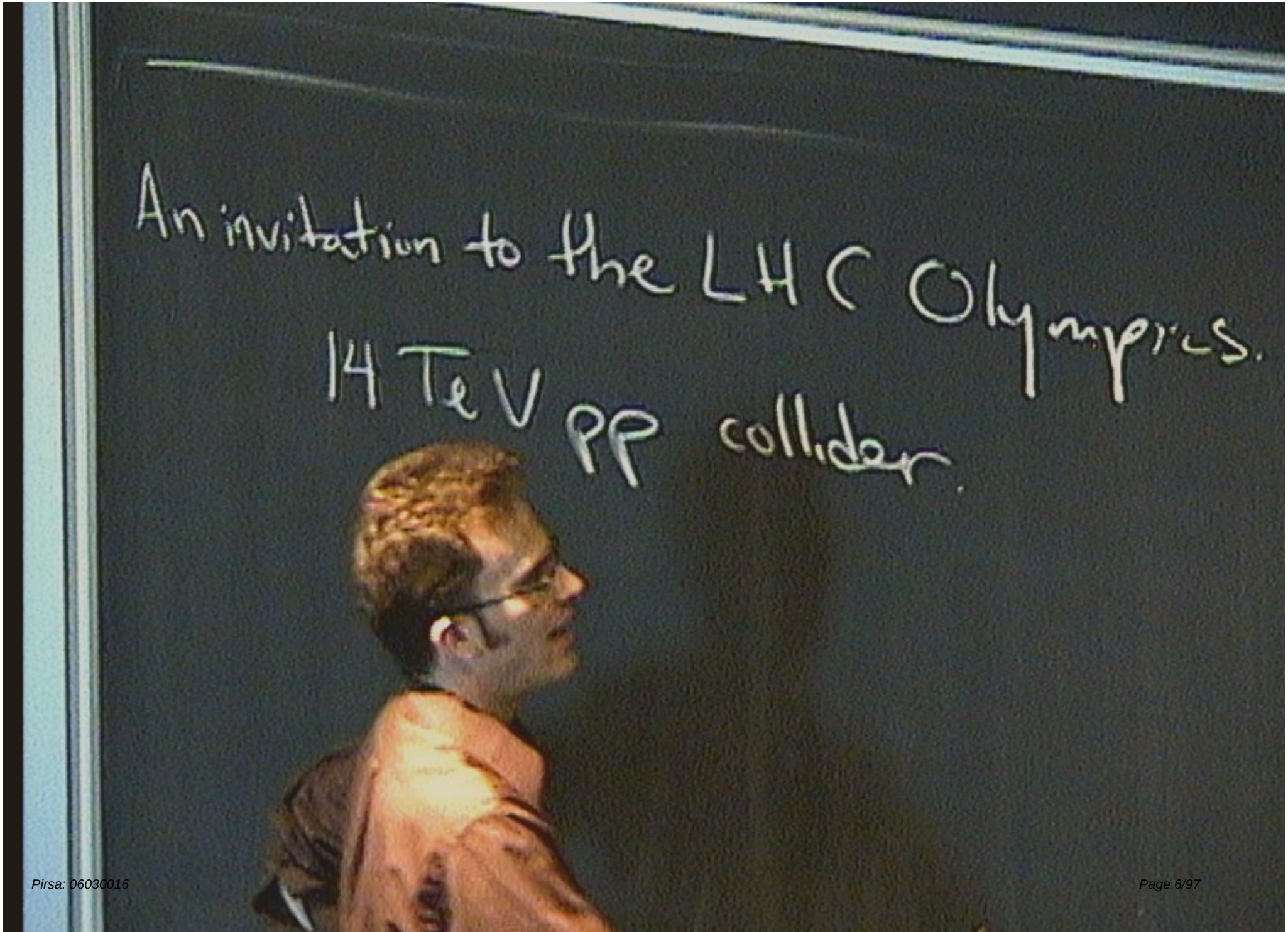
Video Conference :

VRVS appointment in Einstein Virtual Room that belongs to Universe community:

Start at 8:30 the 26 July 2005 Finish at 17:28 the 26 July 2005 Time displayed in Time Zone: GMT +2 summer (Bern/Switzerland)

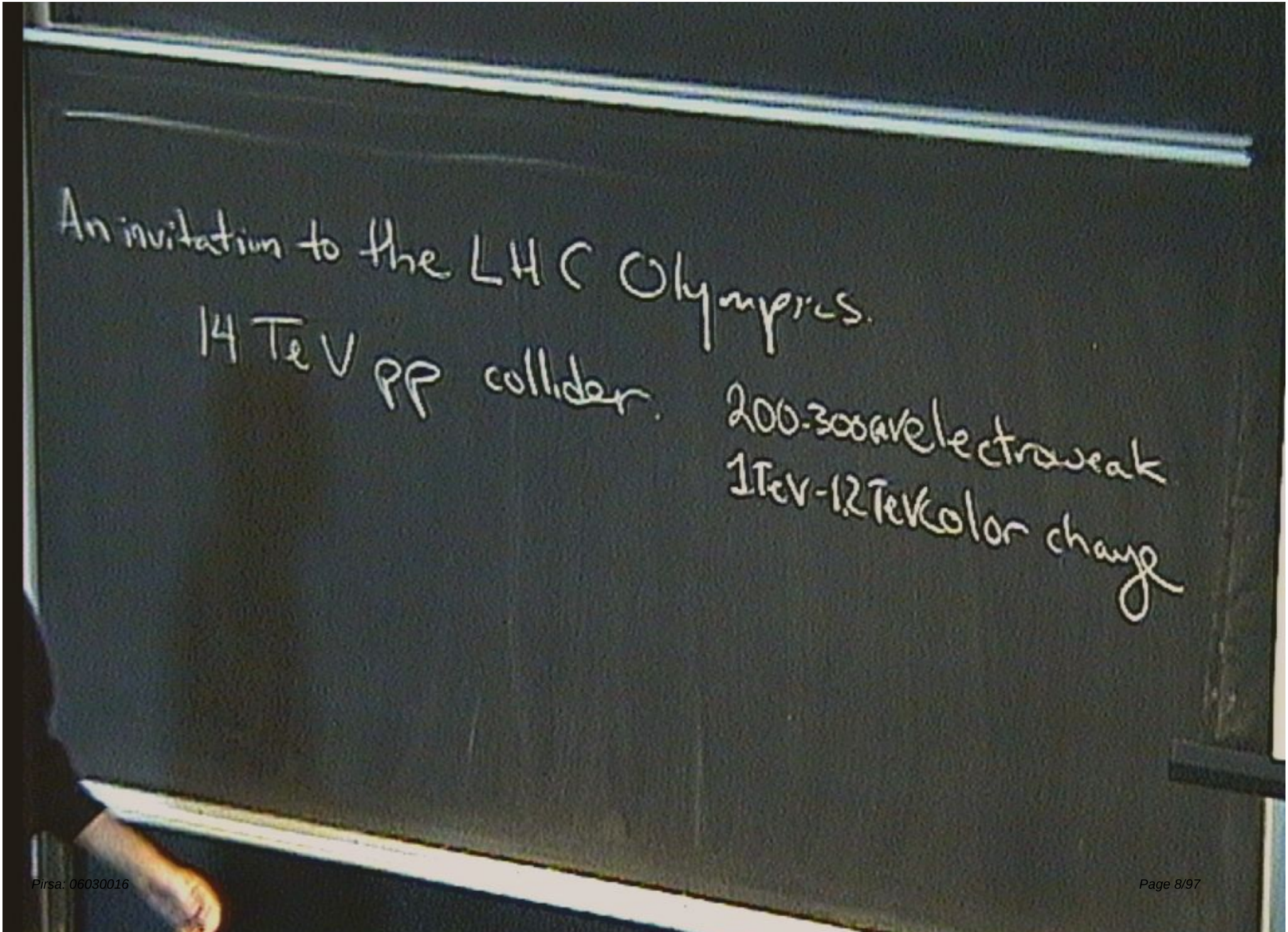
Title: "LHC-Olympics"

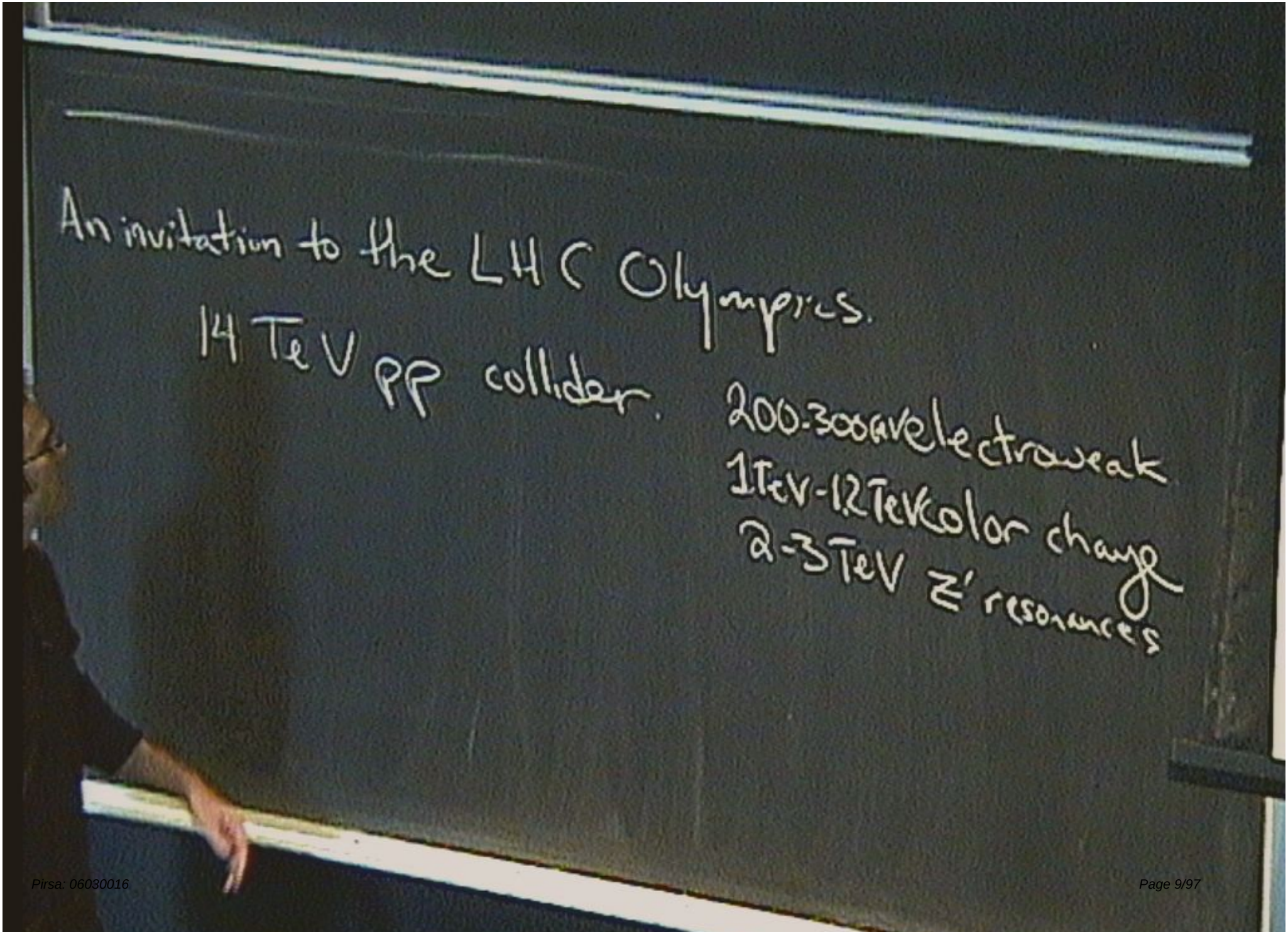
9:30	**Nima Arkani-Hamed**	Highlights from LHC first year prime
10:00	**Piyush Kumar**	The mSUGRA footprint in signature space
10:30	***Coffee Break***	
11:00	**Discussion**	

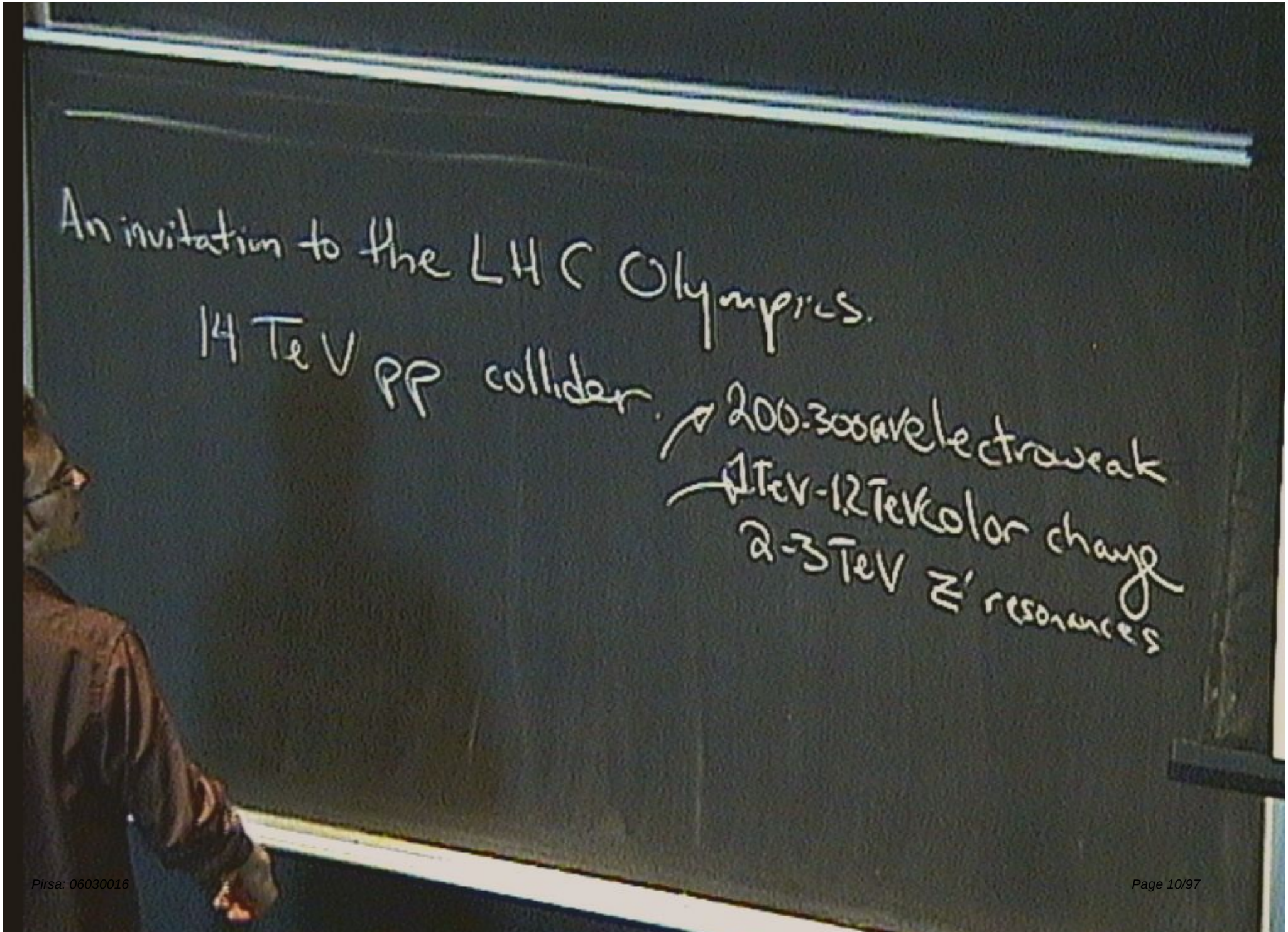

An invitation to the LHC Olympics.
14 TeV pp collider.

An invitation to the LHC Olympics.

14 TeV pp collider. 200-300 a/e lectroweak


An invitation to the LHC Olympics.
14 TeV pp collider.
200-300 ave electroweak
1 TeV - 1.2 TeV color charge


An invitation to the LHC Olympics.
14 TeV pp collider.
200-300 GeV electroweak
1 TeV - 1.2 TeV color charge
2-3 TeV Z' resonances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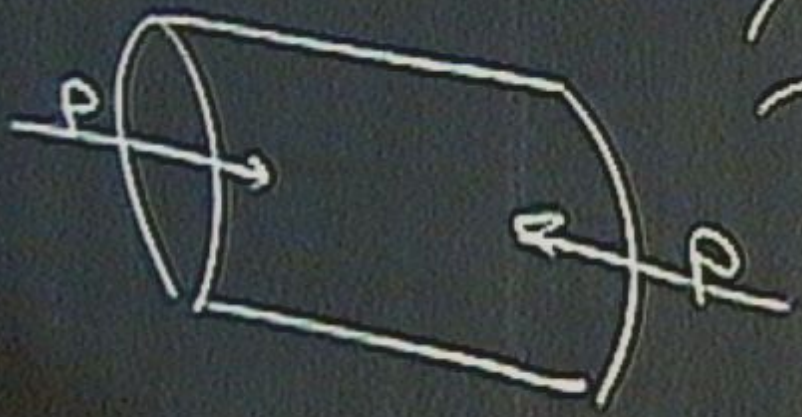

- 200-300 ave electroweak
- 1 TeV - 1.2 TeV color charge
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An invitation to the LHC Olympics.

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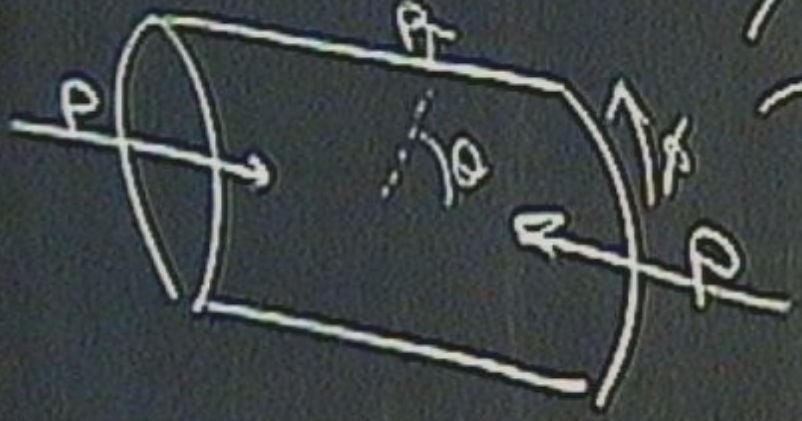


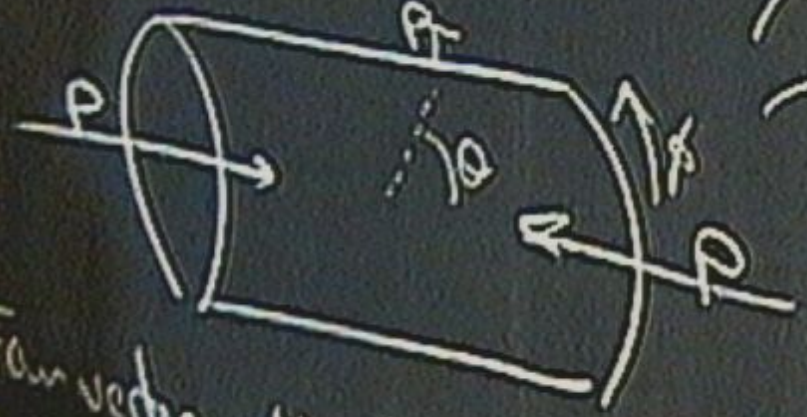
→ 200-300 ave electroweak

→ 1 TeV - 1.2 TeV color charge

→ 2-3 TeV Z' resonances

An invitation to the LHC Olympics.

14 TeV pp collider.



Four vector, M, P_T, η

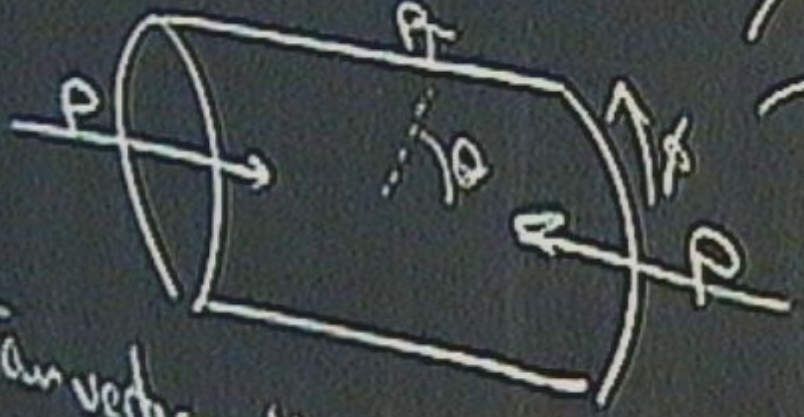
200-300 ave electroweak

1 TeV - 1.2 TeV color charge

2-3 TeV Z' resonances

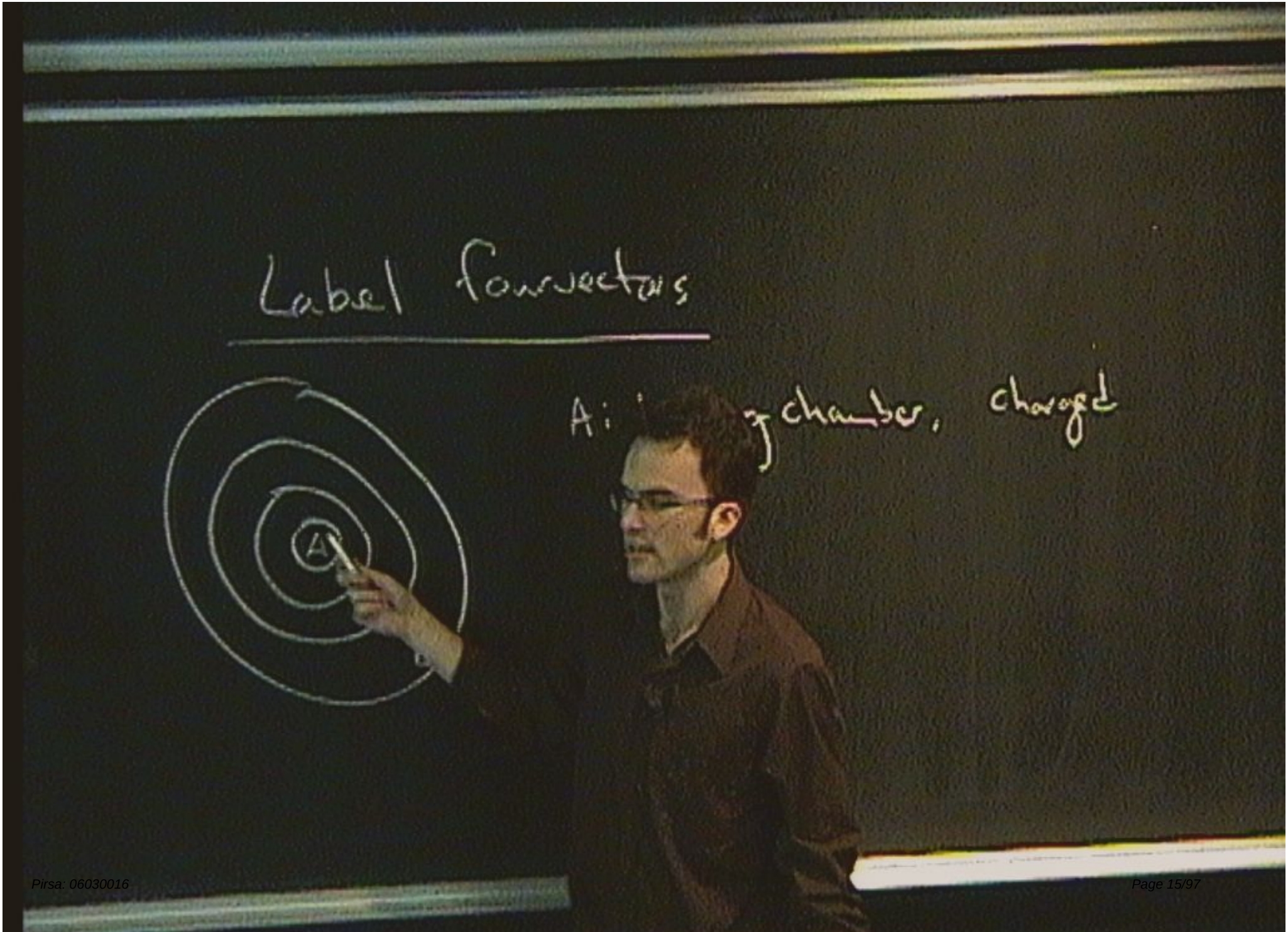
An invitation to the LHC Olympics.

14 TeV pp collider.

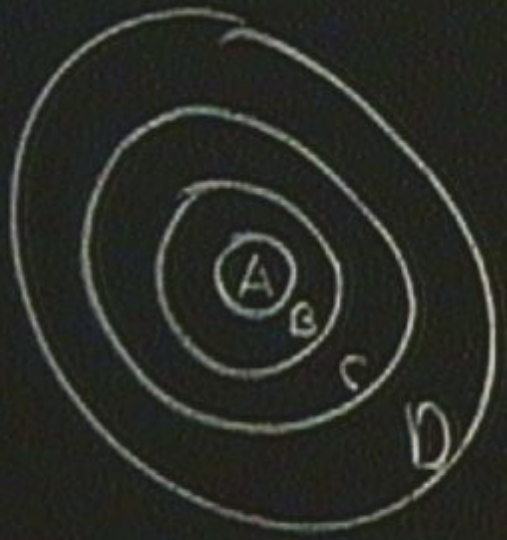


Four vector: M, P_T, η, ϕ

- 200-300 GeV electroweak
- 1 TeV - 12 TeV color charge
- 2-3 TeV Z' resonances


Label connectors
A
chamber, charged

Label four vectors

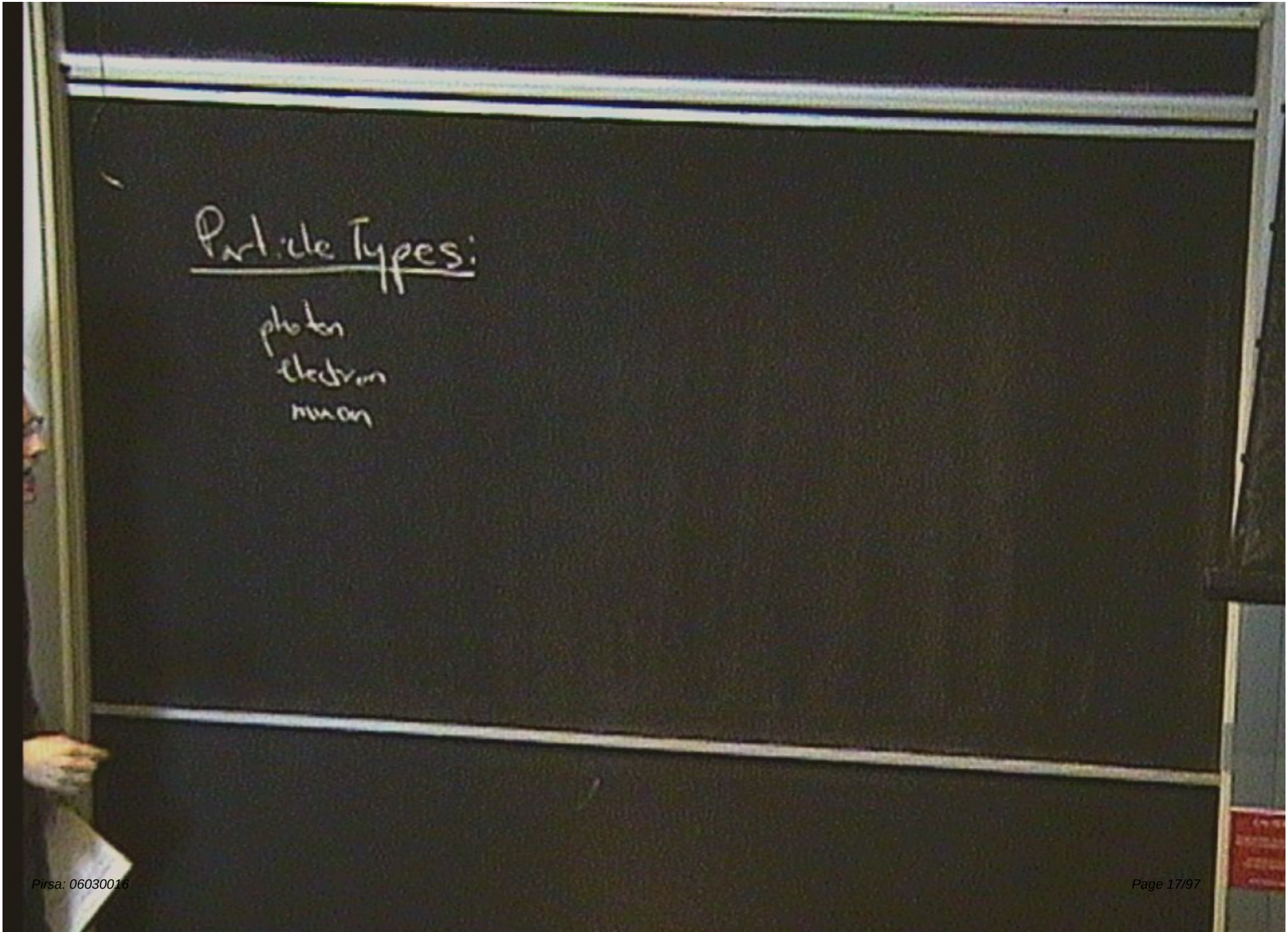


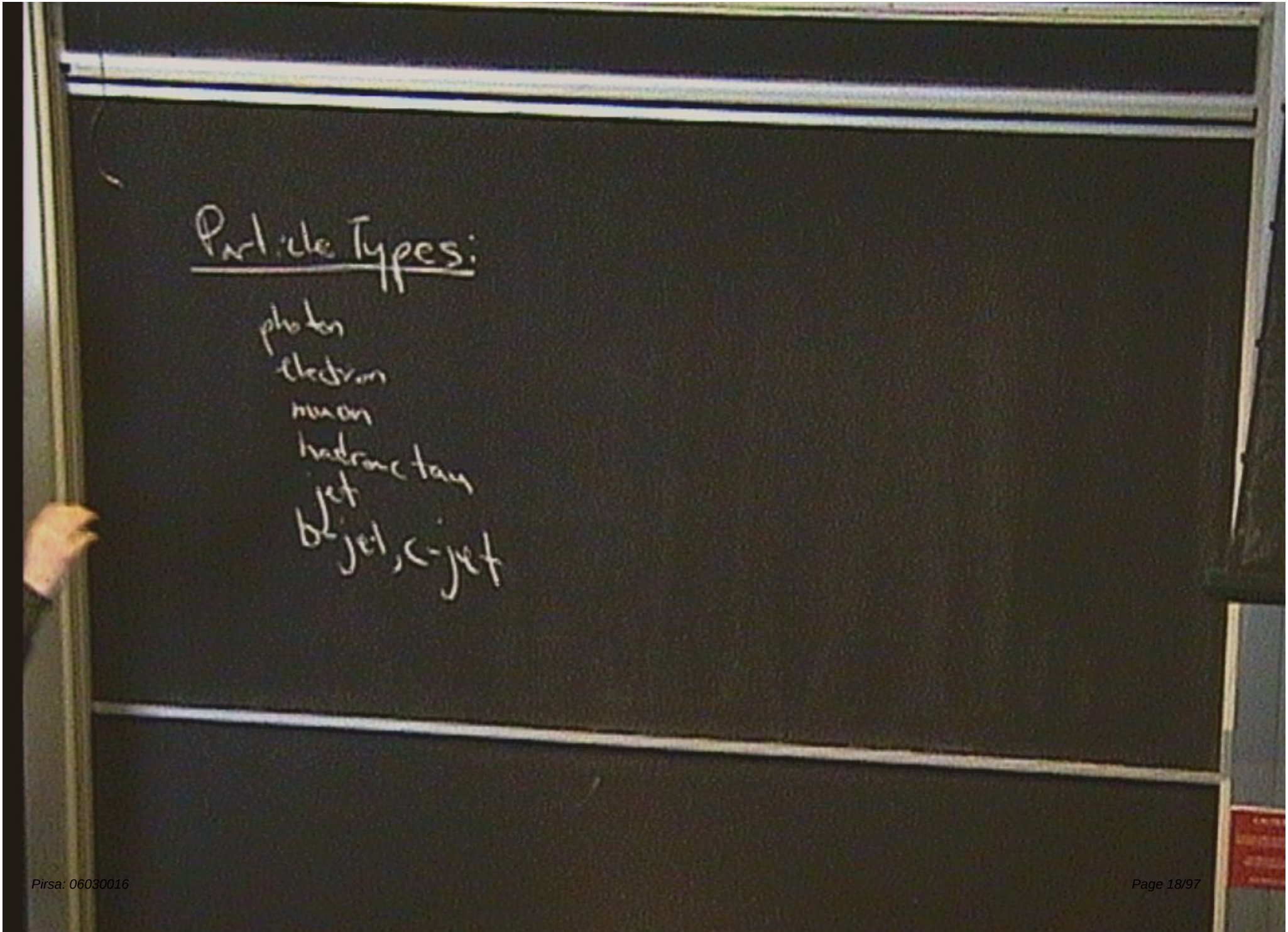
A: tracking chamber, charged

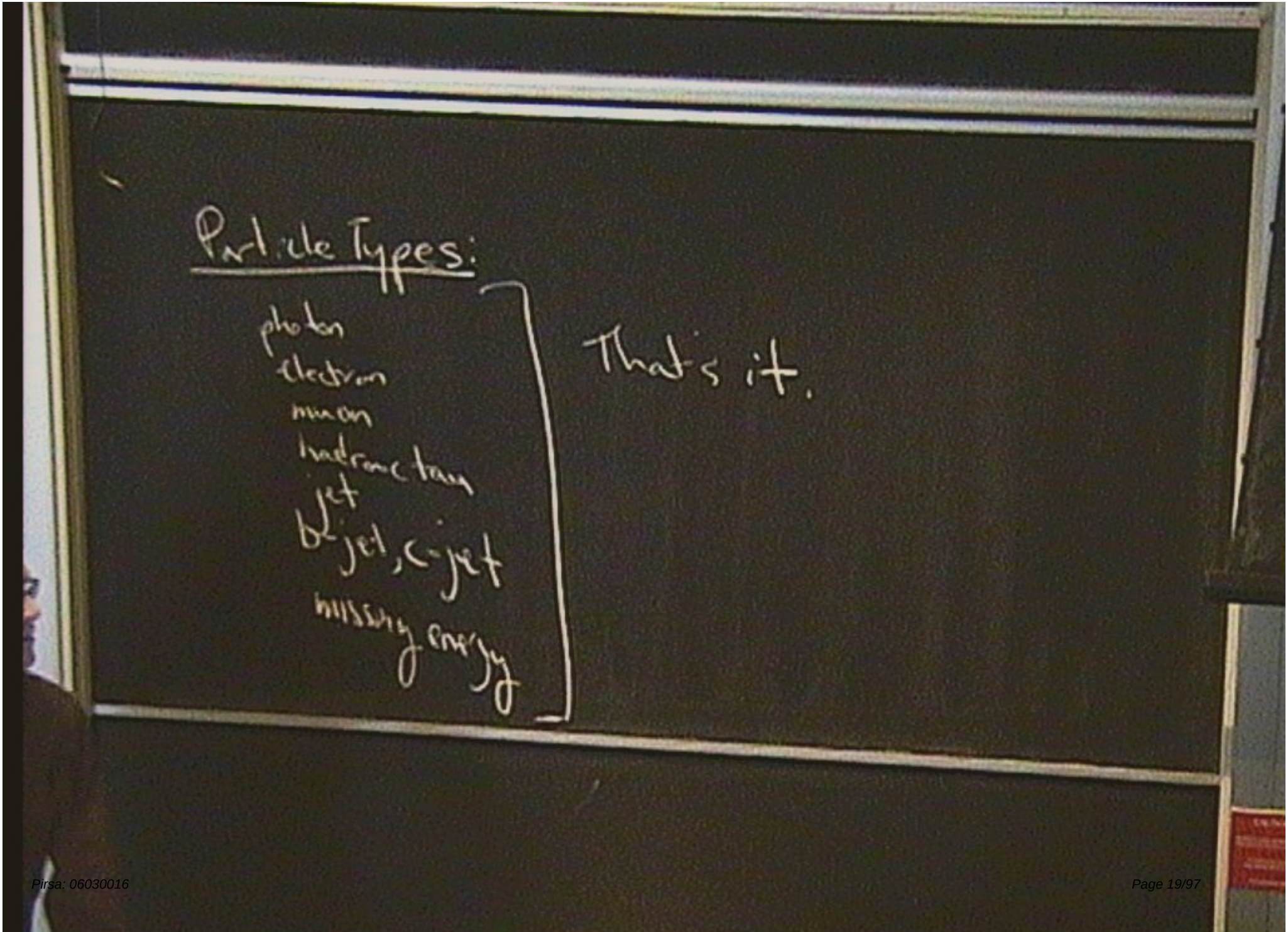
B: EM cal. : γ, $e^{\pm}$

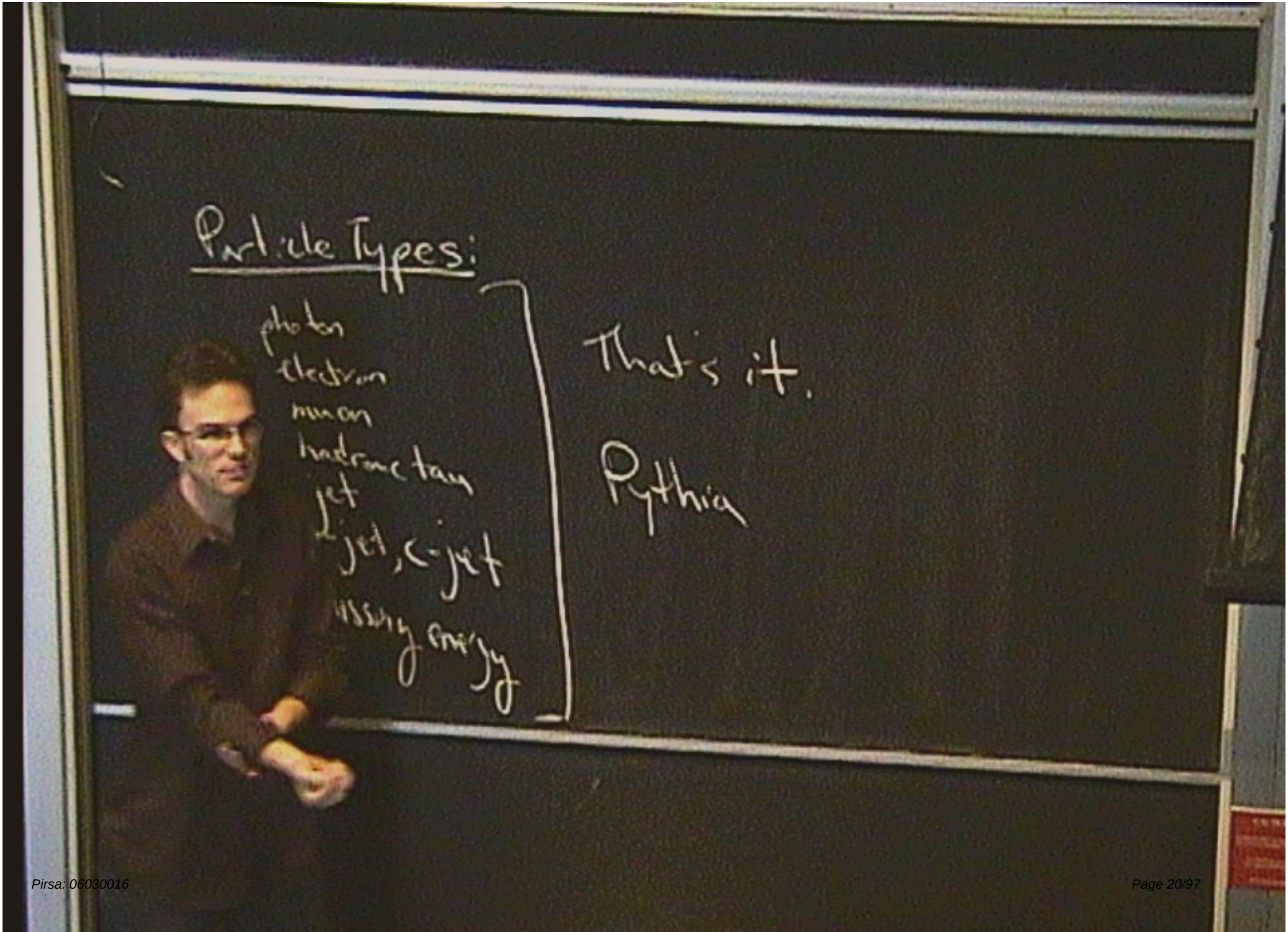
C: Hadronic cal: Colored

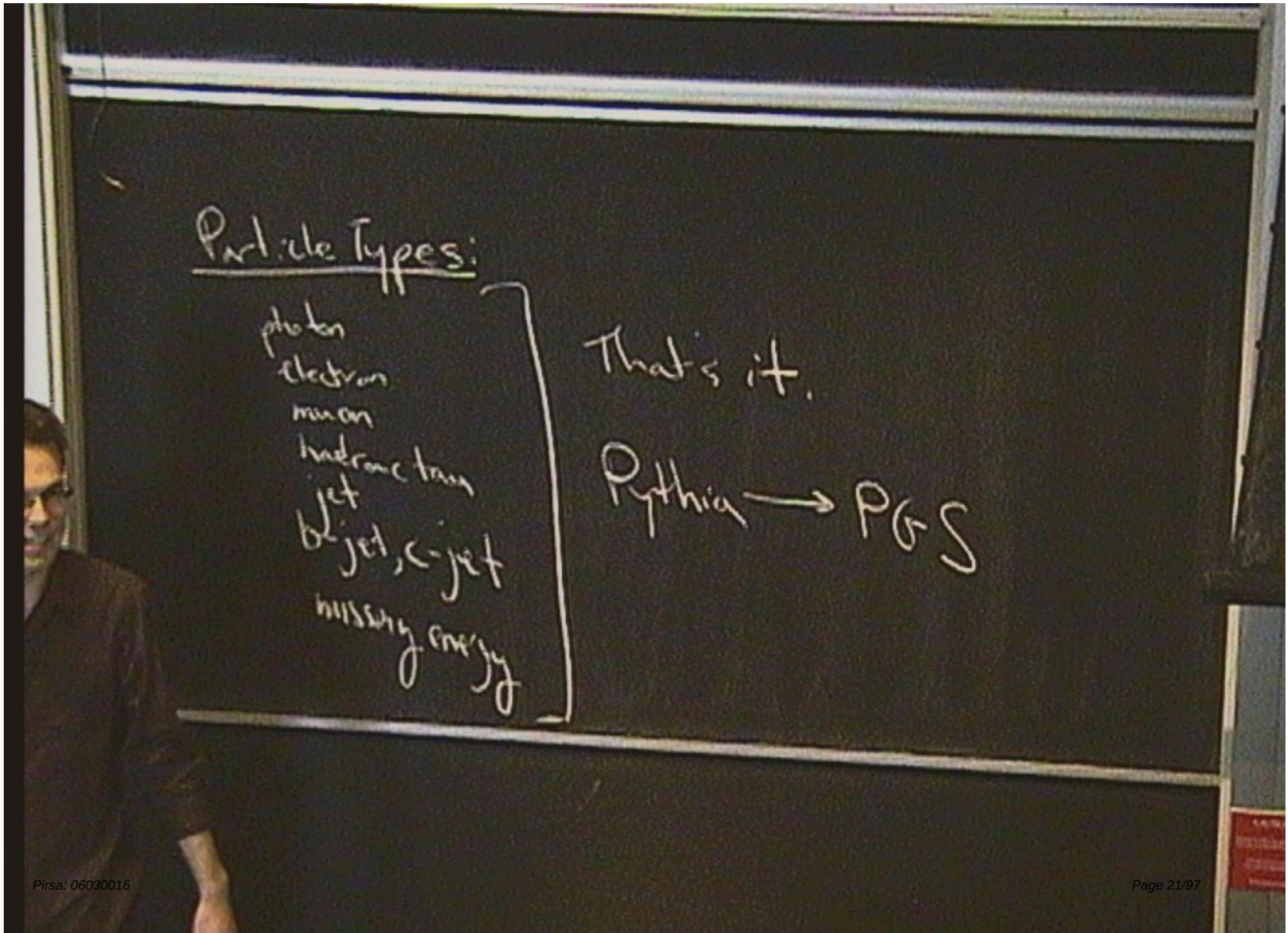
D: Muon chamber.


Particle Types:
photon
electron
muon


Particle Types:
photon
electron
muon
hadronic tau
b-jet
jet, c-jet


Particle Types:
photon
electron
muon
hadronic tau
b-jet
b-jet, c-jet
missing energy
That's it.


Particle Types:
photon
electron
muon
hadronic tau
Jet
b-jet, c-jet
missing energy
That's it.
Pythia

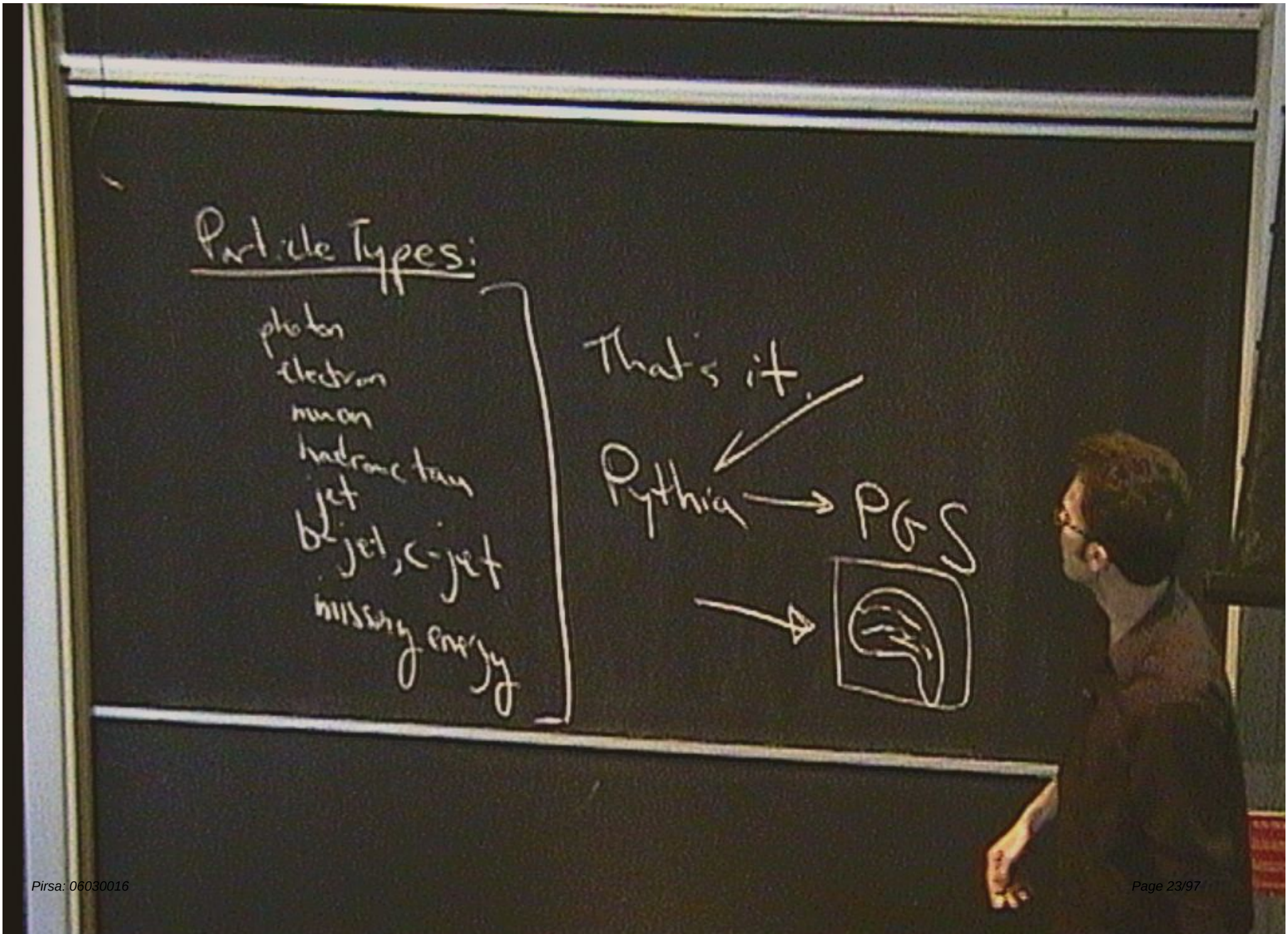

Particle Types:
photon
electron
muon
hadronic tau
b-jet
b-jet, c-jet
missing energy
That's it.
Pythia → PGS

Particle Types:

photon
electron
muon
hadronic tau
b-jet
b-jet, c-jet
missing energy

That's it.

Pythia → PGS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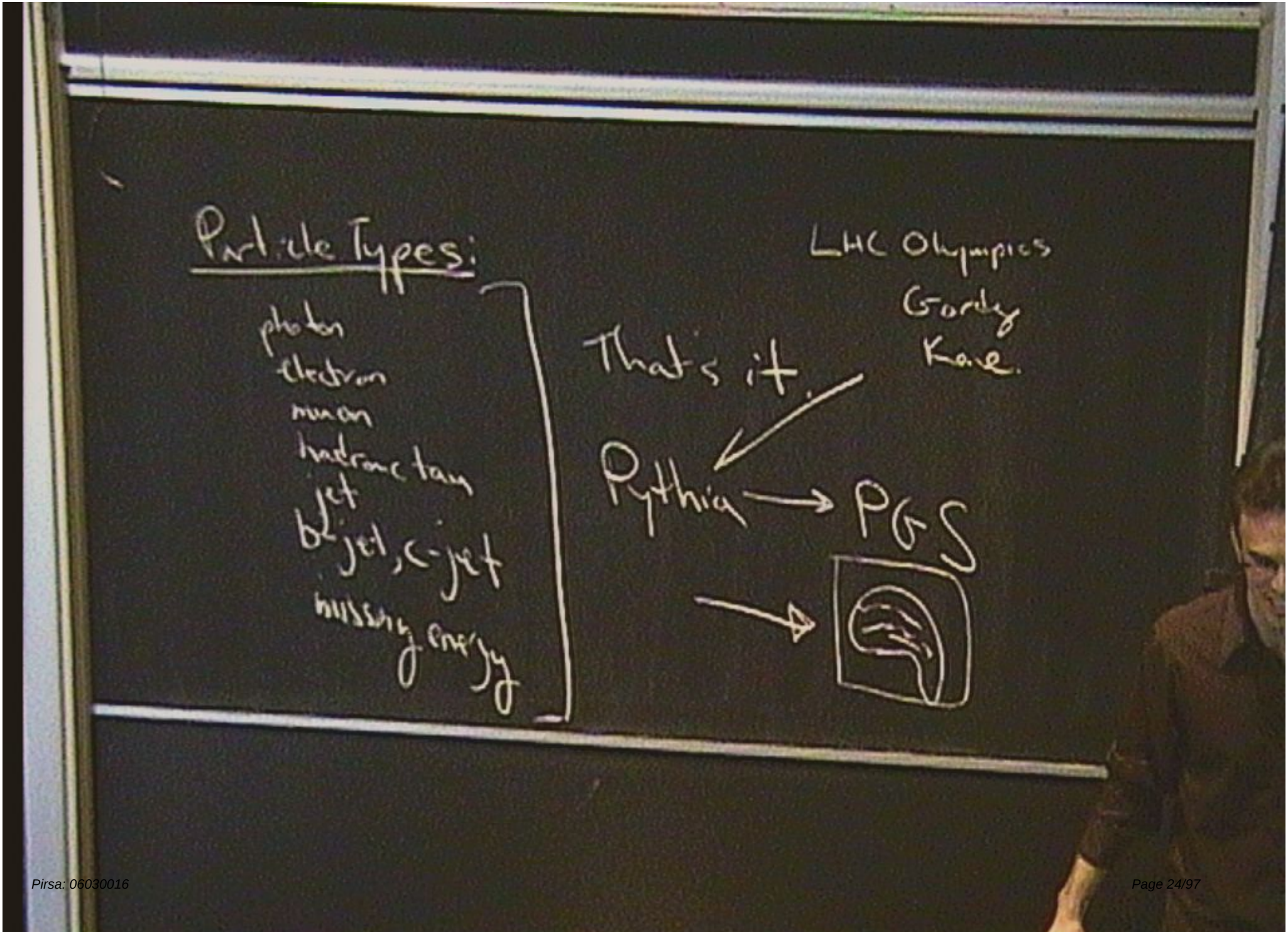
Particle Types:
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jet, c-jet
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LHC Olympics
Gordy
Kane.
Pythia
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Particle Types:

photon
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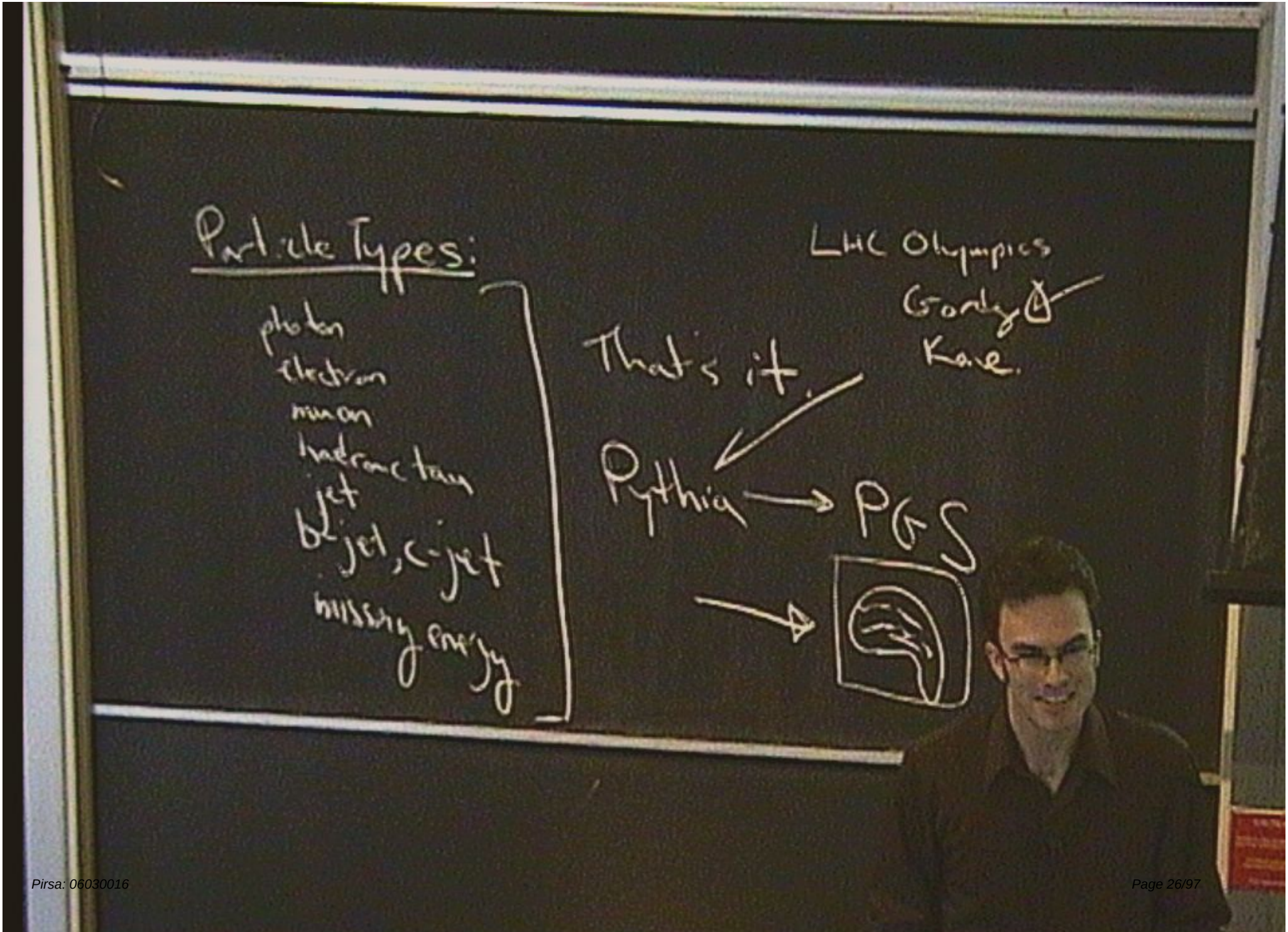
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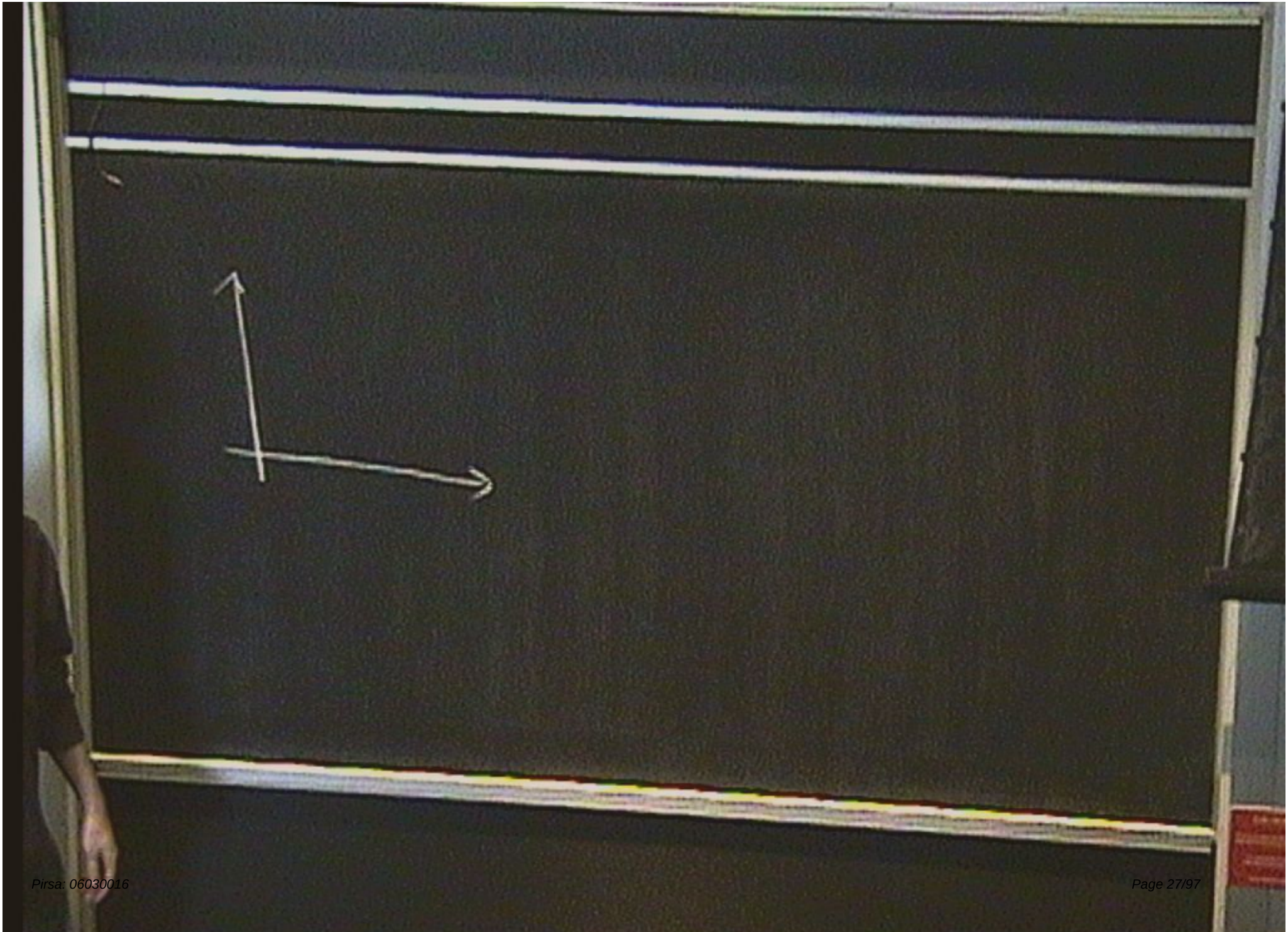
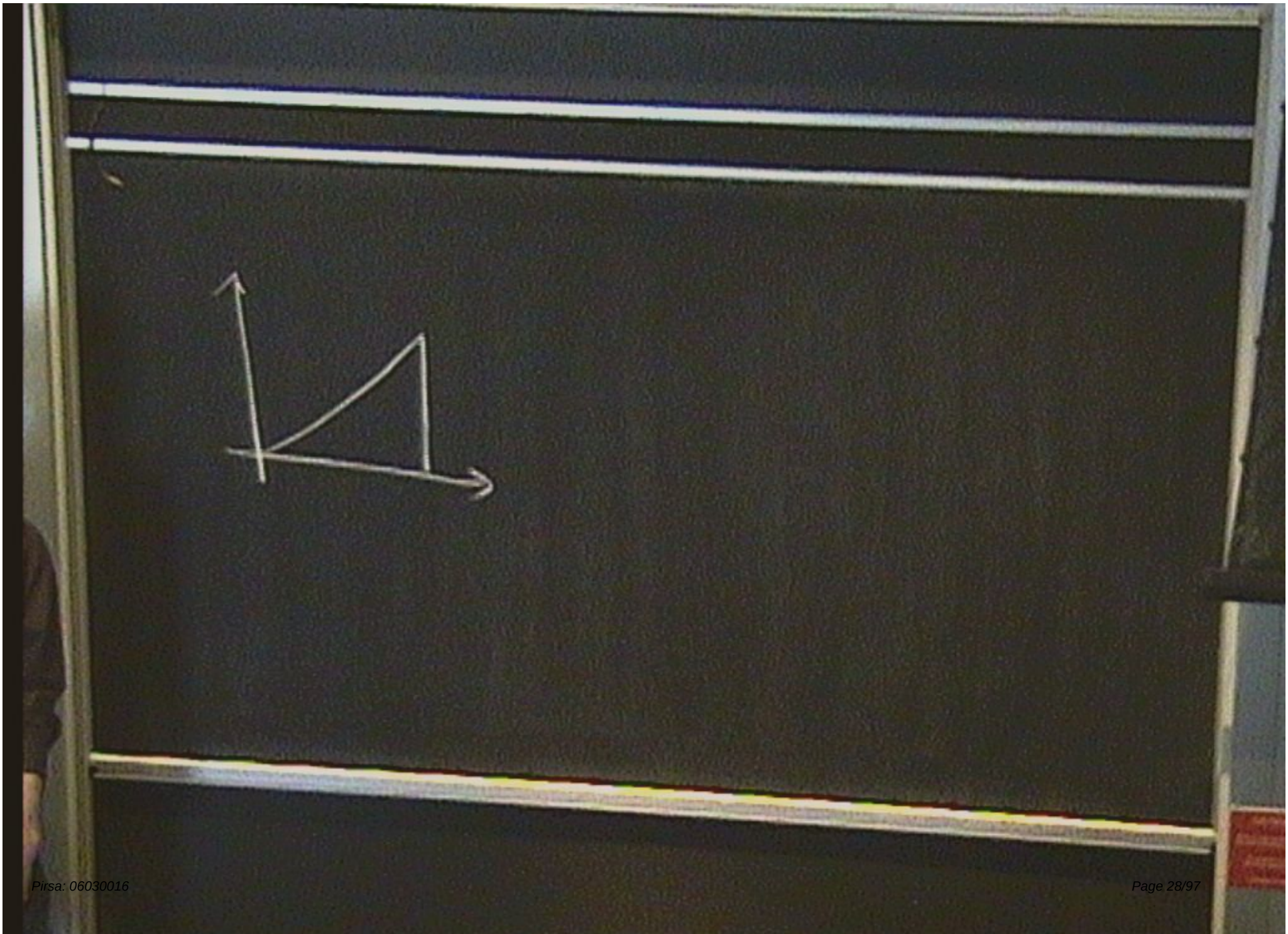
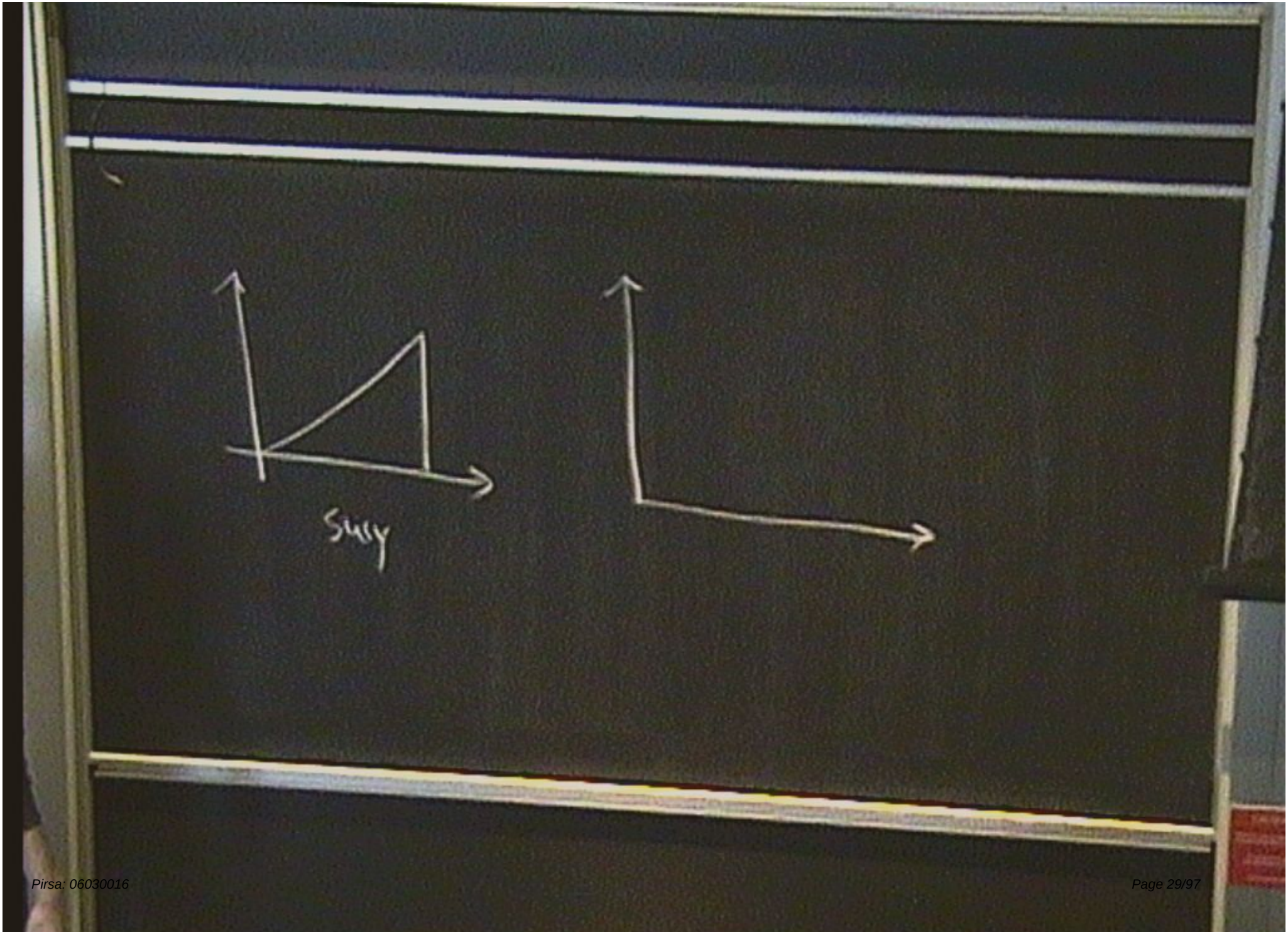
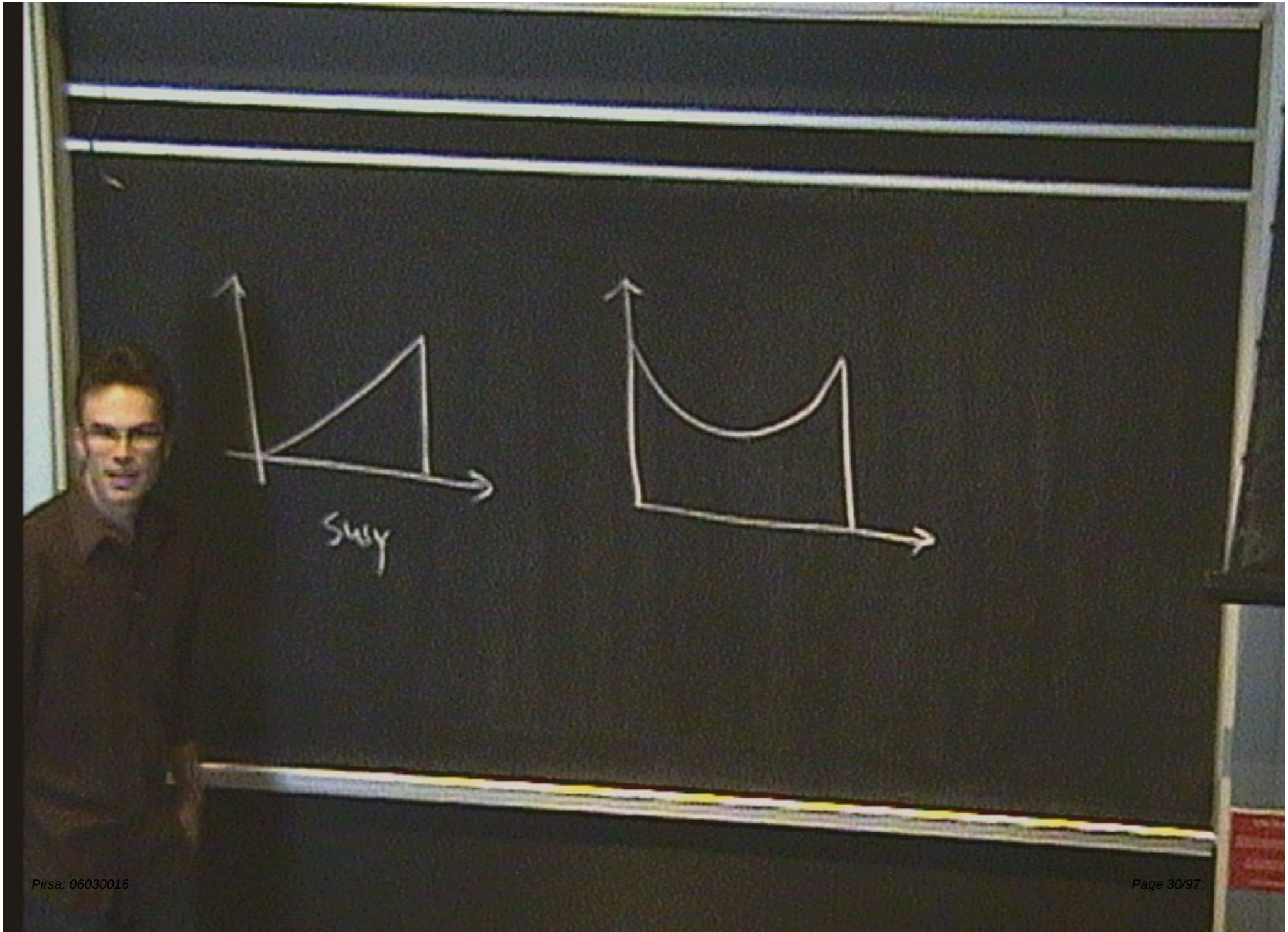
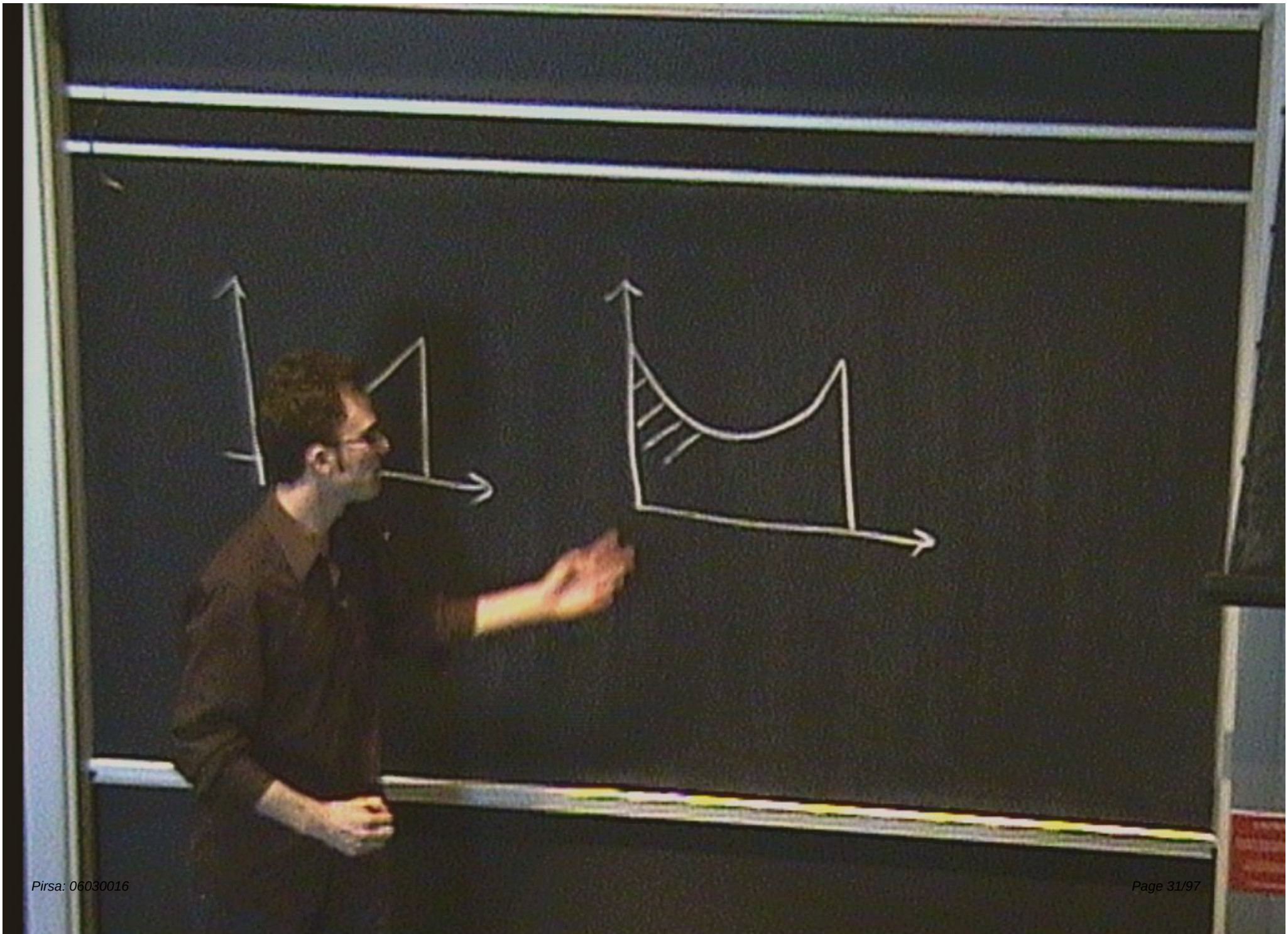
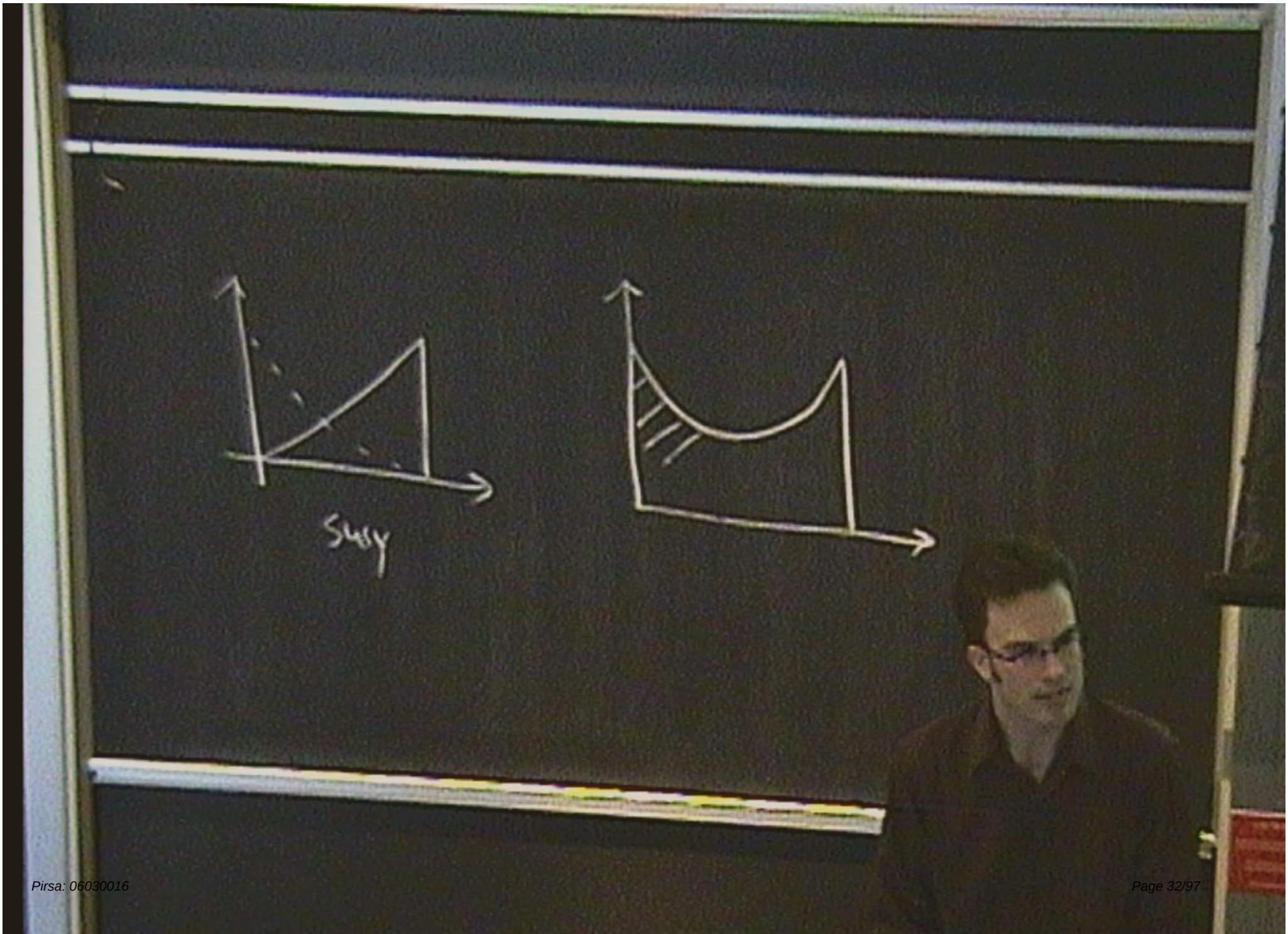


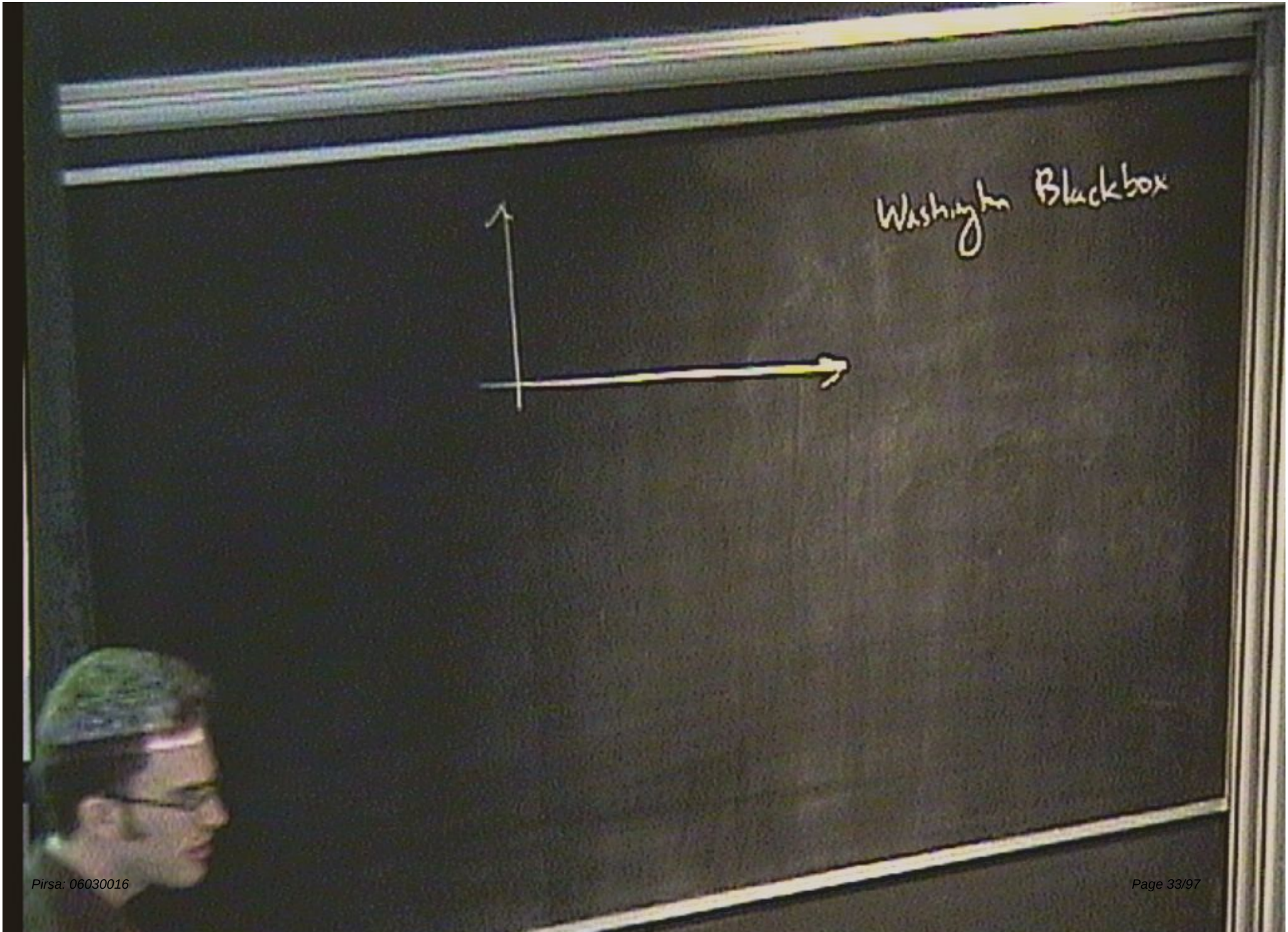


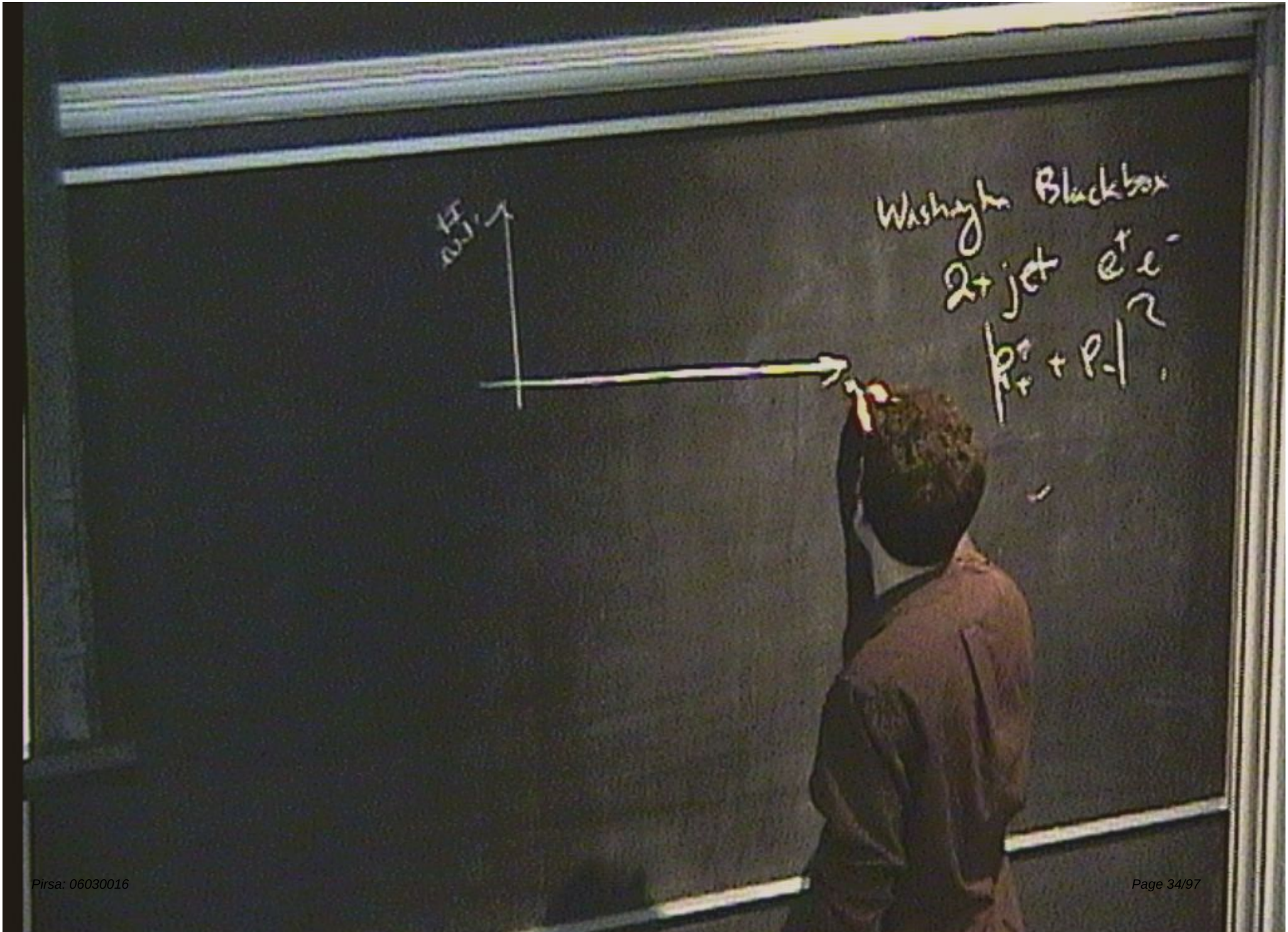

Sun

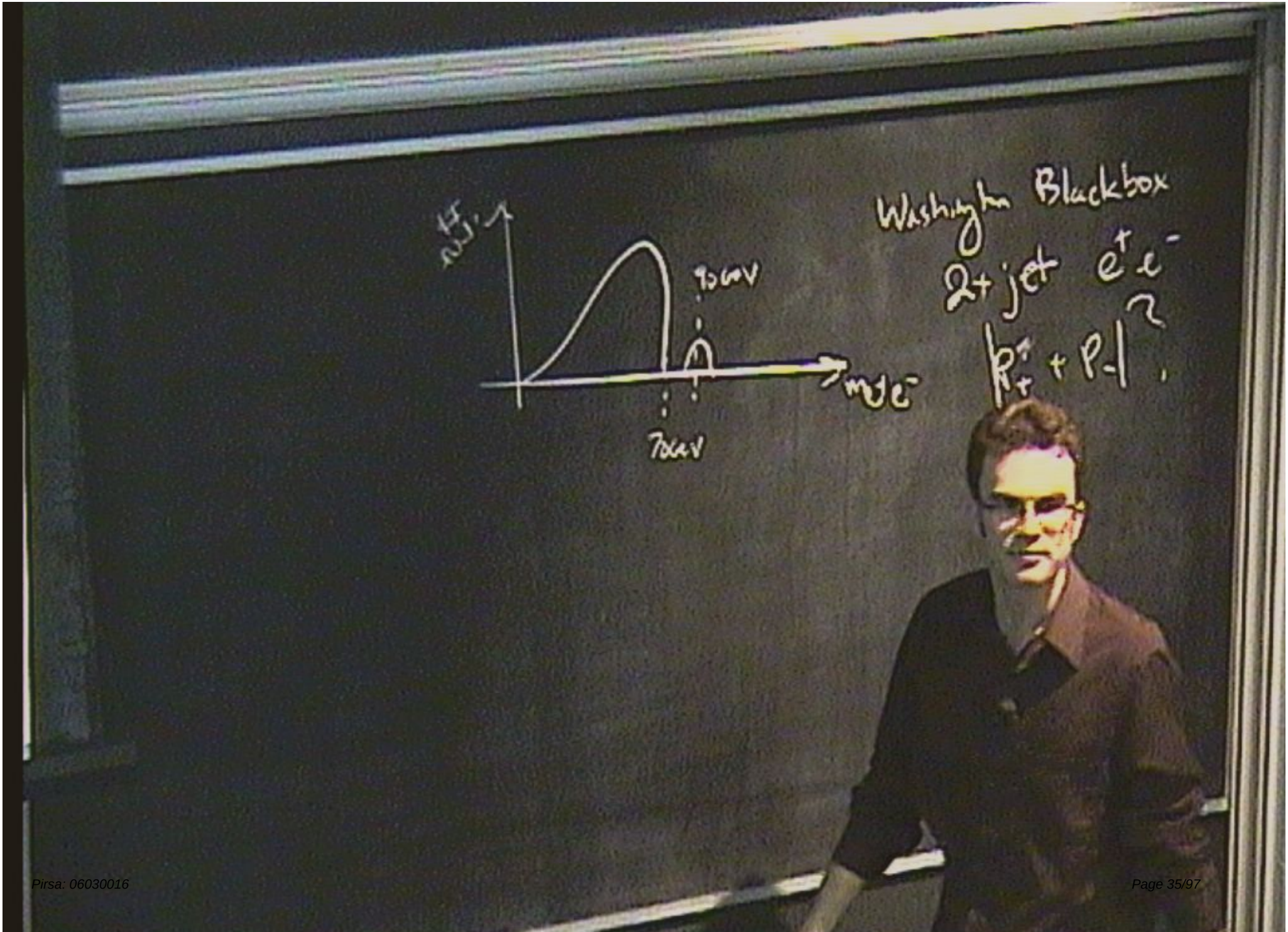

Sway

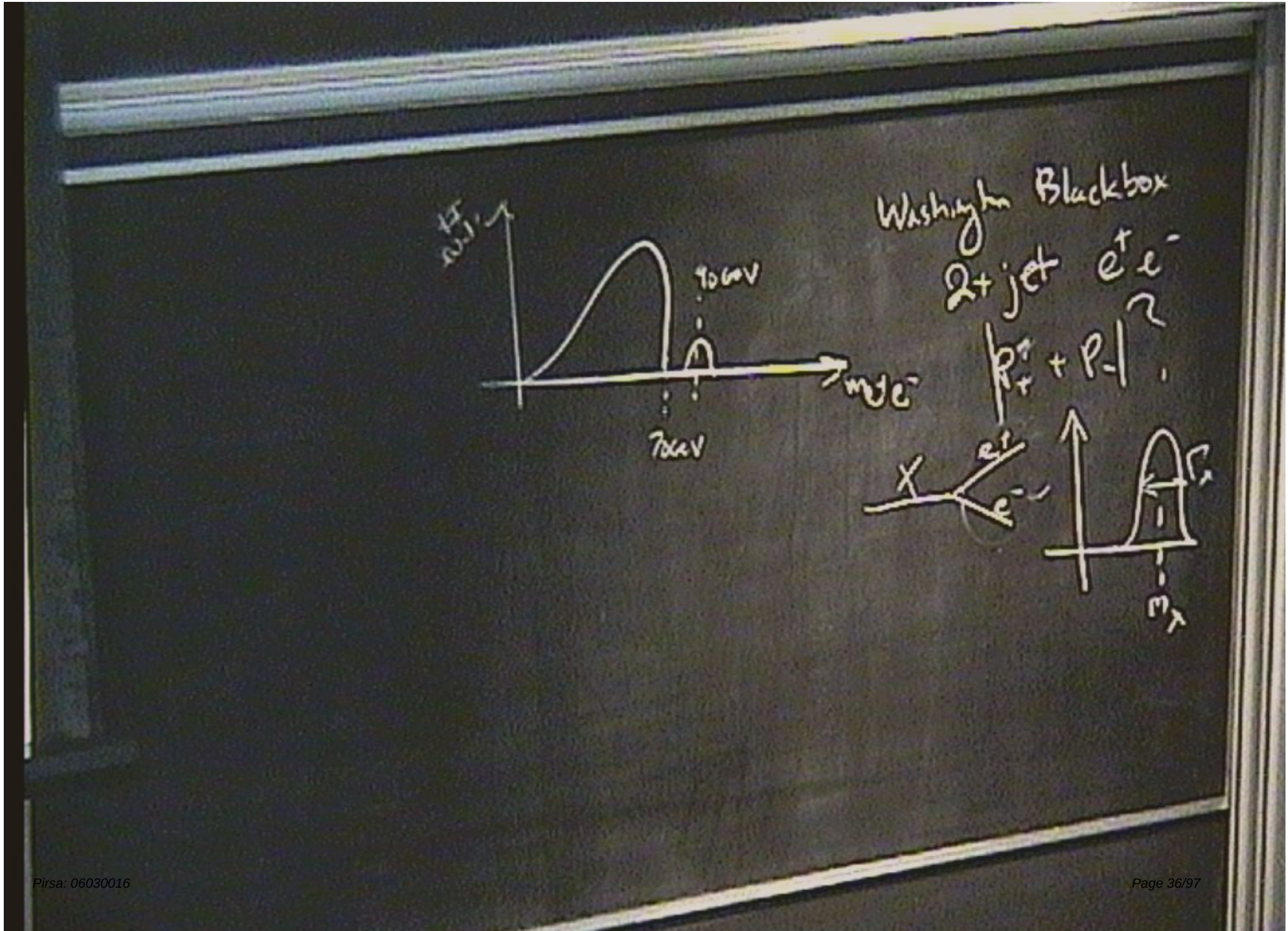


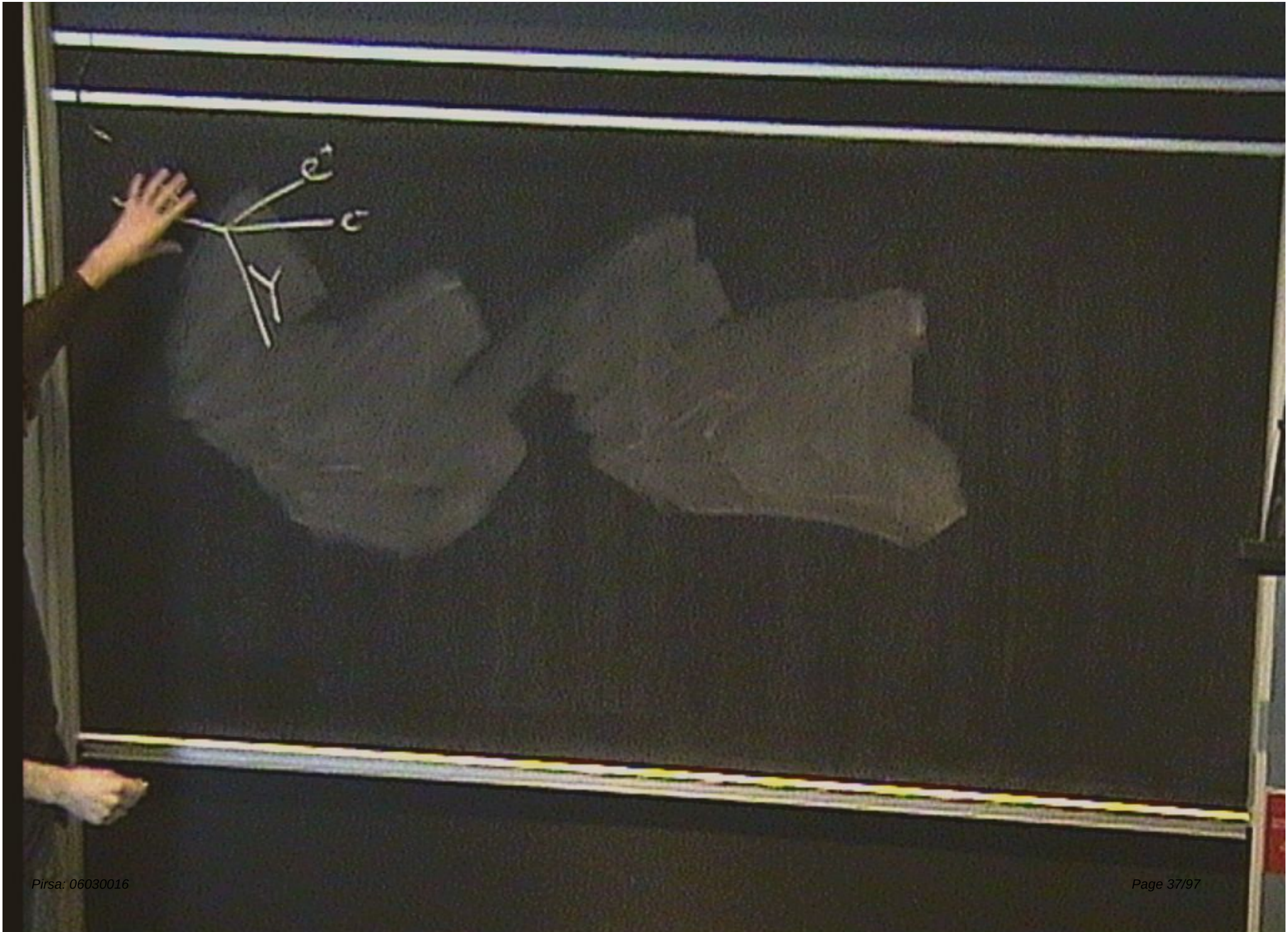

Sway

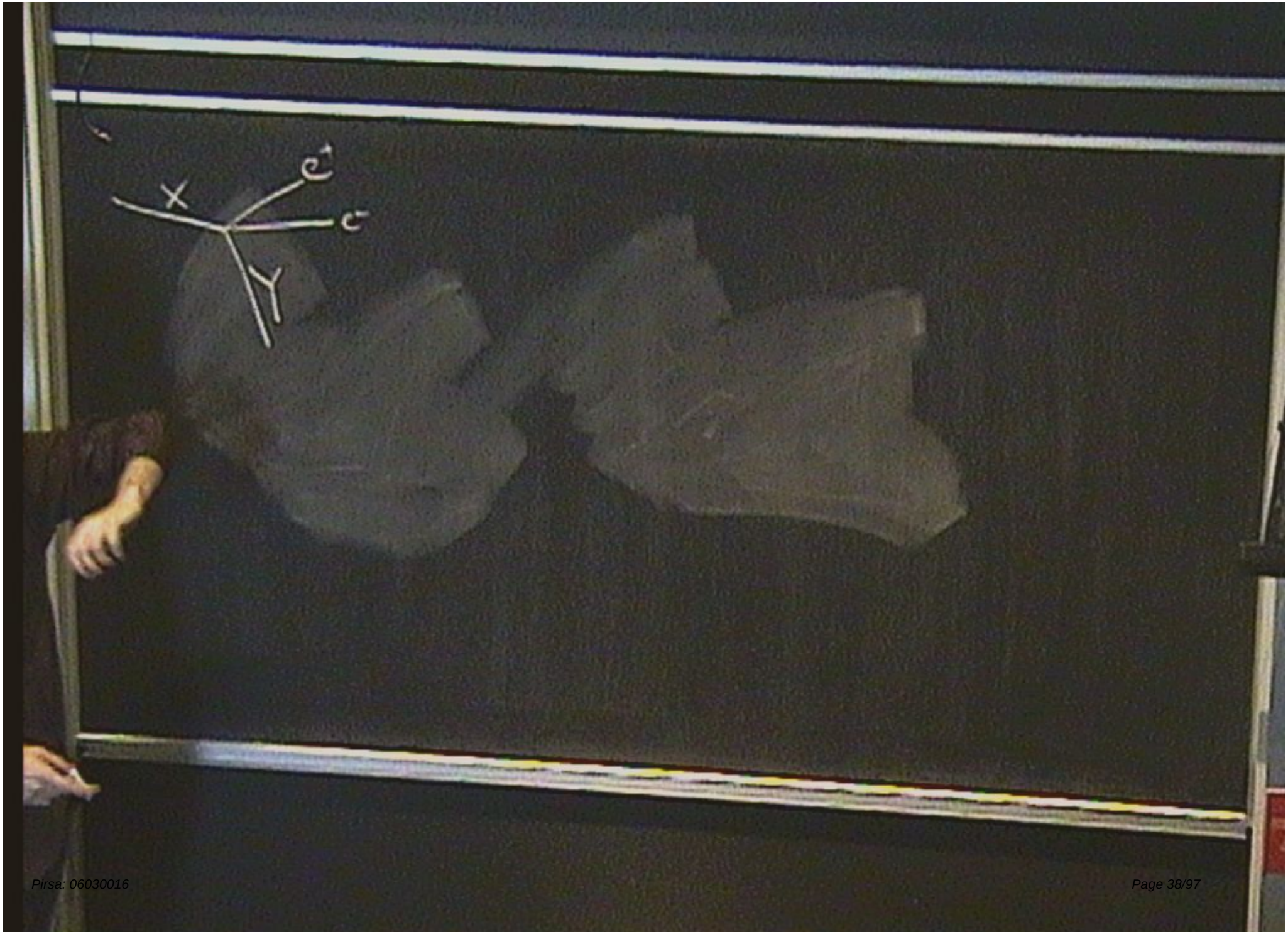

Washington Blackbox

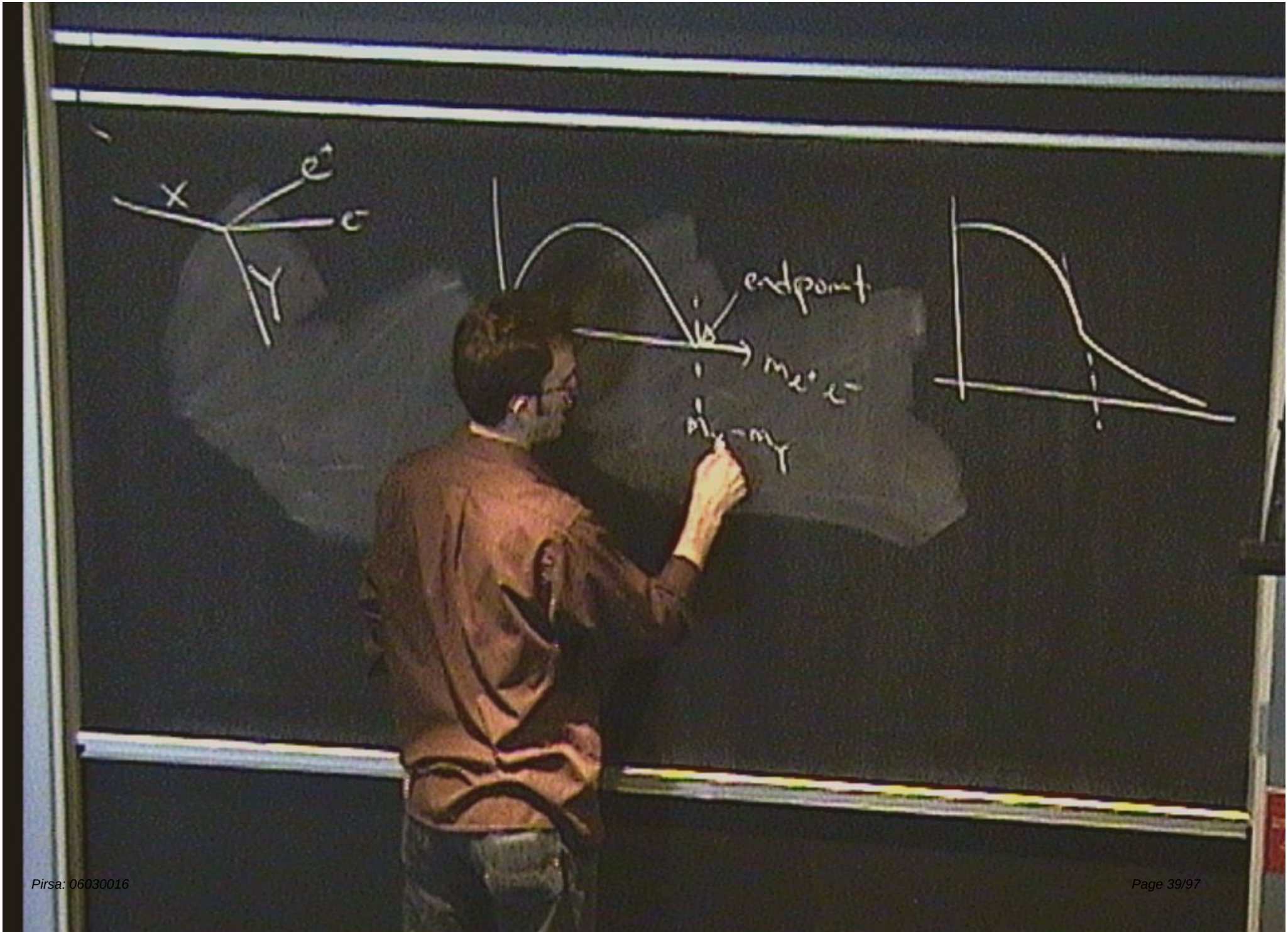

Washington Blackboard
2+ jet e+e-
$|\vec{p}_+ + \vec{p}_-|^2$

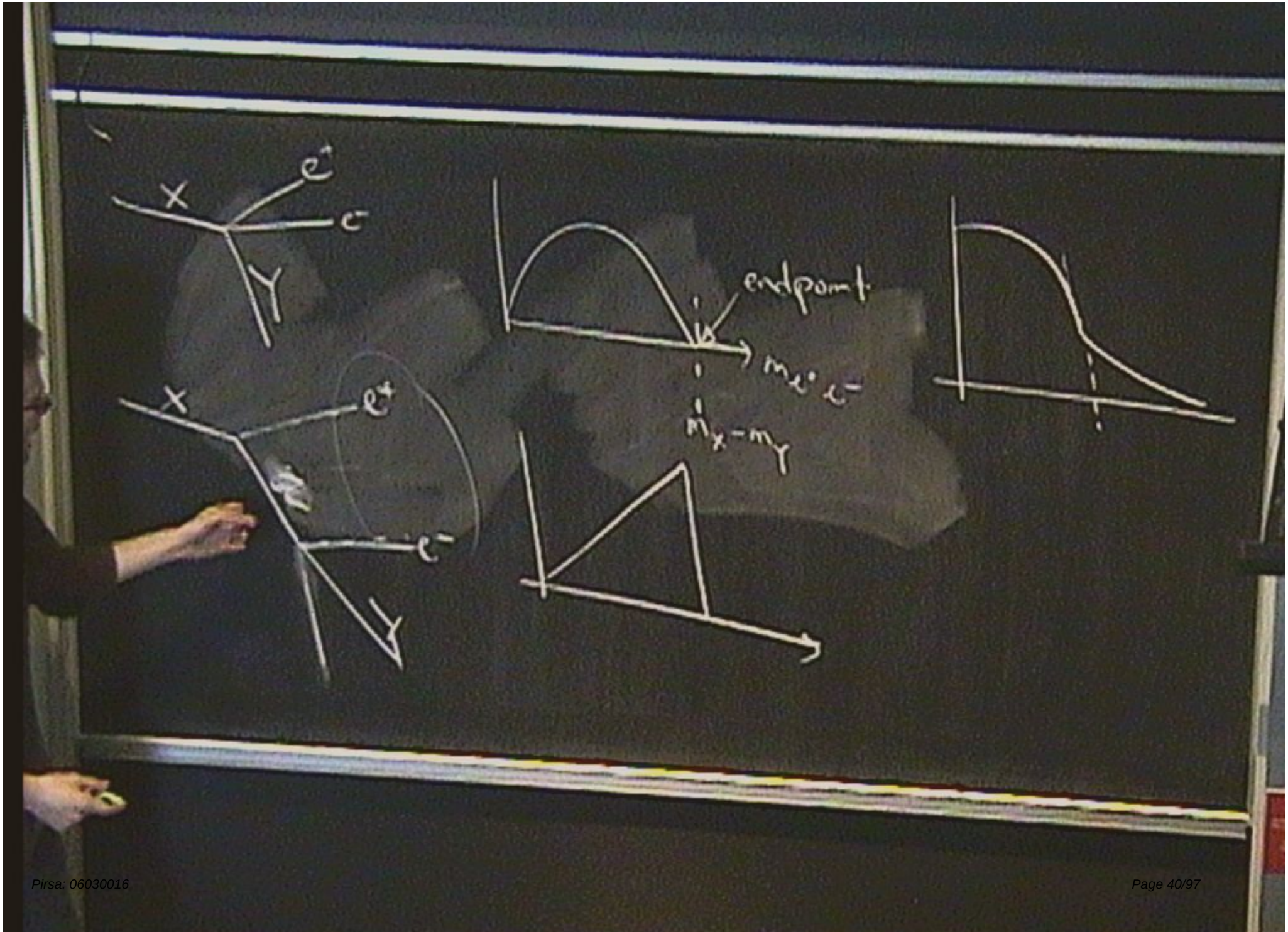

Washington Blackbox
2+ jet e+e-
90 GeV
70 GeV
mass e-

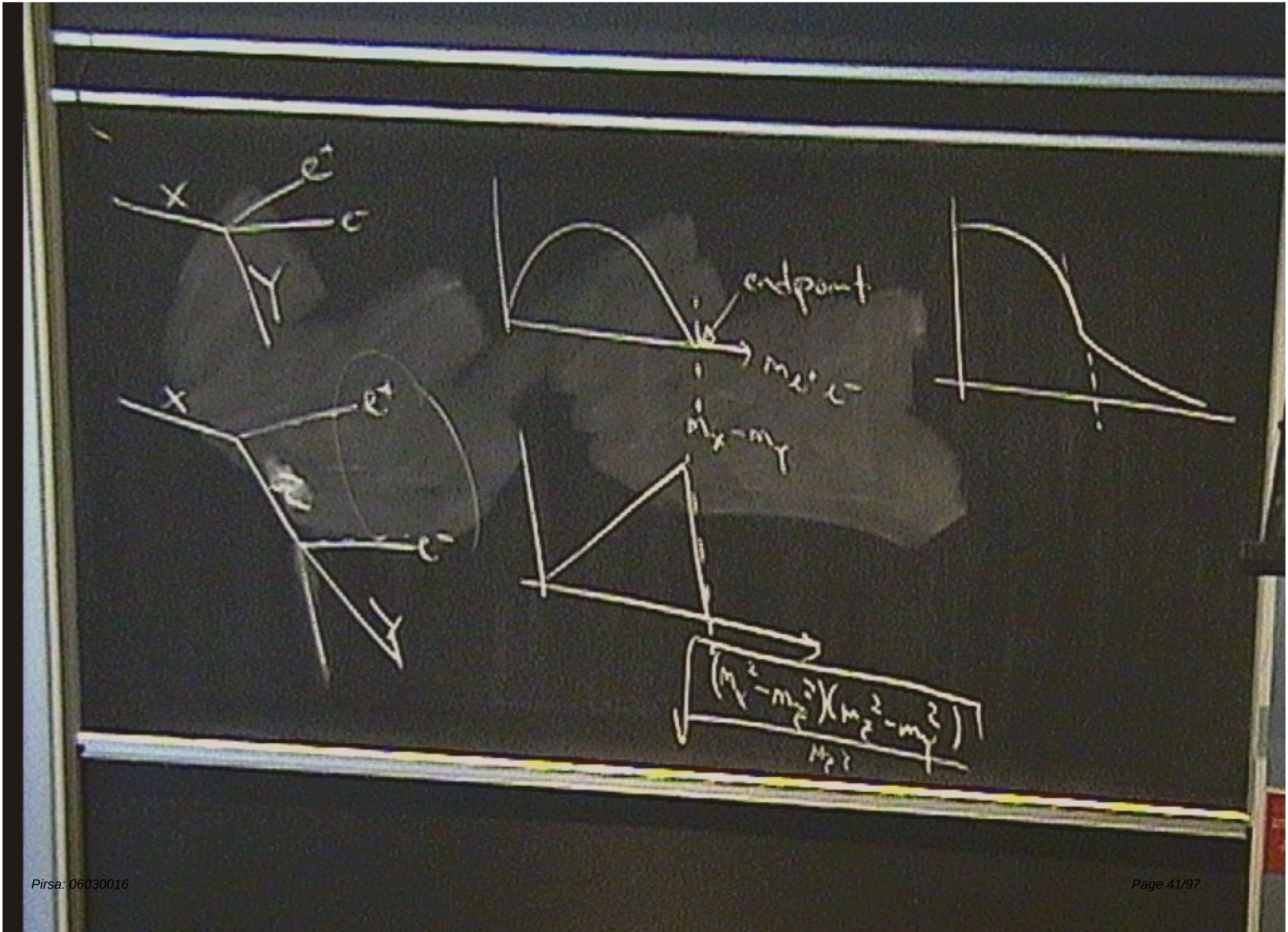

Washington Blackbox
2+ jet e+e-
90 GeV
70 GeV
mass e-

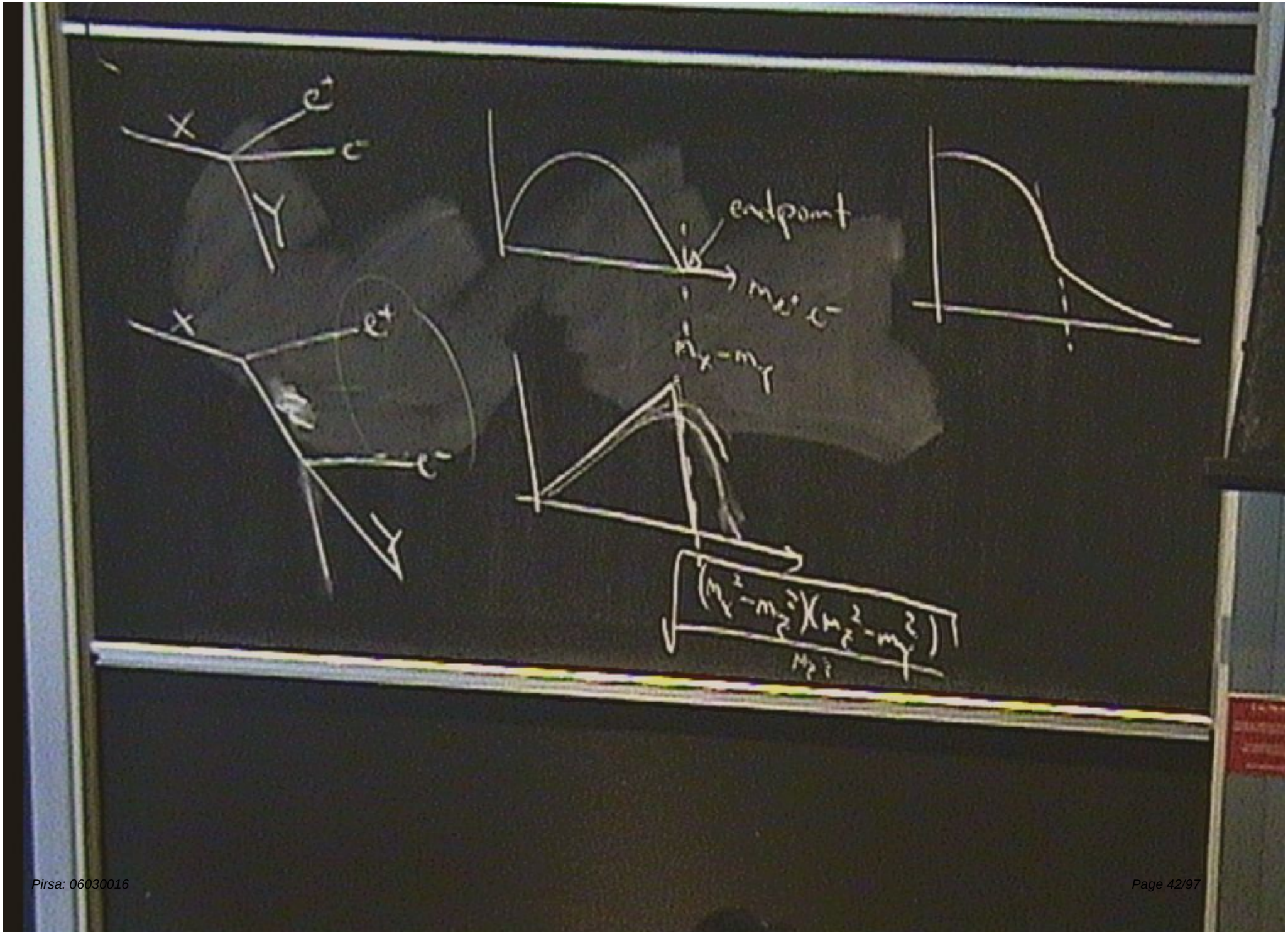

e+
e-
Y

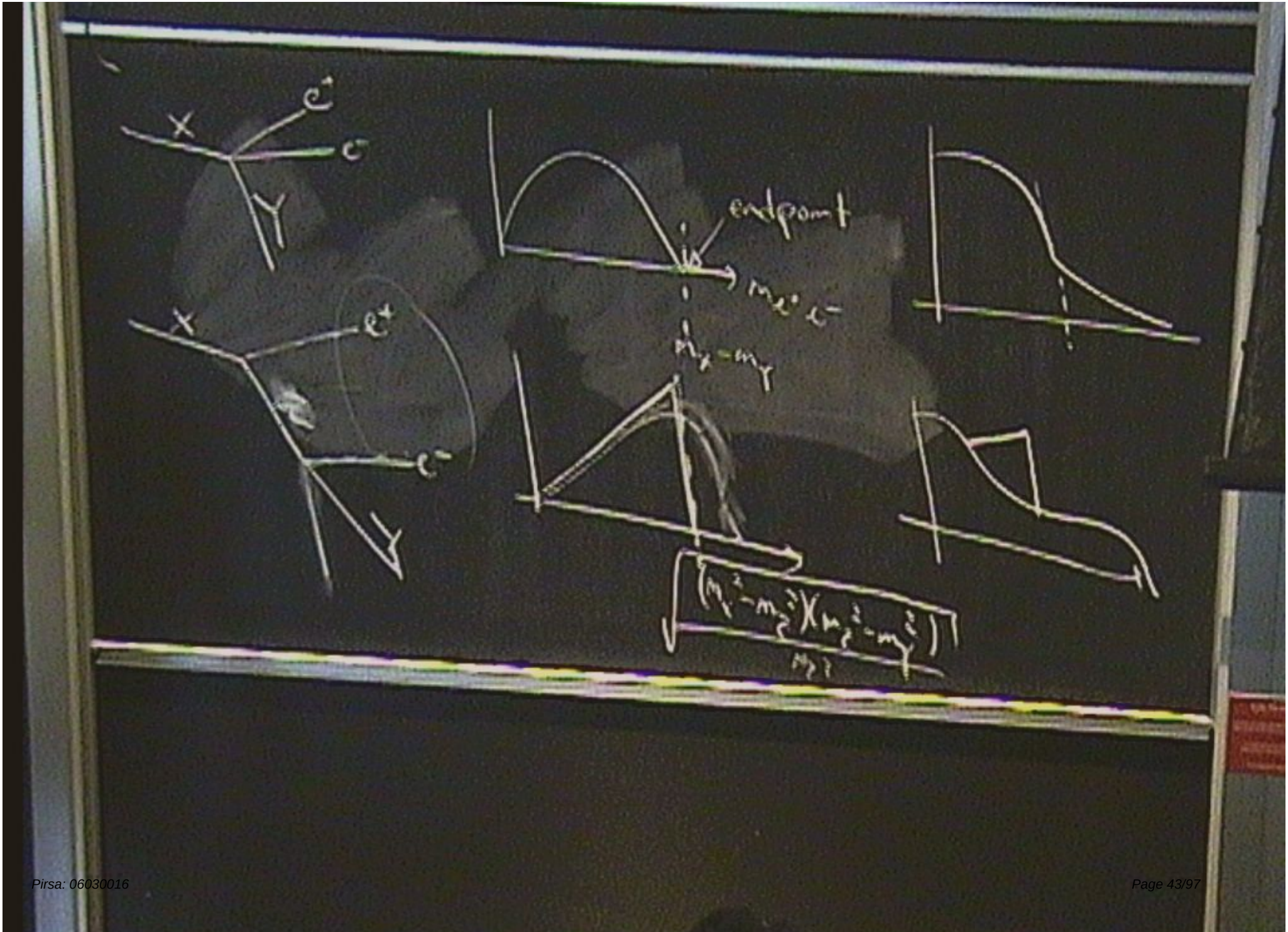

X
e
e
Y

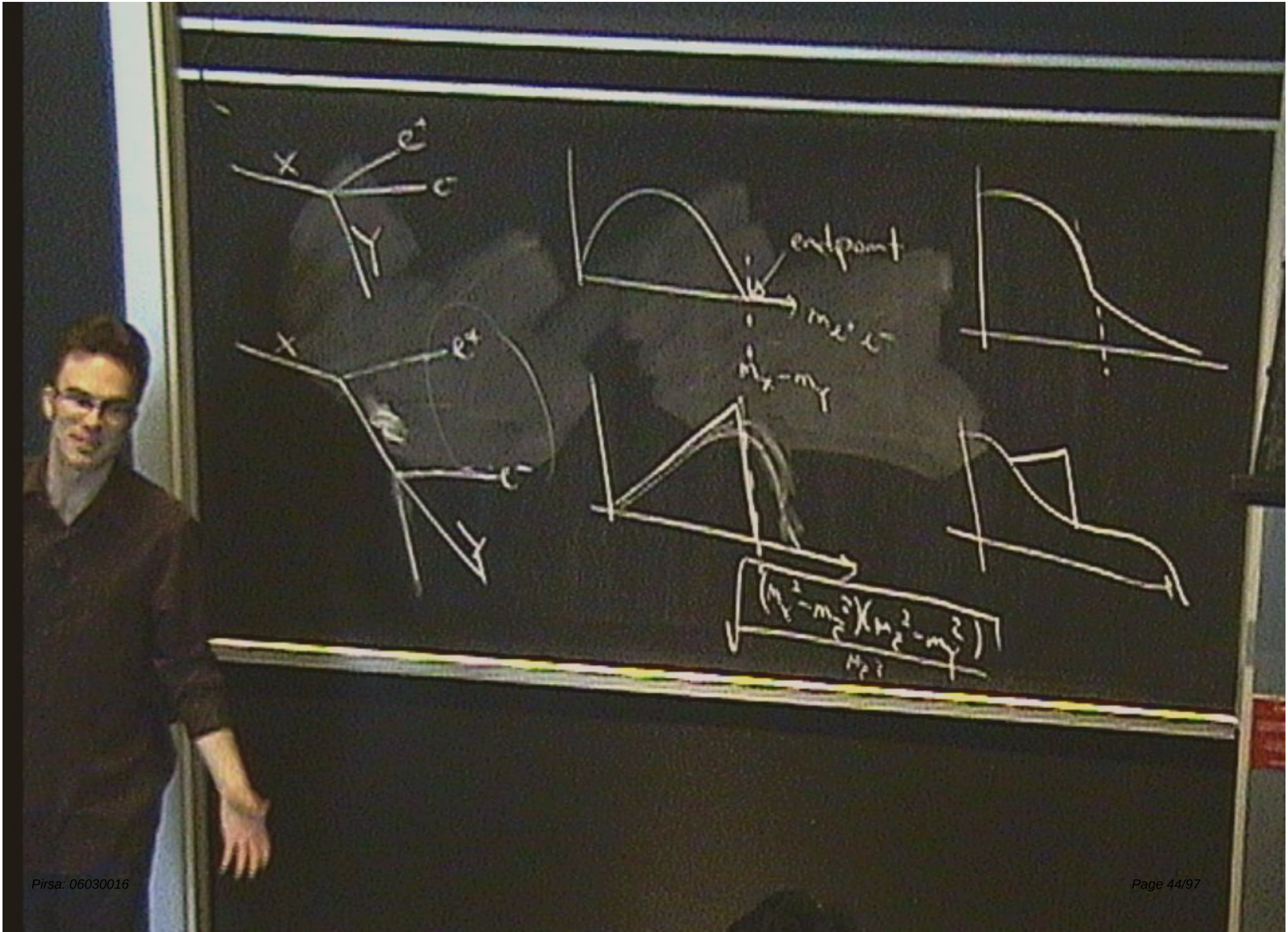

X
e+
e-
Y
endpoint
e-
mY

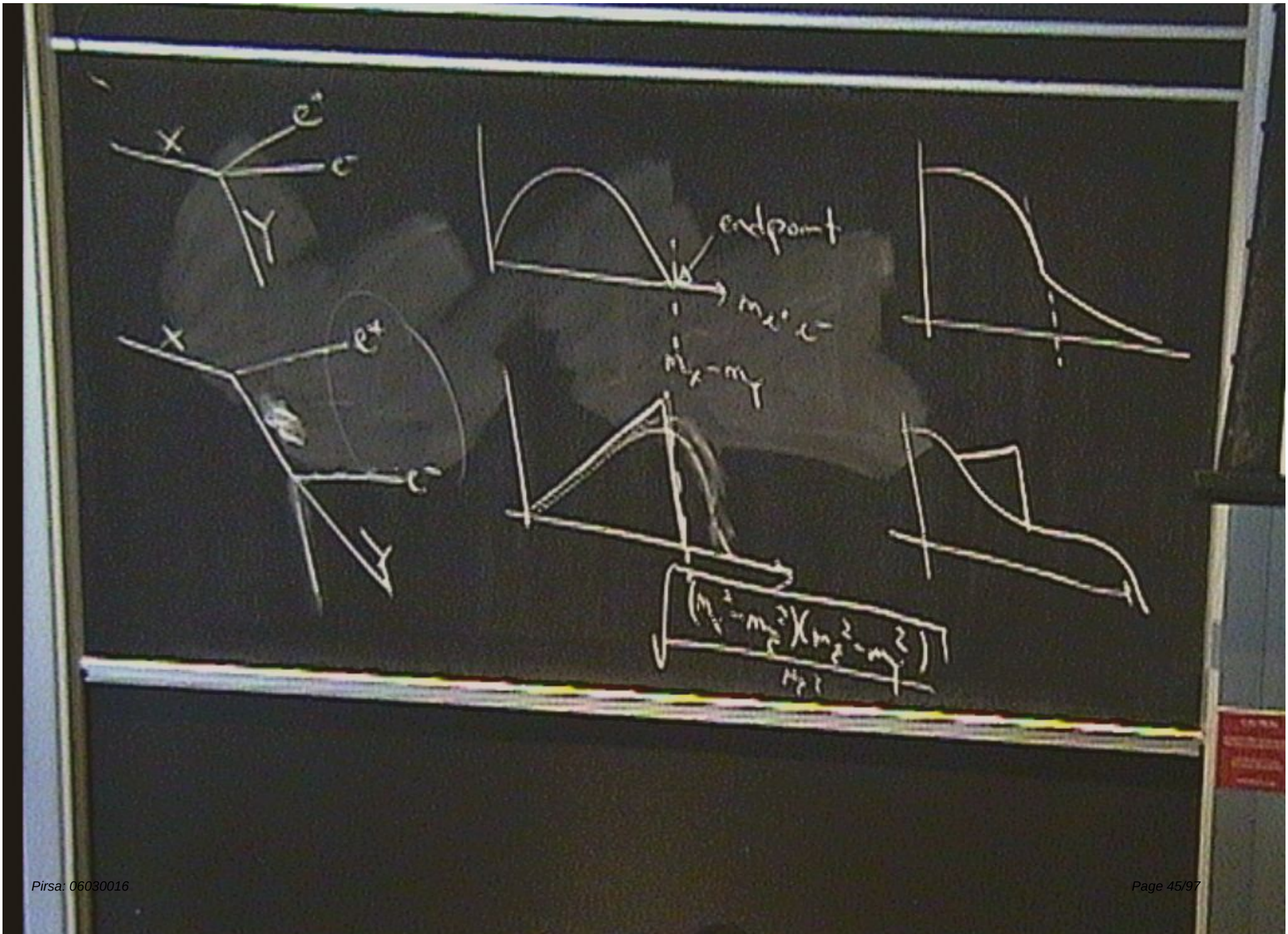

X
e+
e-
Y
endpoint
$m_{e^+e^-}$
$m_X - m_Y$
X
e+
e-
Y


X
e+
e−
Y
endpoint
mX − mY


X
e+
e-
Y
endpoint
X
e+
e-
Y


X
e+
e-
Y
endpoint
X
e+
e-
Y


endpoint
$M_X - m_Y$
$(M_X^2 - m_2^2)(M_2^2 - m_Y^2)$
M_2^2


X
e+
e-
Y
endpoint
X
e+
e-
Y

- The black box data files, the plots and tables, and general information about how use them.
- Why are we doing obviously unrealistic data challenges that lack standard model background?
- Some comments on how to think about standard model backgrounds for the blackbox signals.
- More technical information on how black boxes are generated. *Added update and correction on triggering procedure 12/07/05*
- An important additional caveat about the data samples.

Please Note: Suggested Guidelines for Participants in the LHC OLYMPICS

So that the LHC Olympics can be a useful and enjoyable exercise for people with a wide variety of backgrounds, we suggest that no public announcements of "solutions" to the data challenge be made available in advance of our February conference --- it would spoil the fun! However, other forms of communication, such as

- private consultation between participant groups, involving the sharing of software, discussion of strategies for approaching the data, etc.,
- unpublished presentations **after the February conference**, such as websites, or publicly available powerpoint files or written reports,
- publishable papers on new tools and new approaches that have been motivated by a black box analysis,

are fine and indeed encouraged, as they will contribute to the success of the LHC Olympics effort.

Thanks!!! **[from the organizers]**

Here they are:

The black boxes and calibration samples are in the form of large data files. Each has its own website where you can learn more about it, and where you can look at plots of some distributions and tables of some inclusive signatures. You can also download the data and do some analysis yourself.

Below you can find general information that applies to all of the black boxes --- or more specific information on how to use the plots and tables that the black box creators have provided, how to interpret and use the data files, more details on how the data files were generated, and features/issues with the detector simulation.

I. Black box "classic", which contains 20 *[Not: see below]* inverse femtobarns of data generated with the same *[Not: see below]* physics model as was used in the summer 2005 data challenge, which had only 2 inverse femtobarns of data. (See the important WARNING below.) *[See the new warning, as of 2/04/06, on the following link.]* The black box raw data files, plots and tables extracted from the data, and creators' comments can be found HERE.

II. Black box "uw1", which contains 25 inverse femtobarns of data of a new signal. The black box raw data files, plots and tables extracted from the data, and creators' comments can be found HERE.

III. Black box "harvardbb", which contains two sets of files, one with 5 inverse femtobarns of data of a new signal, and one with 40 inverse femtobarns of the same signal. The black box raw data files, plots and tables extracted from the data, and creators' comments can be accessed HERE.

The calibration samples are

A. a pure ttbar sample.

B. a diboson sample (WW, WZ, and ZZ production.)

Comments on how to use calibration samples are HERE.

ALL PARTICIPANTS: PLEASE READ THIS NOTICE!!

The Plots and Tables ---

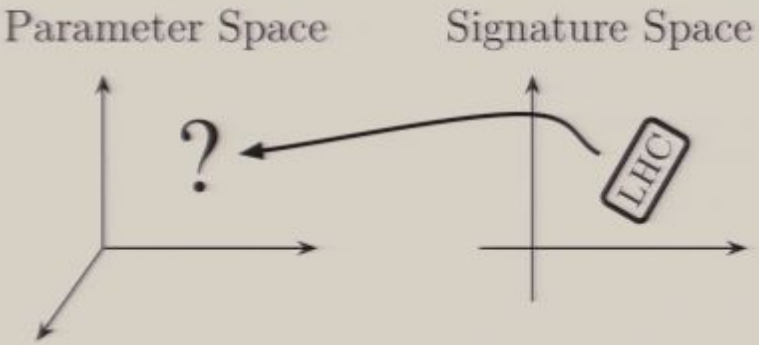
The creators of the black boxes have provided some information about "inclusive signatures", including plots of "kinematic distributions" and tables that show the numbers of events with certain characteristics.

What is an **inclusive signature**? Inclusive signatures are basically anything that can be measured from the full aggregate data (including all types of events) generated through a new physics model. This is to be understood as opposed to what one might *like* to measure (masses of individual new particles, branching fractions of individual new particles) but which may not be possible to extract experimentally, particularly at a hadron

lhc olympics : fall 2005

black box | signatures | software

The Harvard Black Box



The Harvard LHC Olympics group has constructed a black box of new physics signals, representing 40 fb^{-1} of collected data at the LHC. Some of the obvious aspects of the data and relevant plots are presented below. The most prominent features are the presence of events with missing energy and events with diphotons. Also, a histogram of the dilepton invariant mass has a prominent bump near 1.5 TeV.

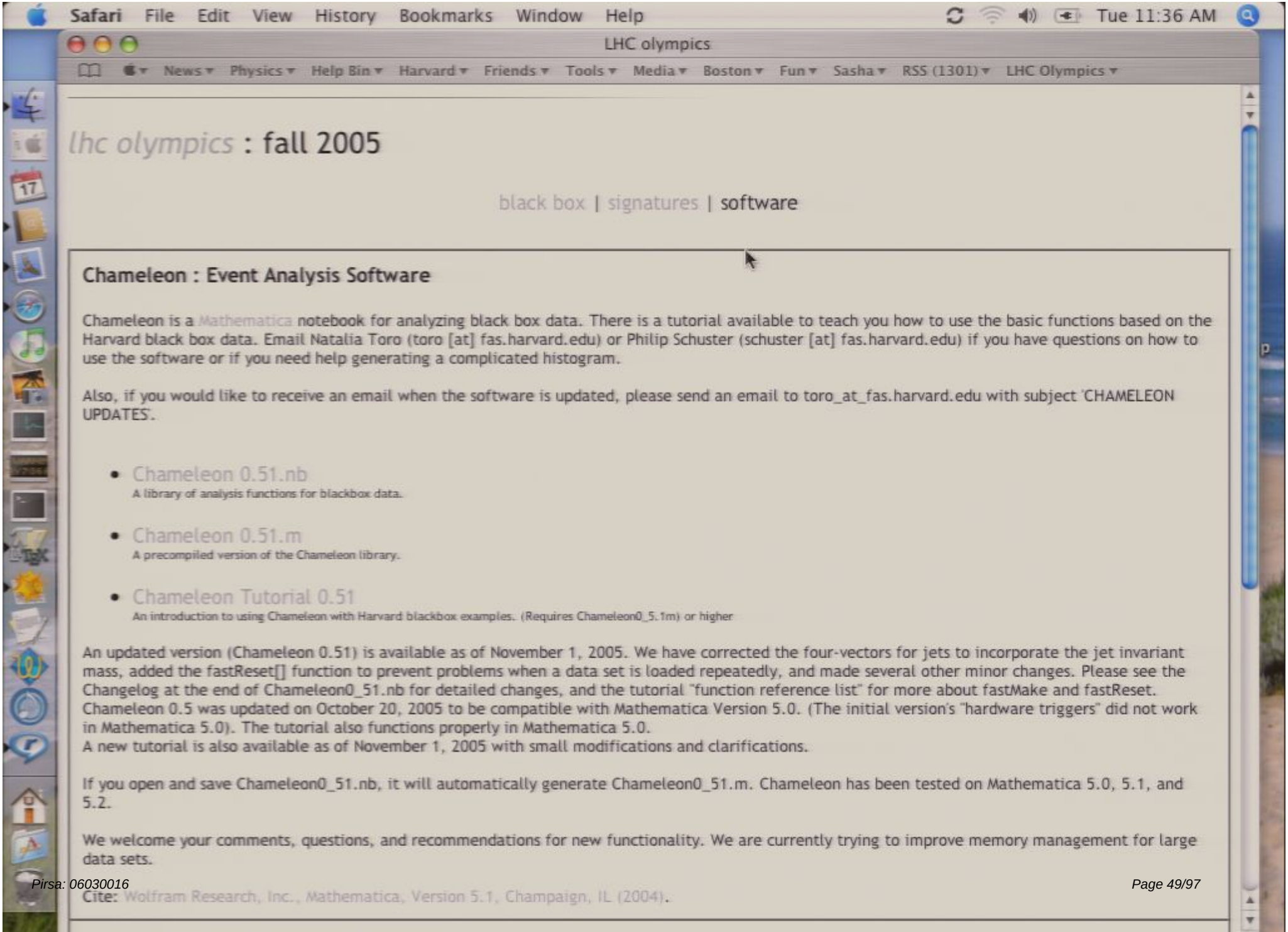
We have developed a user-friendly Mathematica package allowing a simple way to make histograms of any desired distributions, for any black box sample. A tutorial for this package together with many worked examples has been provided. This should make it easy and fun for *anyone* to play with any of the black box data sets.

The Harvard LHC Olympics group consists of Nima Arkani-Hamed, Lian-Tao Wang, as well as a team of graduate students who have been largely responsible for generating the black box and writing the analysis software codes. The black box was generated by Matt Baumgart, Cliff Cheung, Liam Fitzpatrick, Tom Hartman, Can Kilic, and Jesse Thaler. The Mathematica analysis package was written by Philip Schuster and Natalia Toro, with additional functionality and C code cross checks by the generation team.

See the Official LHC Olympics page for more information on how events were generated and techniques for analysis. Email Jesse Thaler if you are having trouble downloading any of the files on this page.

Black Box Data

The Harvard Black Box is stored on the Fermilab servers. You must enter your email address to access the data, so that we can keep you informed about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black box | signatures | software
Chameleon : Event Analysis Software
Chameleon is a Mathematica notebook for analyzing black box data. There is a tutorial available to teach you how to use the basic functions based on the Harvard black box data. Email Natalia Toro (toro [at] fas.harvard.edu) or Philip Schuster (schuster [at] fas.harvard.edu) if you have questions on how to use the software or if you need help generating a complicated histogram.
Also, if you would like to receive an email when the software is updated, please send an email to toro_at_fas.harvard.edu with subject 'CHAMELEON UPDATES'.
Chameleon 0.51.nb
A library of analysis functions for blackbox data.
Chameleon 0.51.m
A precompiled version of the Chameleon library.
Chameleon Tutorial 0.51
An introduction to using Chameleon with Harvard blackbox examples. (Requires Chameleon0_5.1m) or higher
An updated version (Chameleon 0.51) is available as of November 1, 2005. We have corrected the four-vectors for jets to incorporate the jet invariant mass, added the fastReset[] function to prevent problems when a data set is loaded repeatedly, and made several other minor changes. Please see the Changelog at the end of Chameleon0_51.nb for detailed changes, and the tutorial "function reference list" for more about fastMake and fastReset.
Chameleon 0.5 was updated on October 20, 2005 to be compatible with Mathematica Version 5.0. (The initial version's "hardware triggers" did not work in Mathematica 5.0). The tutorial also functions properly in Mathematica 5.0.
A new tutorial is also available as of November 1, 2005 with small modifications and clarifications.
If you open and save Chameleon0_51.nb, it will automatically generate Chameleon0_51.m. Chameleon has been tested on Mathematica 5.0, 5.1, and 5.2.
We welcome your comments, questions, and recommendations for new functionality. We are currently trying to improve memory management for large data sets.
Cite: Wolfram Research, Inc., Mathematica, Version 5.1, Champaign, IL (2004).

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We welcome your comments, questions, and recommendations for new functionality. We are currently trying to improve memory management for large data sets.

Cite: Wolfram Research, Inc., Mathematica, Version 5.1, Champaign, IL (2004).

BlackBox : Event Generation Software

The following is a modified version of the official LHC Olympics blackbox generation software that we used at Harvard to generate our black box. See the main LHC Olympics page for the official version of this software. Note that this version is not sanctioned by the LHC Olympics, or by the authors of Pythia, CPyth, CompHEP, StdHEP, CERNLIB, or PGS. Use at your own risk.

Information on how to use and install the software is available on the LHC Wiki. Email questions, comments, and bug reports to Jesse Thaler.

- blackbox software
  black box event generation software

Terse Instructions

More detailed instructions, including information on installing the software on Linux, Mac OS X, and Windows, is available at the LHC Wiki.

```
Download blackbox.tgz

tar xvzf blackbox.tgz
cd blackbox
make all                    # This script does the necessary installation steps (in principle).
./run.sh                    # See if it works.  Should be self-explanatory.
```

LHCO Activity at Princeton

Team members: LR, HV

Recent additions: Ian Low, Radovan Dermisek, ...

Expert advise from: Chris Tully

Root analysis by: Chris Rogan

Pythia help from: Matt Buican, Diego Hofman

Key discussions with: Brent Nelson, Jesse Thaler, Lian-Tao Wang

Some basic analysis and a shameless guess for UW1 BB

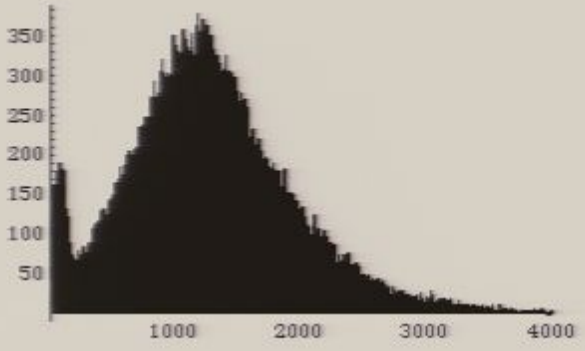
The "easiest" blackbox?

Know *a priori* it is PYTHIA-MSSM

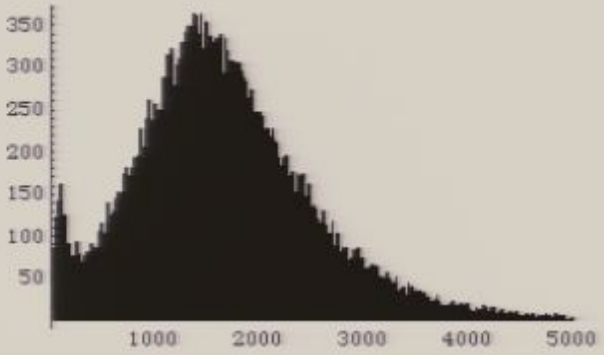
Back and forth between systematic bottom/up approach and serendipity...

Usual disclaimers apply

Basic energy scales



Meff

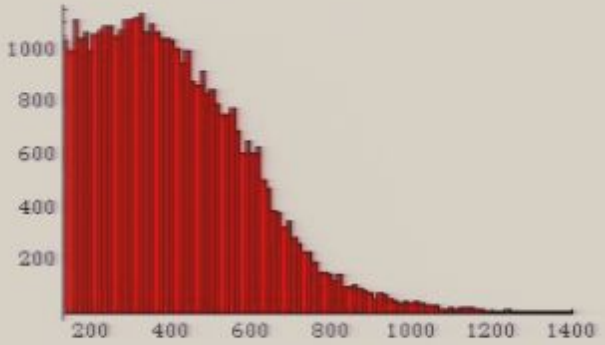


InvMass

$M_{\text{eff}} \equiv \sum |p_T|$

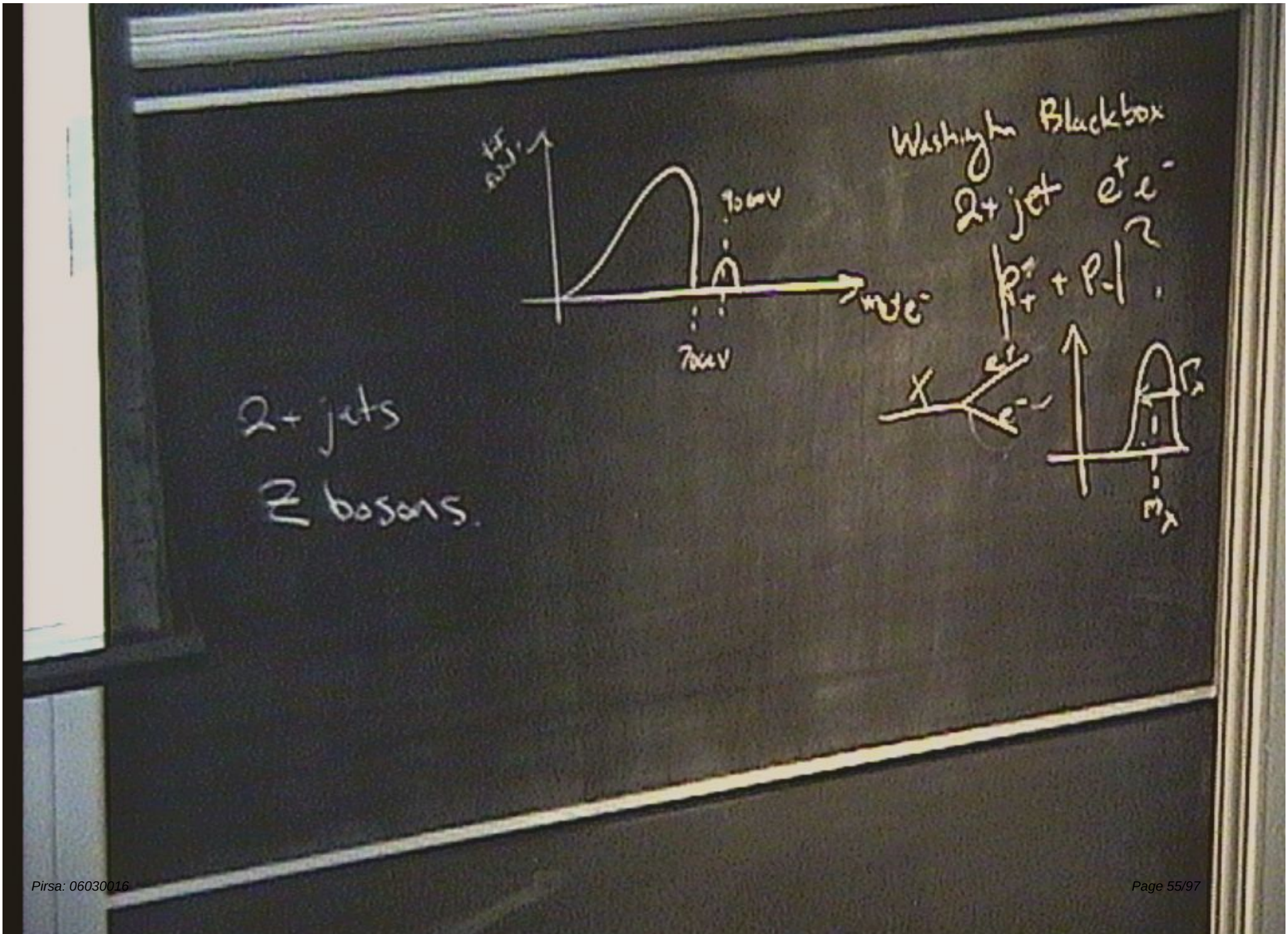
$M_{new} \sim 750/800$ GeV

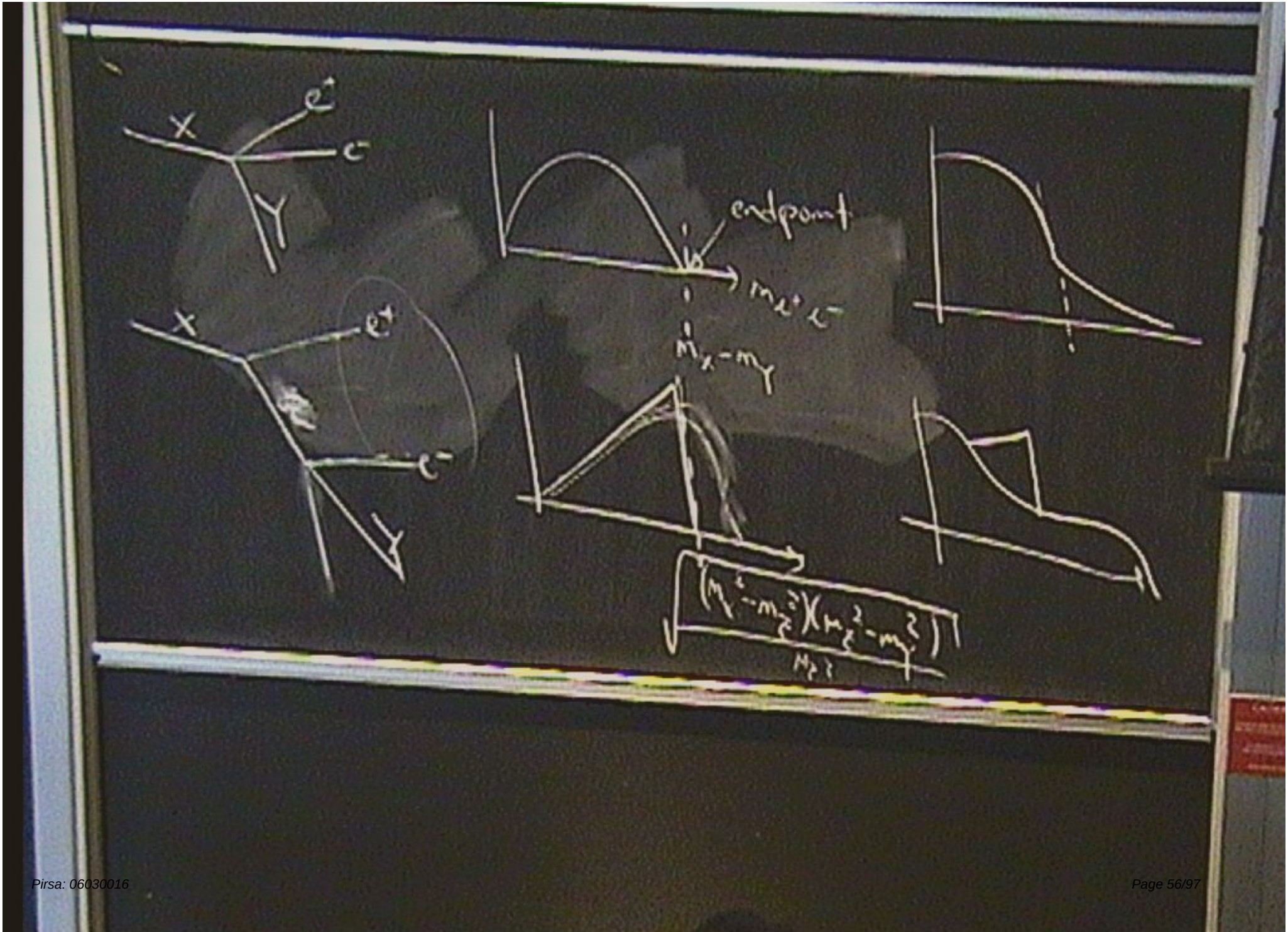
A feature at low energy

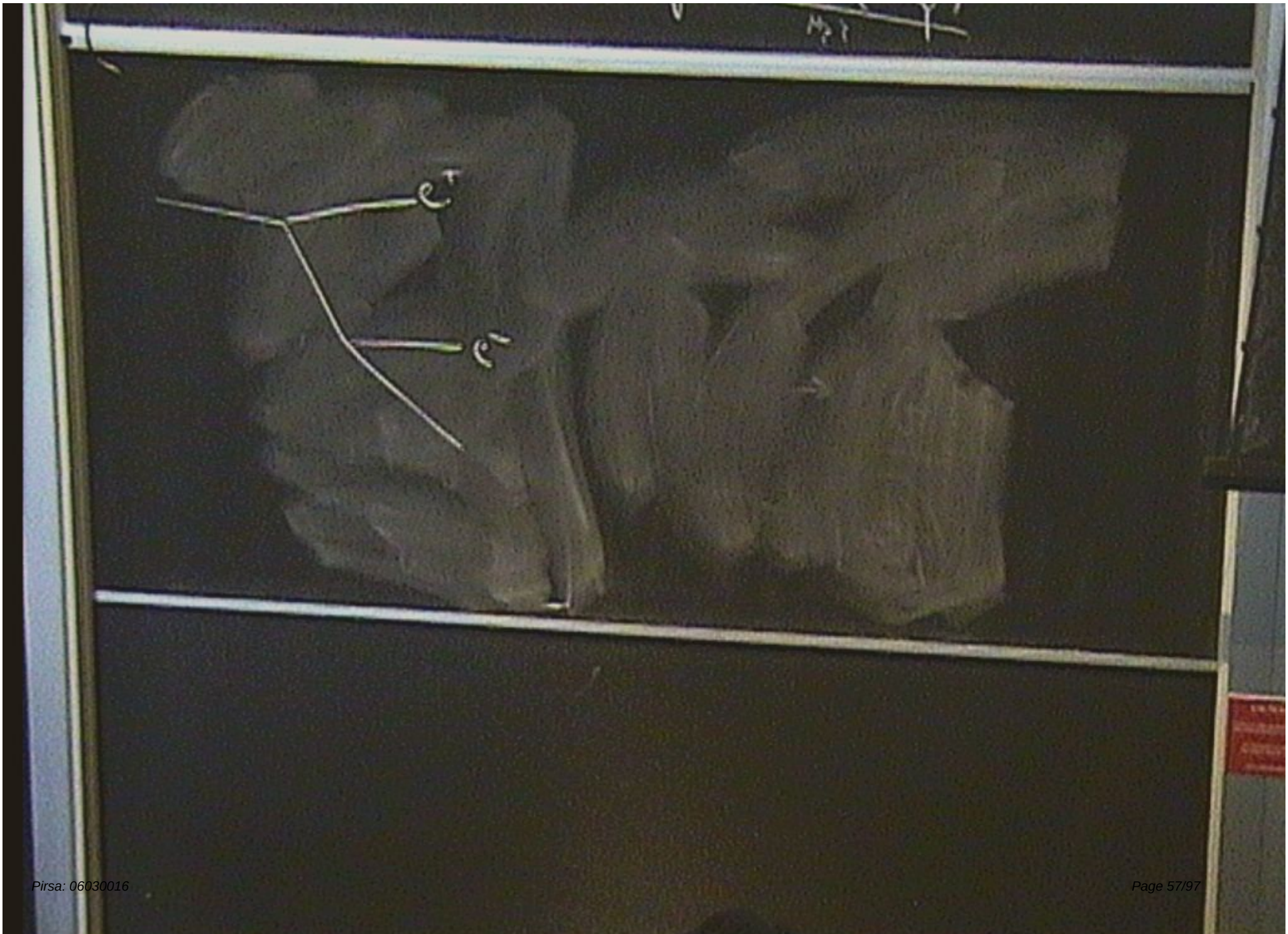


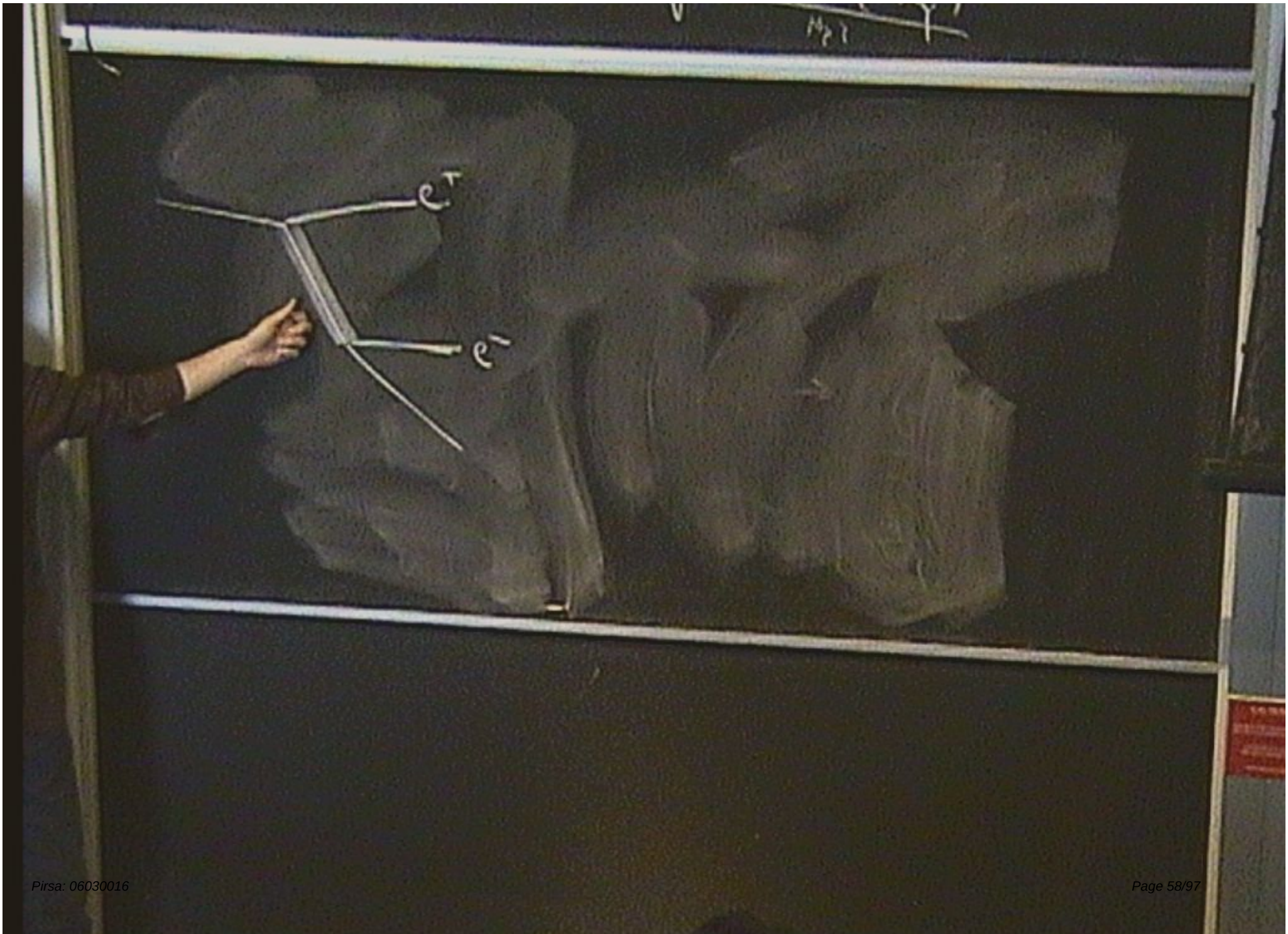
Missing ET

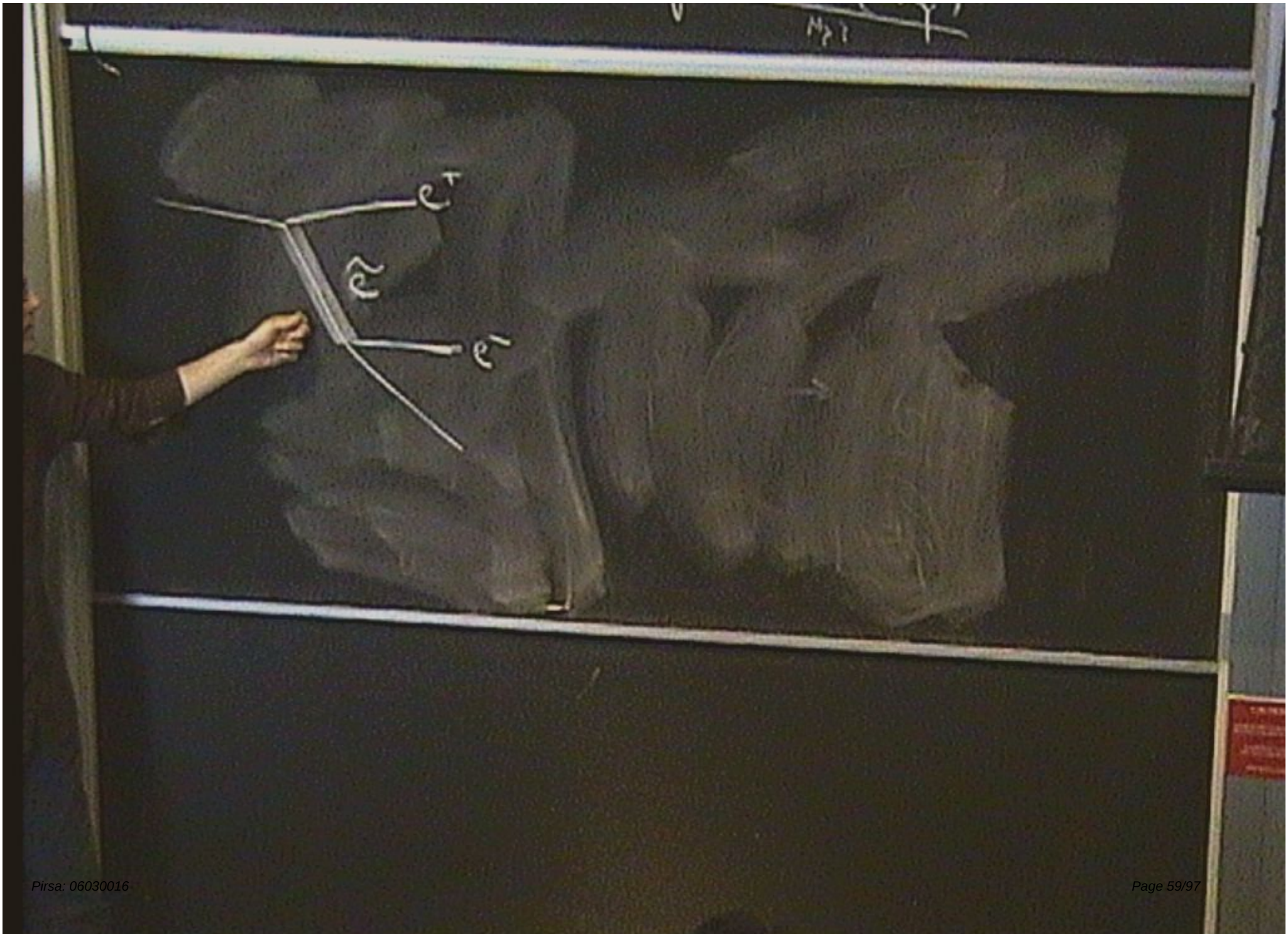
Stable LSP

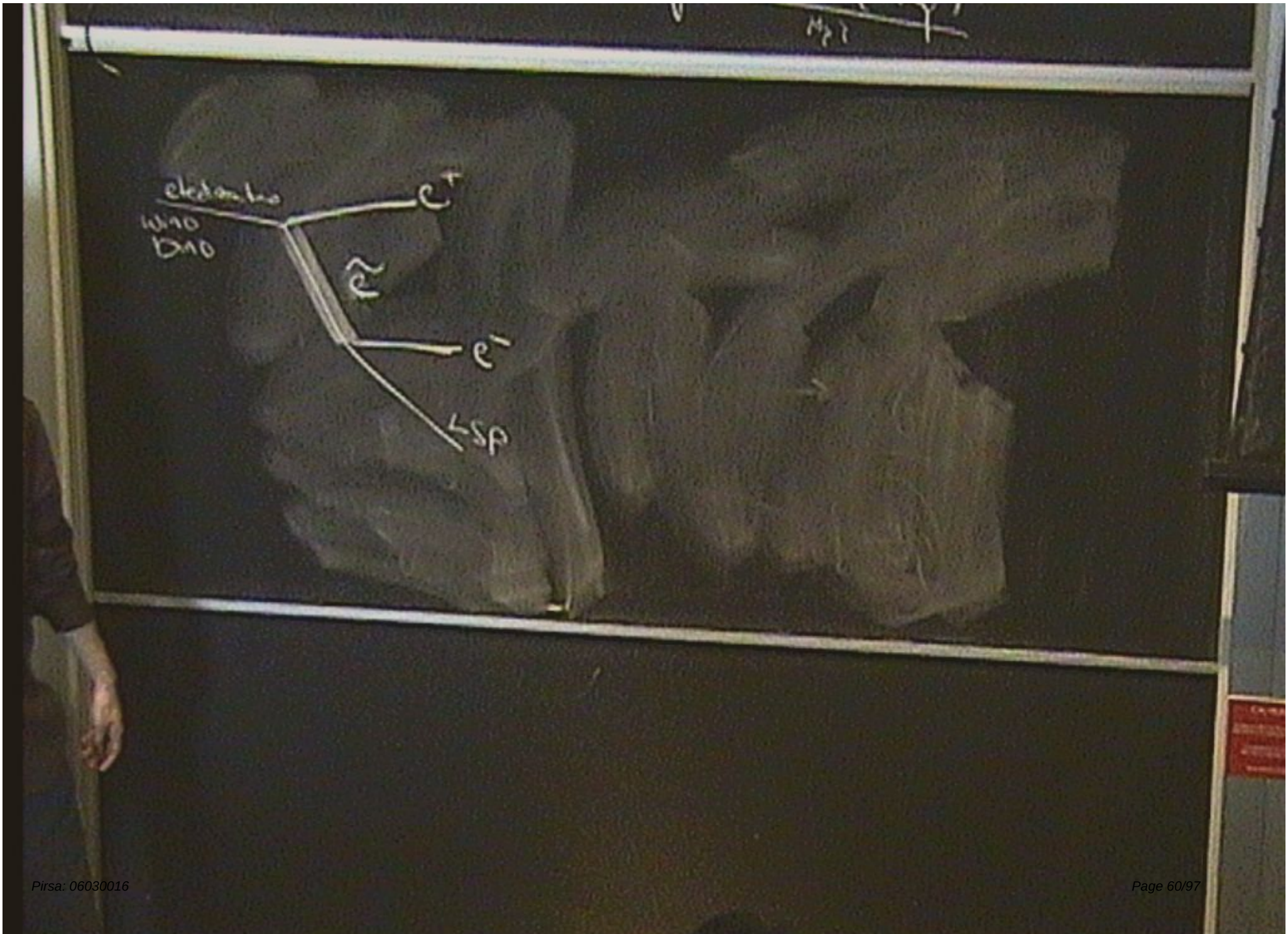

90 GeV
70 GeV
Washington Blackbox
2+ jet e^+e^-
$|\vec{P}_+ + \vec{P}_-|^2$
2+ jets
2 bosons.

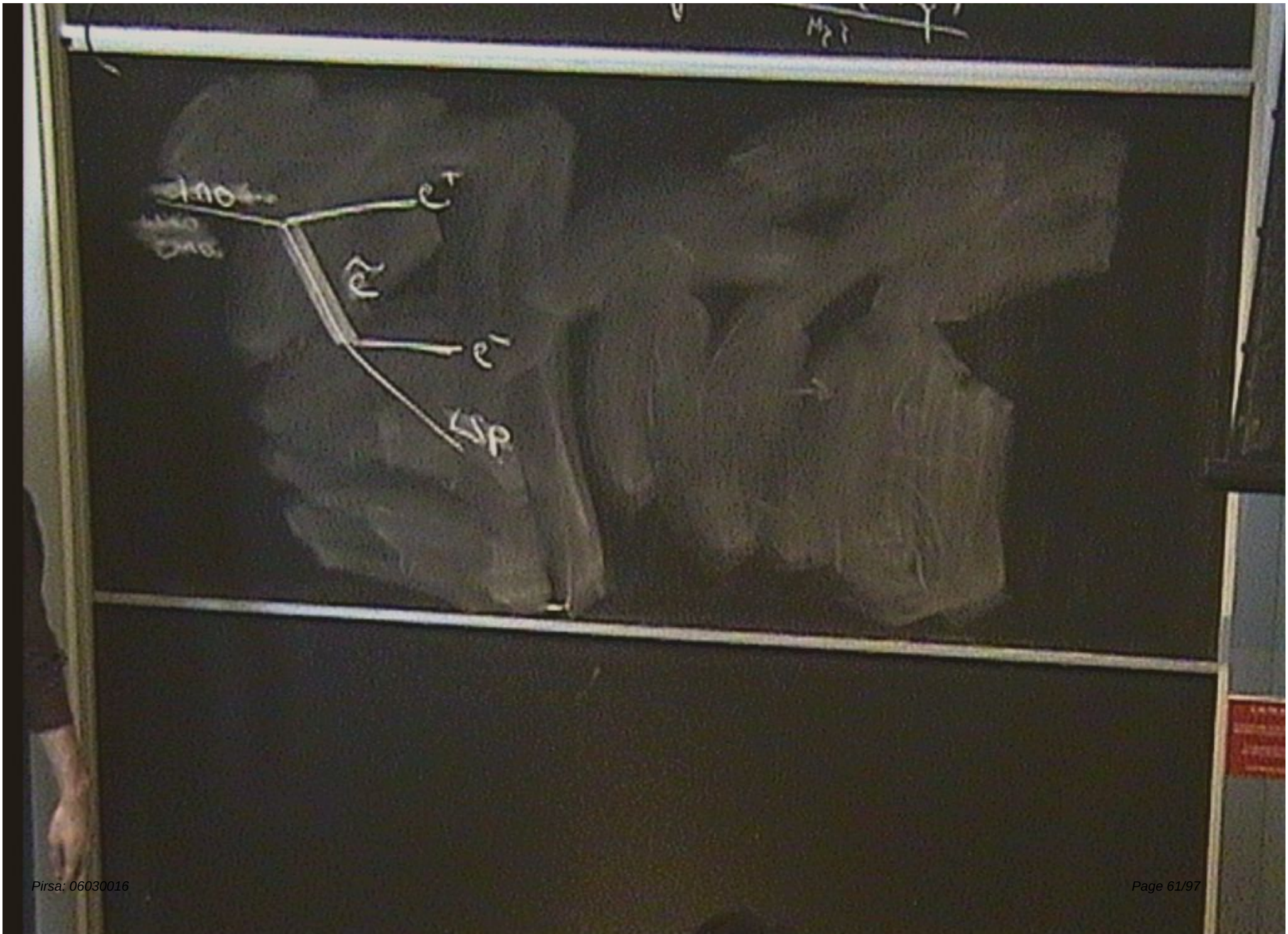

X
e+
e-
Y
endpoint
$m_{e^+e^-}$
$M_X - m_Y$
X
e+
e-
Y
$(M_X^2 - m_Z^2)(m_Z^2 - m_Y^2)$
M_Z^2

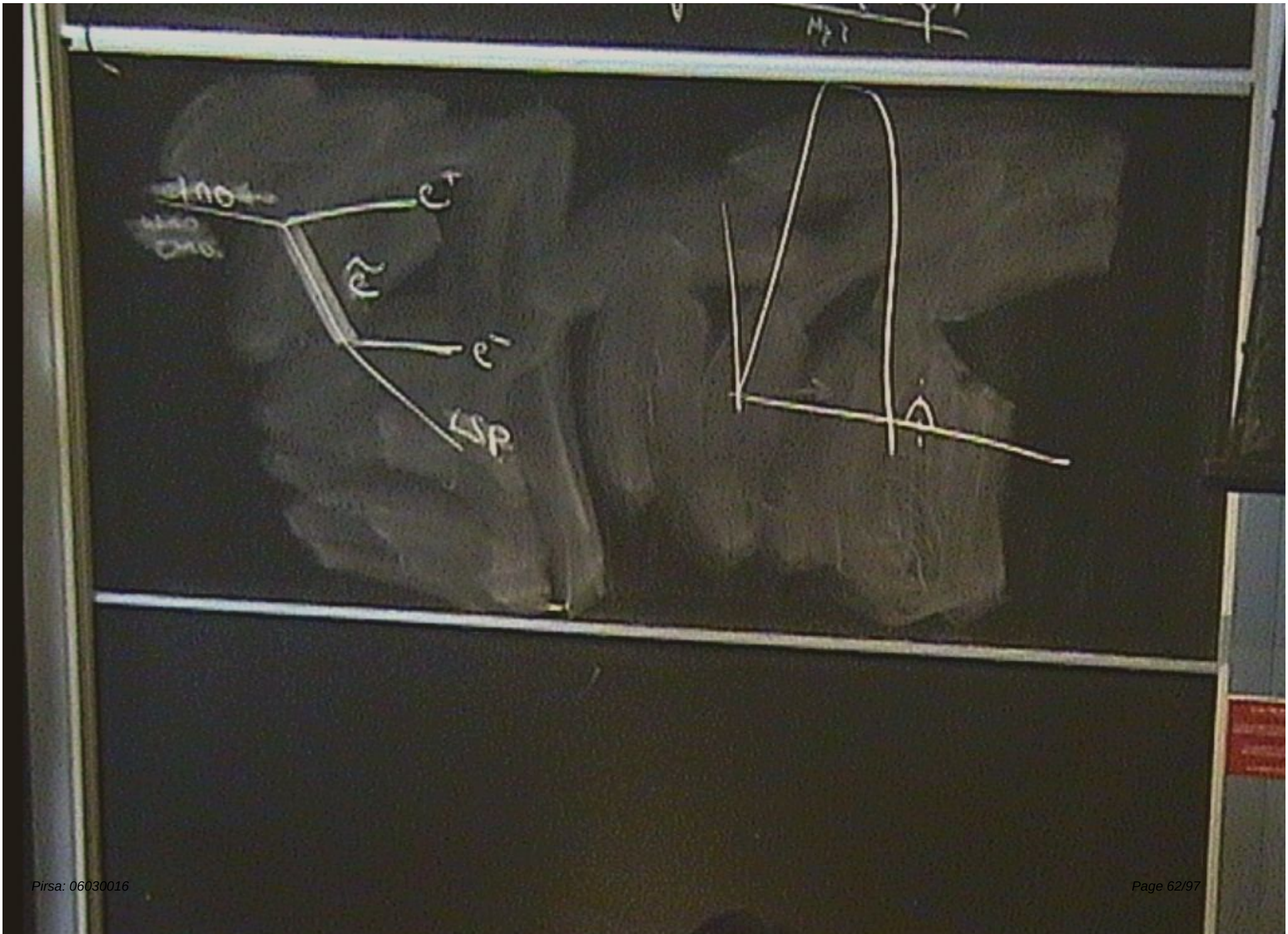

e^+
e^-

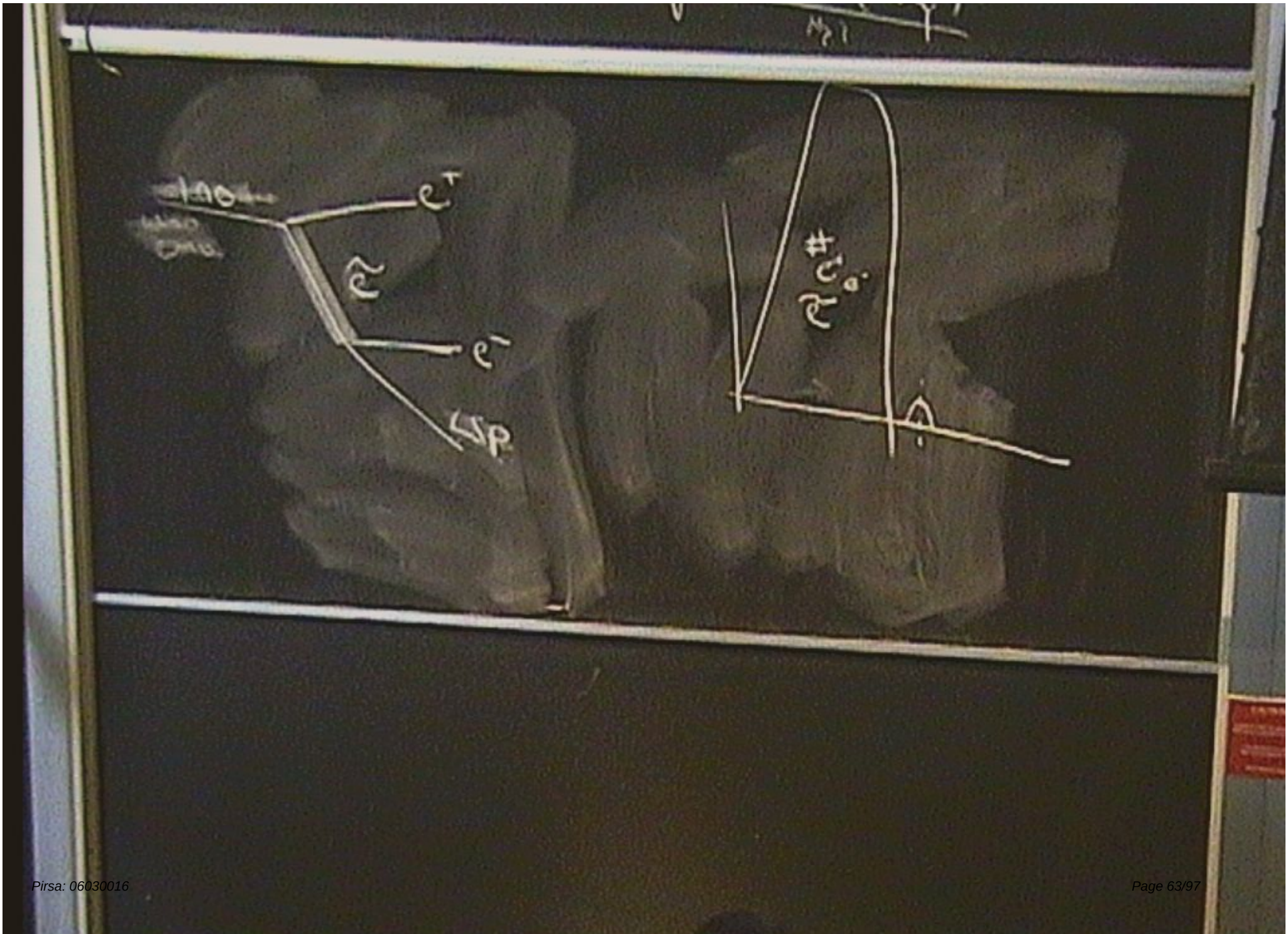

e^+
e^-

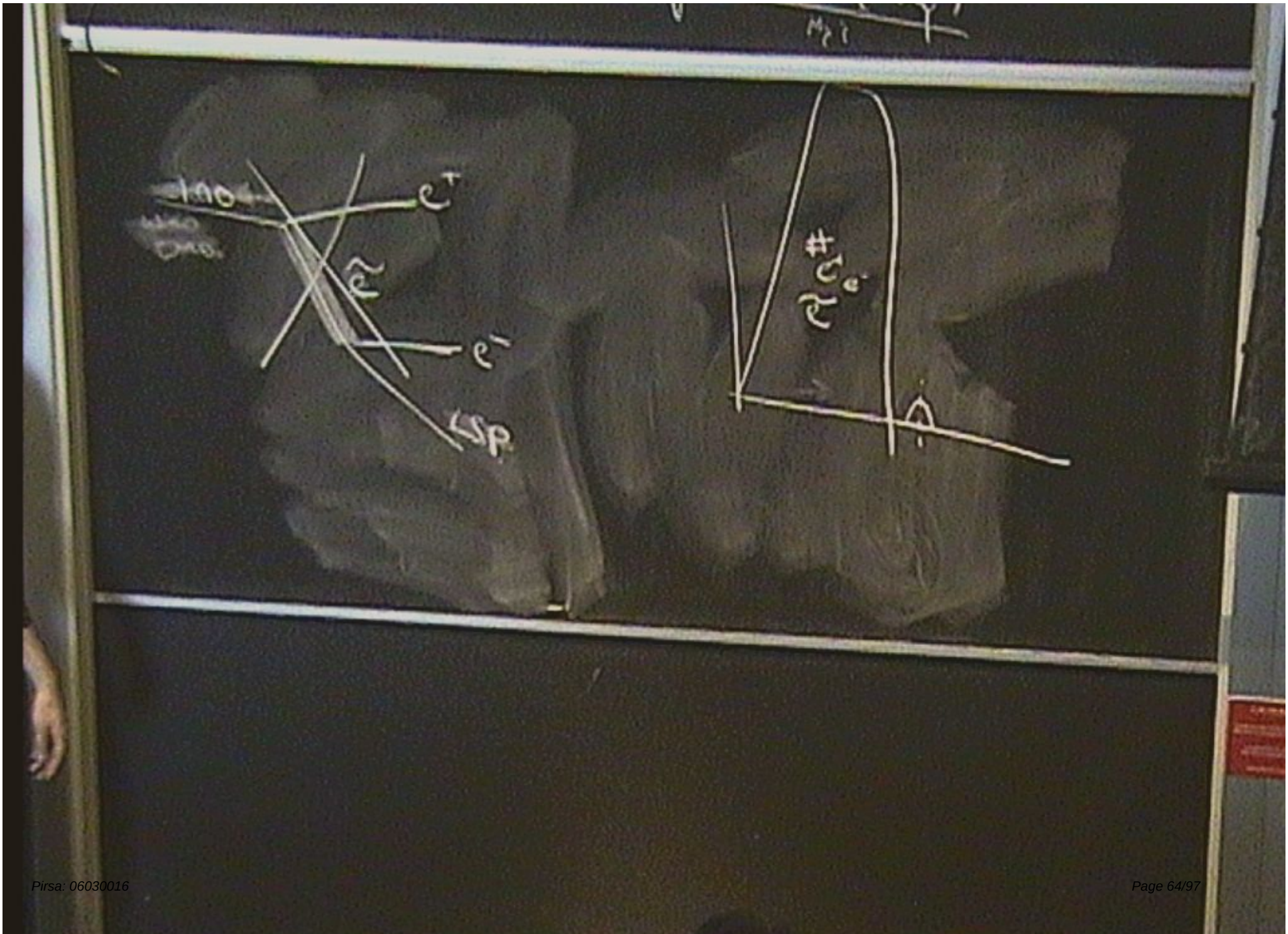

e^+
$\tilde{e}$
e^-

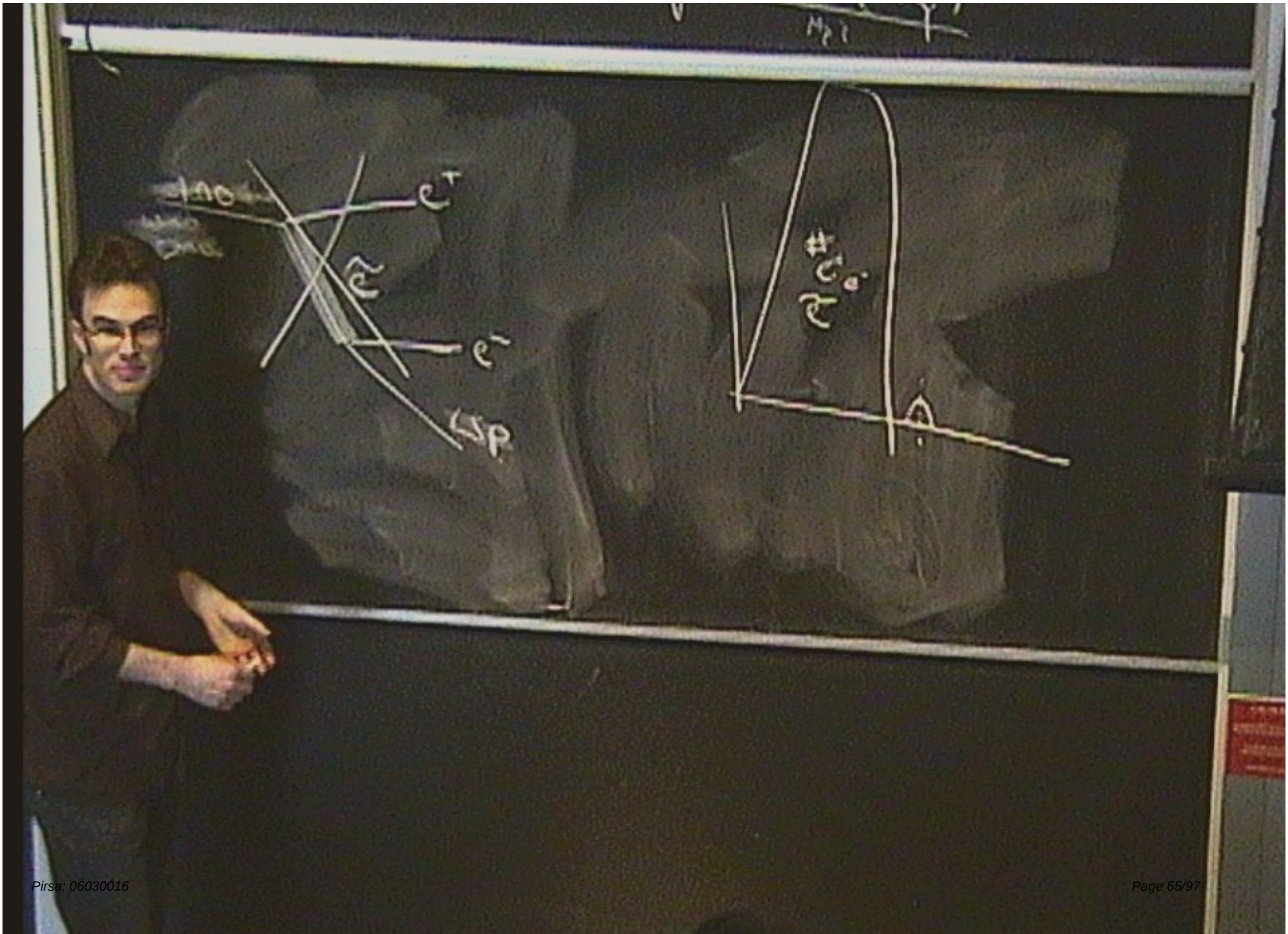

electron-like
W90
D10
e+
e~
e-
LSP


e^+
$\tilde{\chi}_2^0$
e^-
LSP


e^+
$\tilde{e}$
e^-
LSP
$M_{\tilde{e}}$


e^+
$\tilde{e}$
e^-
LSP
#
$\tilde{e}$


e^+
$\tilde{e}$
e^-
LSP
#
$\tilde{e}_L$
$\tilde{e}_R$
A


e^+
e^-
LSP
M_Z

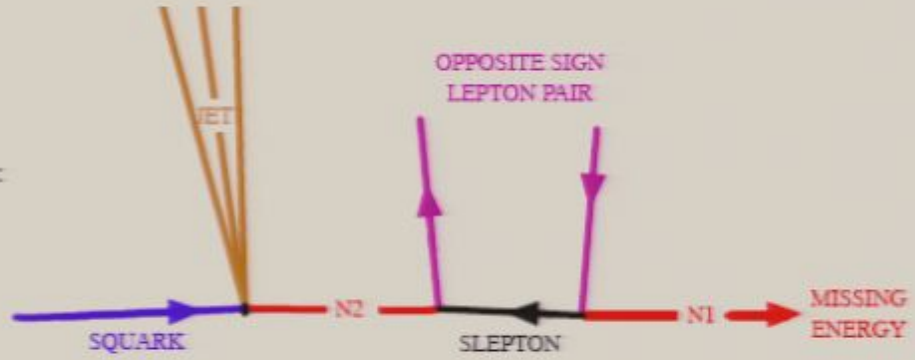
Our first guess: a squark cascade

$$\tilde{q}_{1,2} \to \text{jet} + \chi_2^0$$

$$\chi_2^0 \to l_{1,2}^+ + \tilde{l}_{1,2}^-$$

$$\tilde{l}_{1,2}^- \to l_{1,2}^- + \tilde{\chi}_0^1$$

Al =



$$M_{\ell^+\ell^-} = \frac{\sqrt{\left(m^2_{\chi_2^0} - m^2_{\tilde{\ell}}\right)\left(m^2_{\tilde{\ell}} - m^2_{\chi_1^0}\right)}}{m_{\tilde{\ell}}}.$$

Try and simulate. Couldn't quite do it!

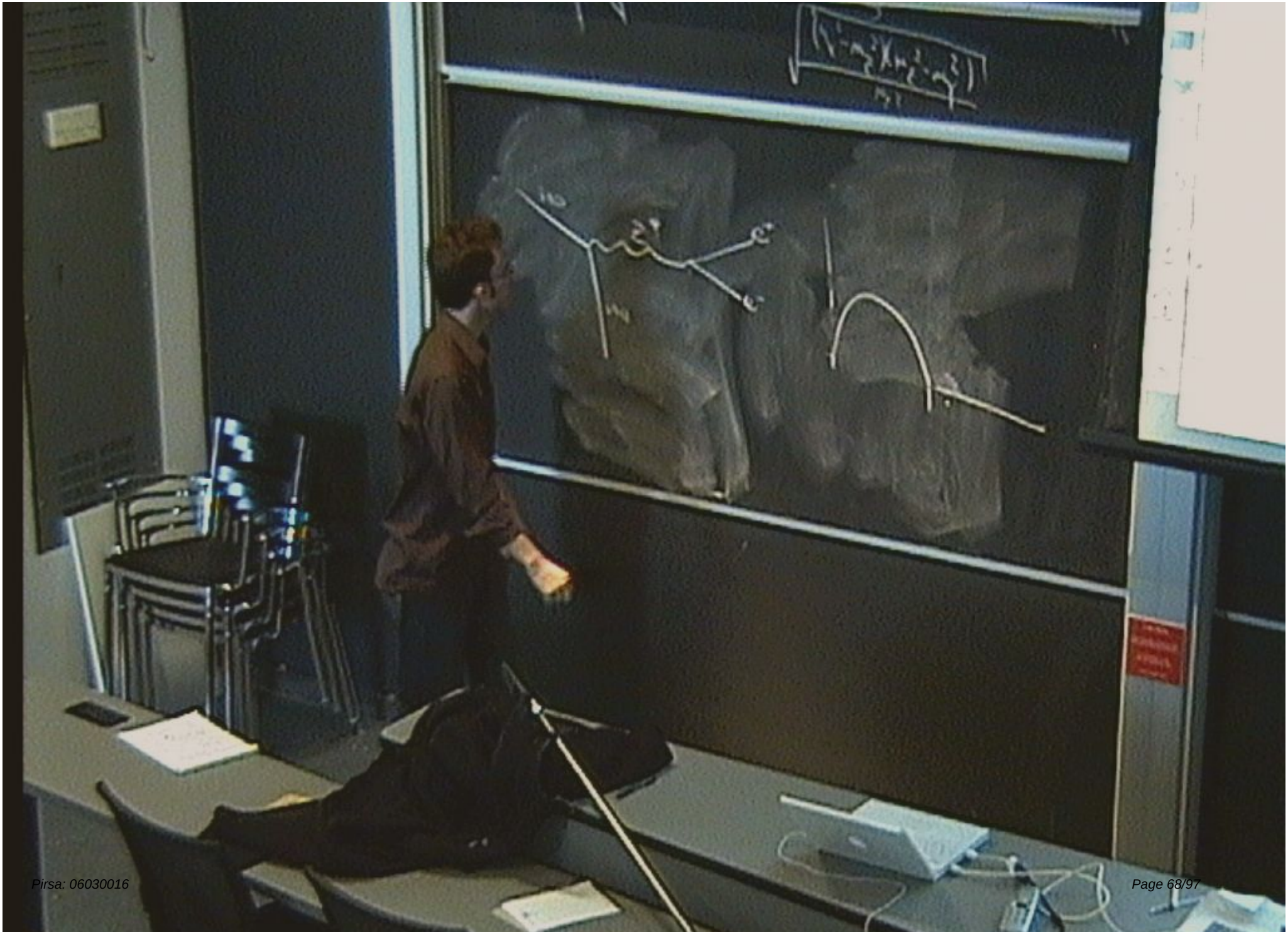
Generic problem: on-shell slepton leads to too high dilepton rate

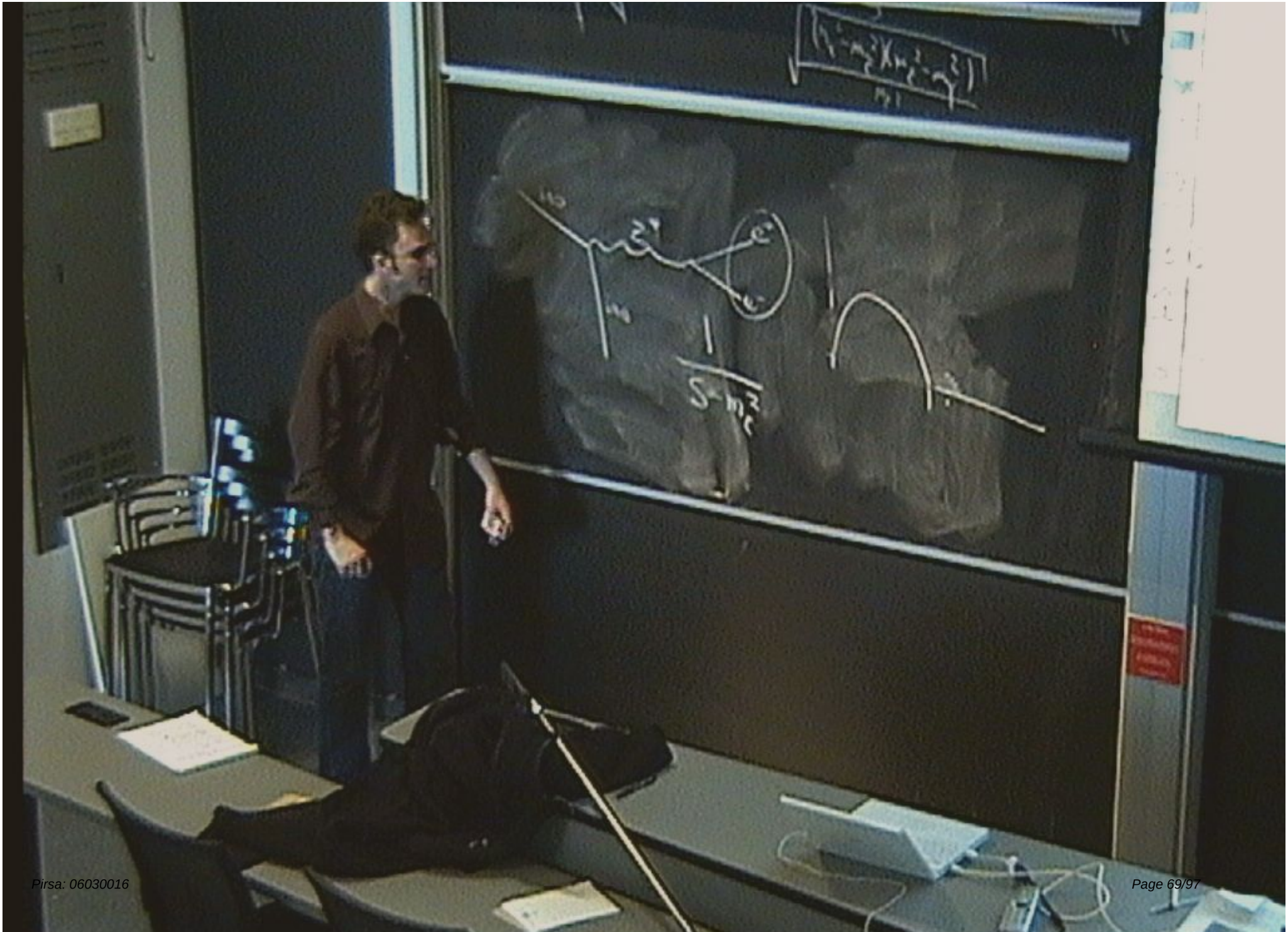
Also, typically need $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} > M_Z$.

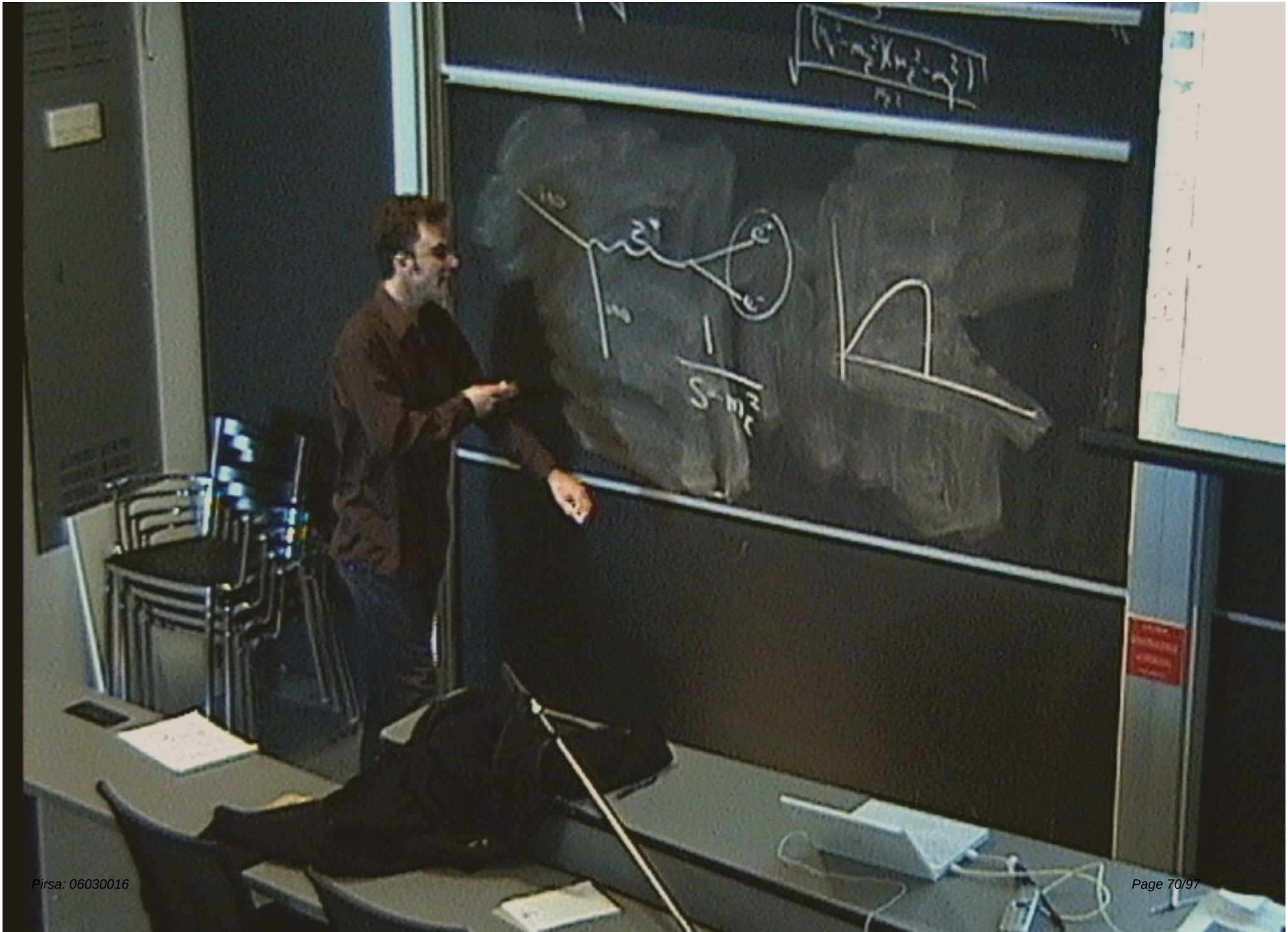
If $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are taken to be mostly Higgsinos, too many Z's from $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + Z$

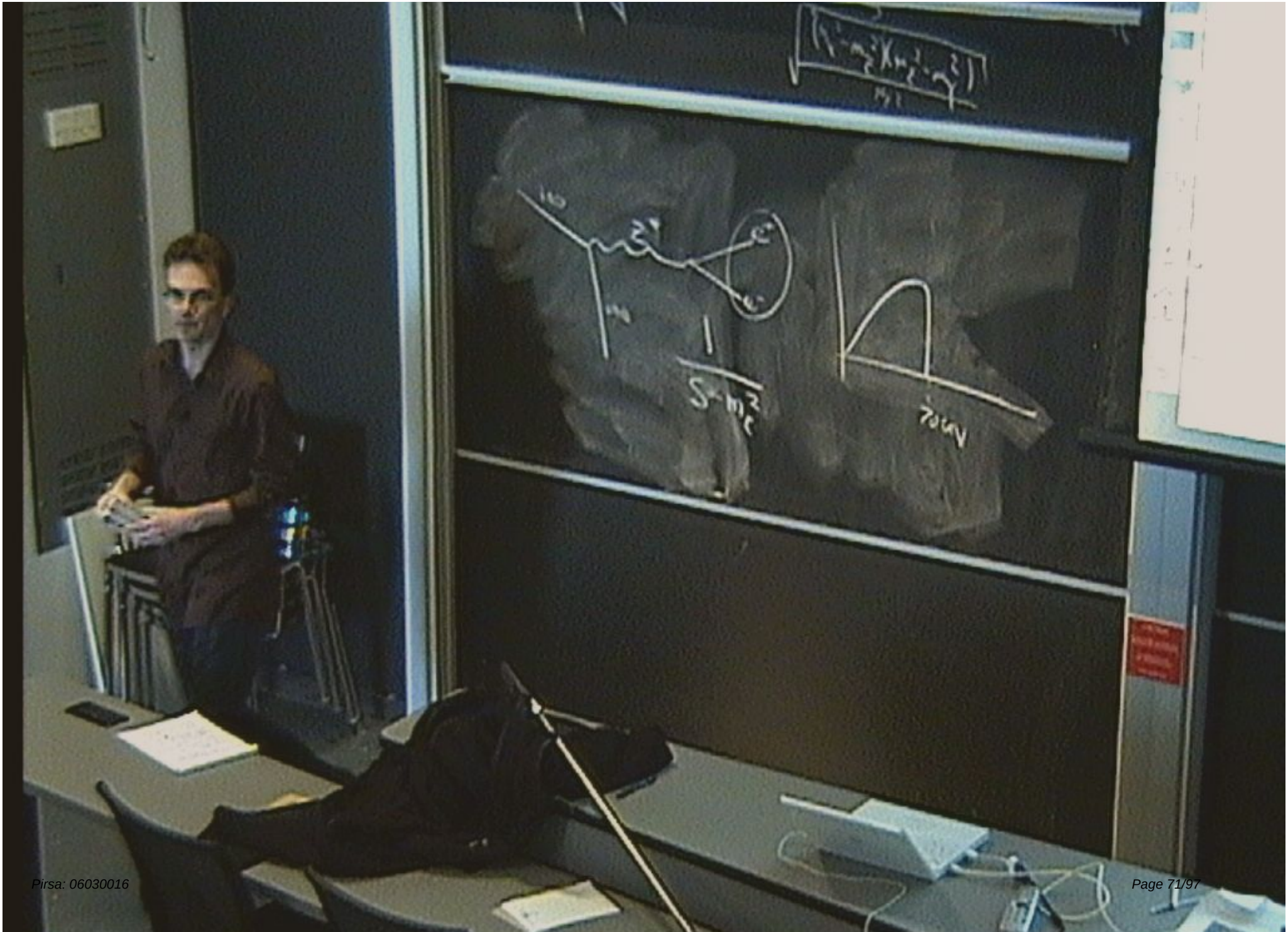
Trying to take them to be mostly bino/wino, Z rates are ok but still no match

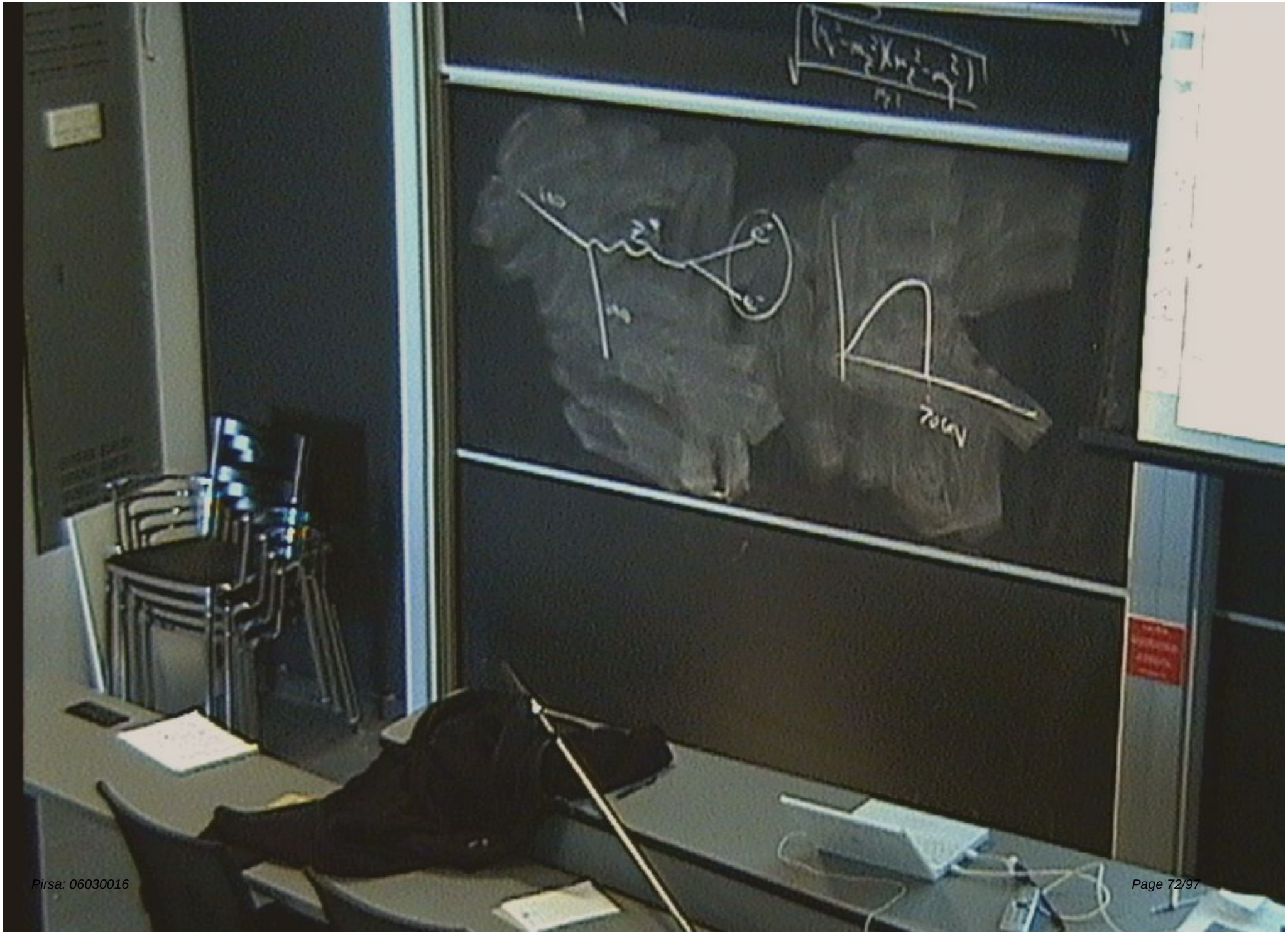
In these attempts the two dileptons are not symmetric, while they seem to be in UW1 BB

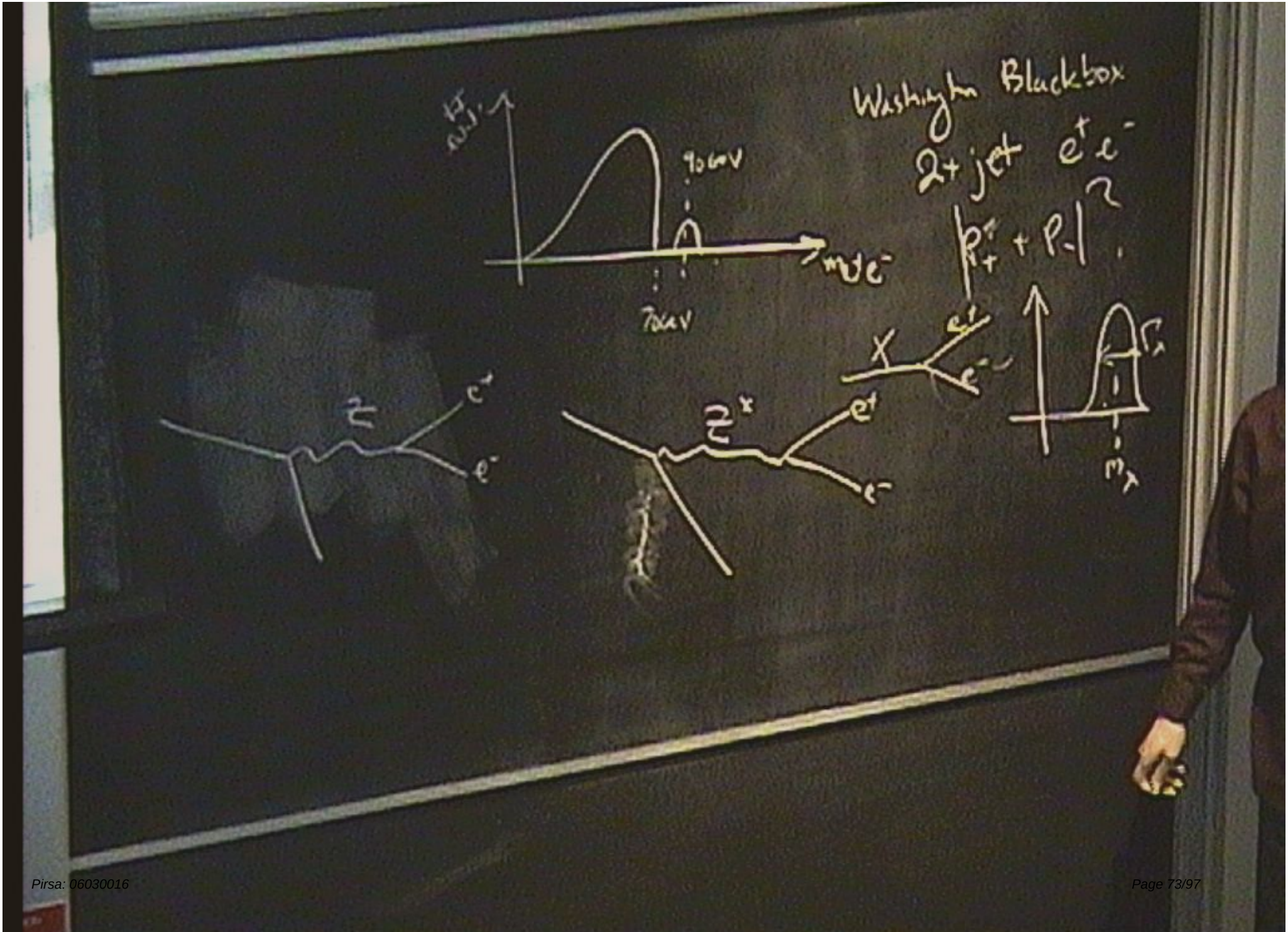


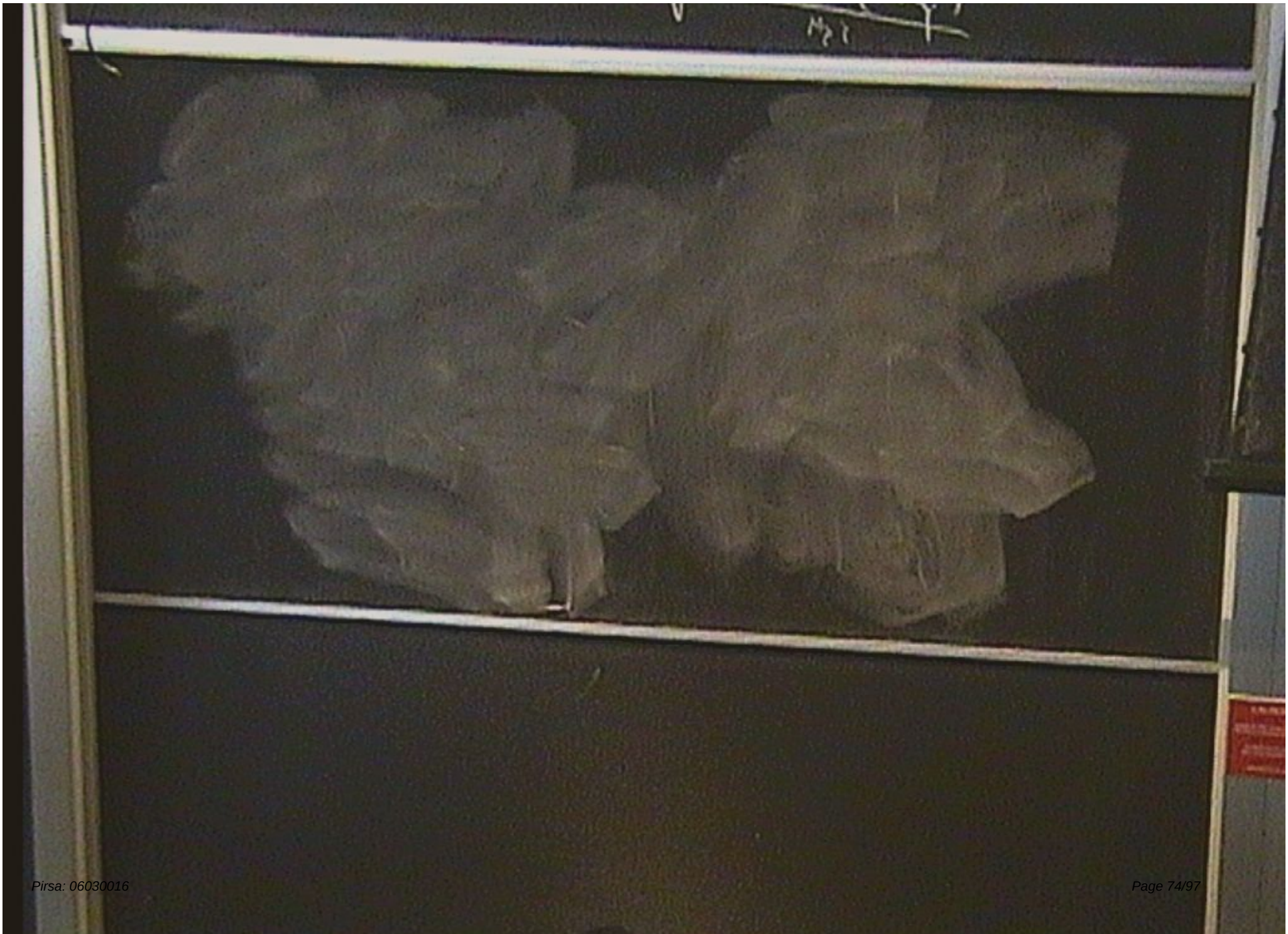






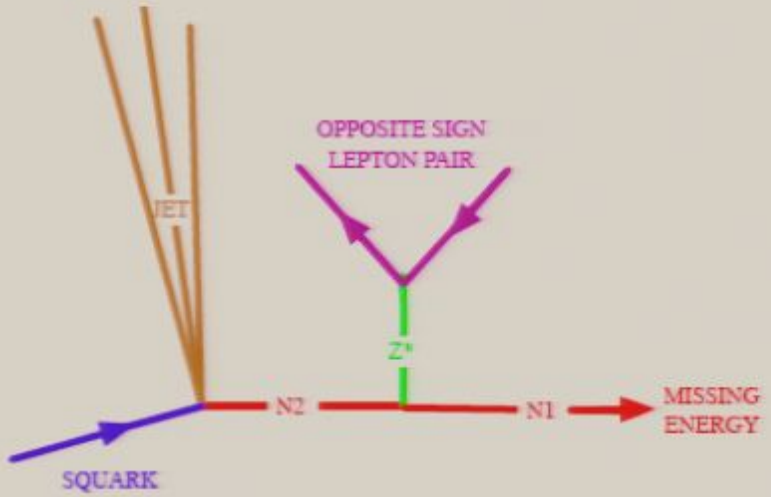



Washington Blackbox
2+ jet e+e-
90 GeV
70 GeV
mJe-
Z
e+
e-
Z*
e+
e-
X
e+
e-



Instead, we believe we are seeing an off-shell $Z^* \to l^+ l^-$

A2 =



Infer

$M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} \sim 70$ GeV

Thus we "conclude" (!)

$M_{\tilde{q}_{1,2}} \sim 800$ GeV

$M_{\tilde{\chi}_0^1} \sim 250$ GeV

$M_{\tilde{\chi}_0^2} \sim 320$ GeV

In neutralino sector, pick the hierarchy $M_B < \mu \ll M_W$

Need also a relatively heavy stop,

$M_{\tilde{t}} \sim 1400$ GeV

Rationales:

- Lighter stop seems to give too high b-jets rates.
- We want $M_h = 117 GeV$. Need heavy stop running in loops. Take high trilinear couplings $A_t = A_b = 800$ GeV.

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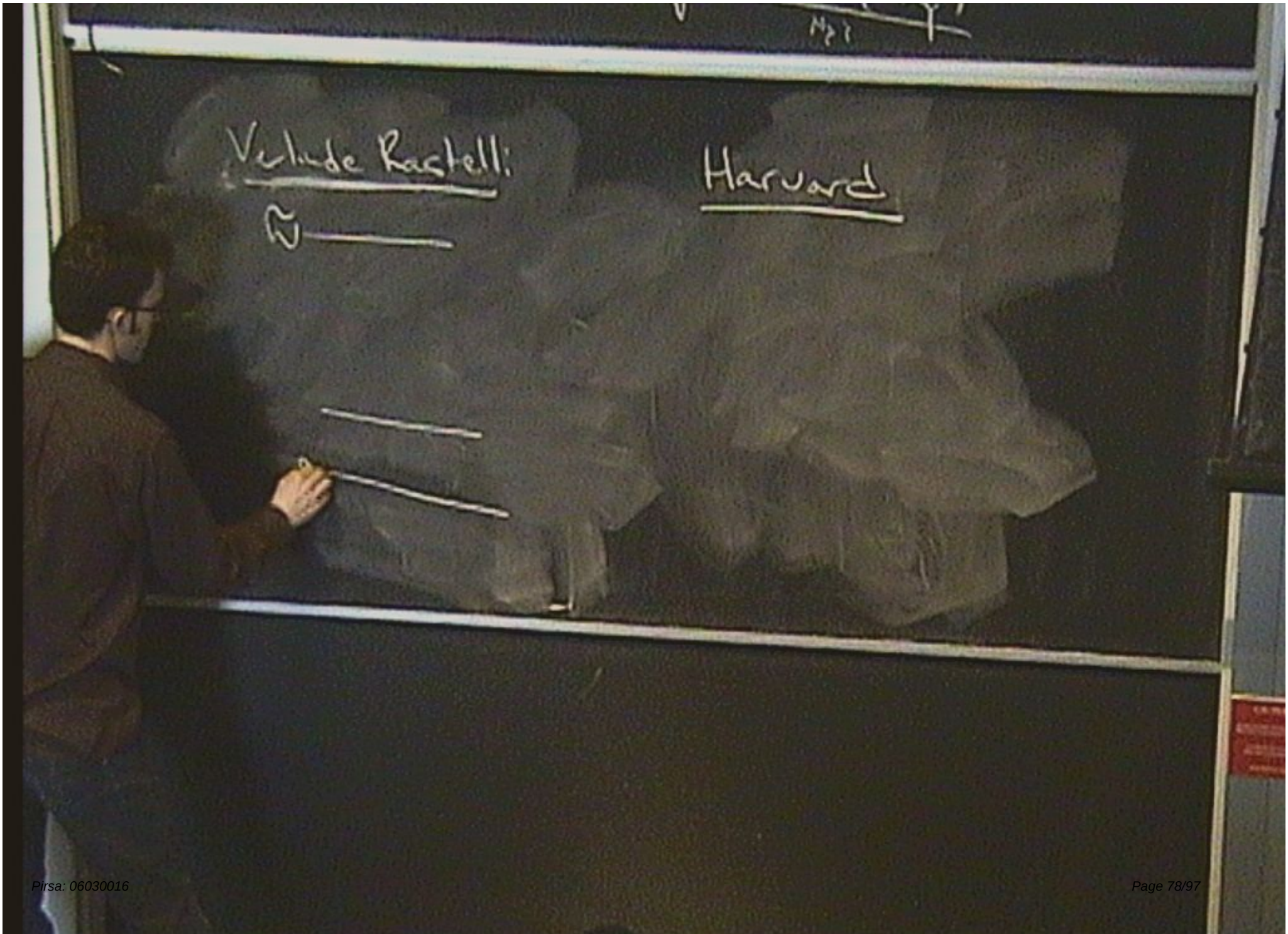
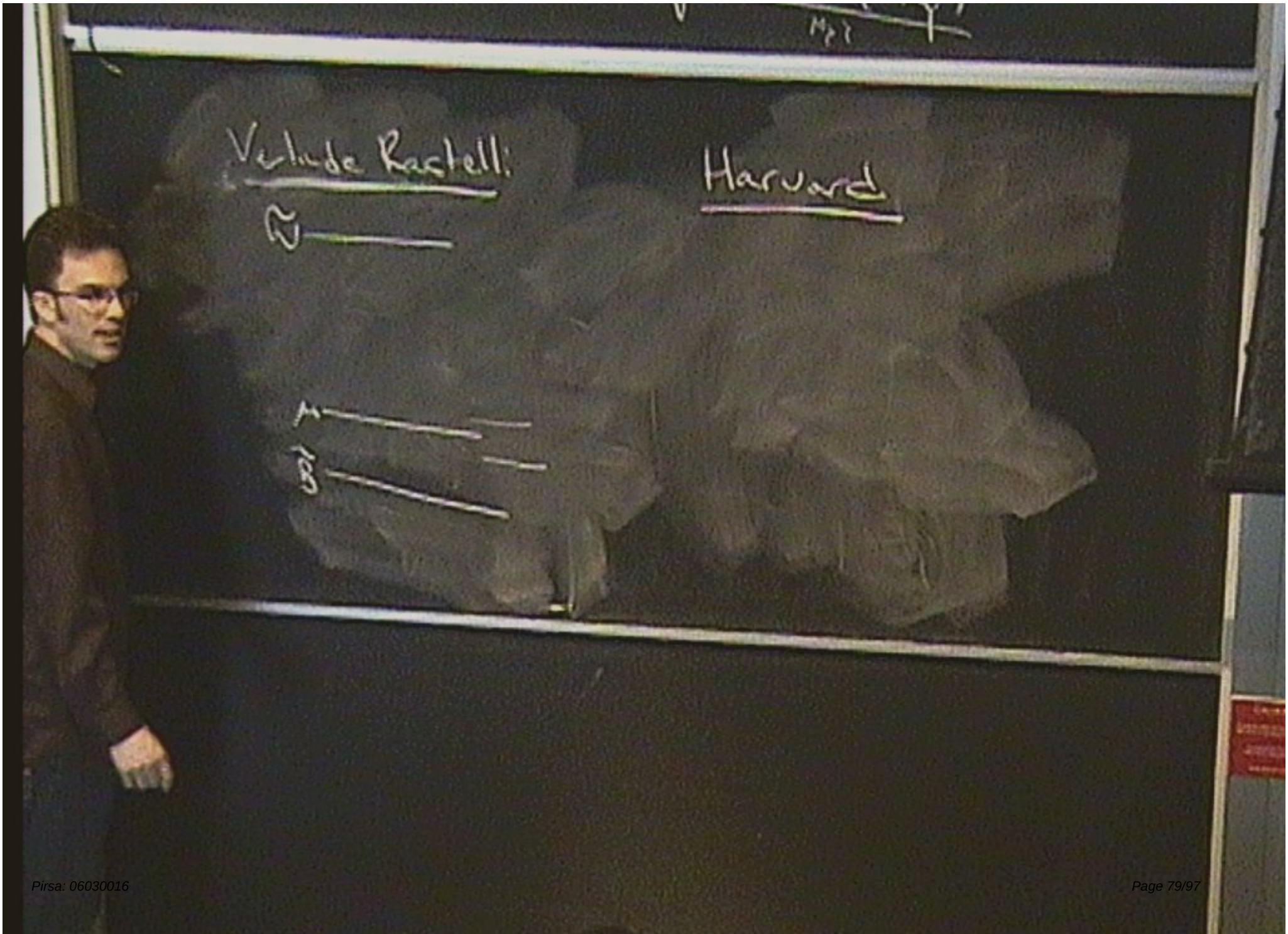
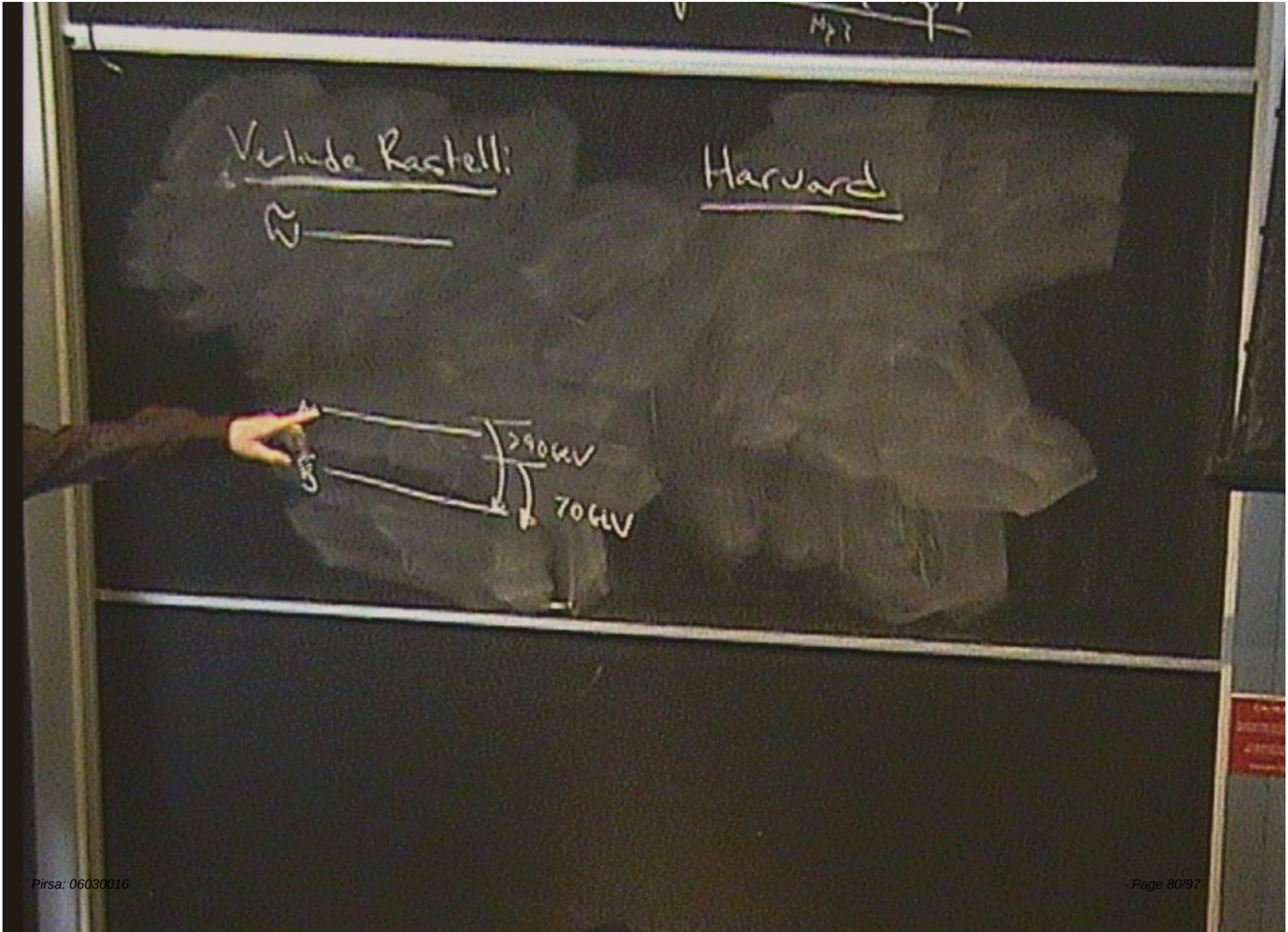
Model A

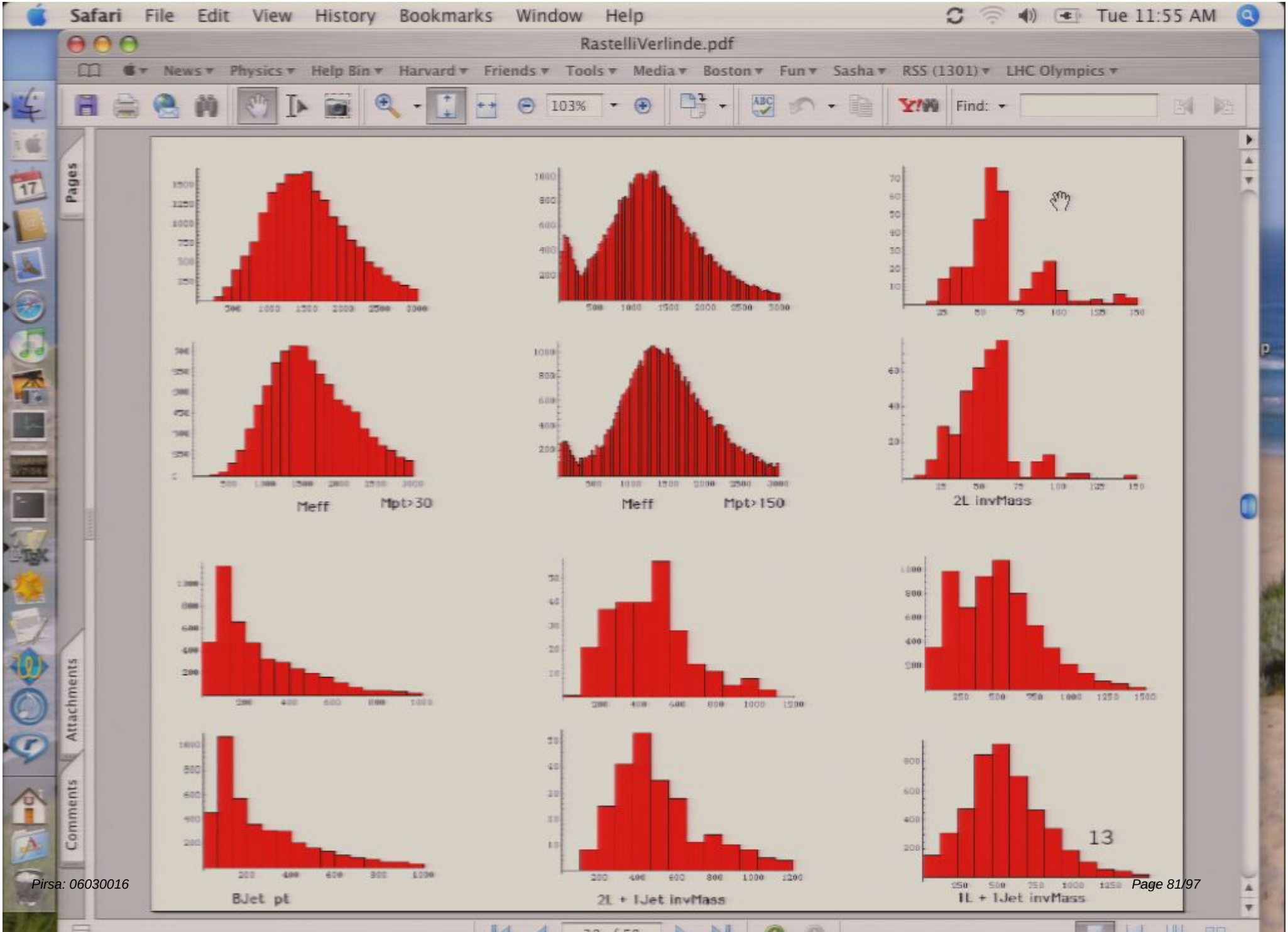
jan29.par

RMSS(1) = 255 bino
RMSS(2) = 790 wino
RMSS(3) = 1550 gluino
RMSS(4) = 290 mu
RMSS(5) = 30 tan beta
RMSS(6) = 805. left slepton (1st-2nd)
RMSS(7) = 806 right slepton (1st-2nd)
RMSS(8) = 815 left squark (1st-2nd)
RMSS(9) = 960 right down squark (1st-2nd)
RMSS(10) = 1260 left squark (3rd)
RMSS(11) = 1400 right down squark (3rd)
RMSS(12) = 1400 right up squark (3rd)
RMSS(13) = 1140 left slepton (3rd)
RMSS(14) = 1200 right slepton (3rd)
RMSS(15) = 800. bottom trilinear
RMSS(16) = 800. top trilinear
RMSS(17) = 0. tau trilinear
RMSS(19) = 550. pseudo-scalar Higgs mass
RMSS(22) = 986. right up squark (1st-2nd)


Vulnde Rastelli
Harvard


Vernde Rachell:
Harvard


Melinda Rastelli
Harvard
290 GeV
70 GeV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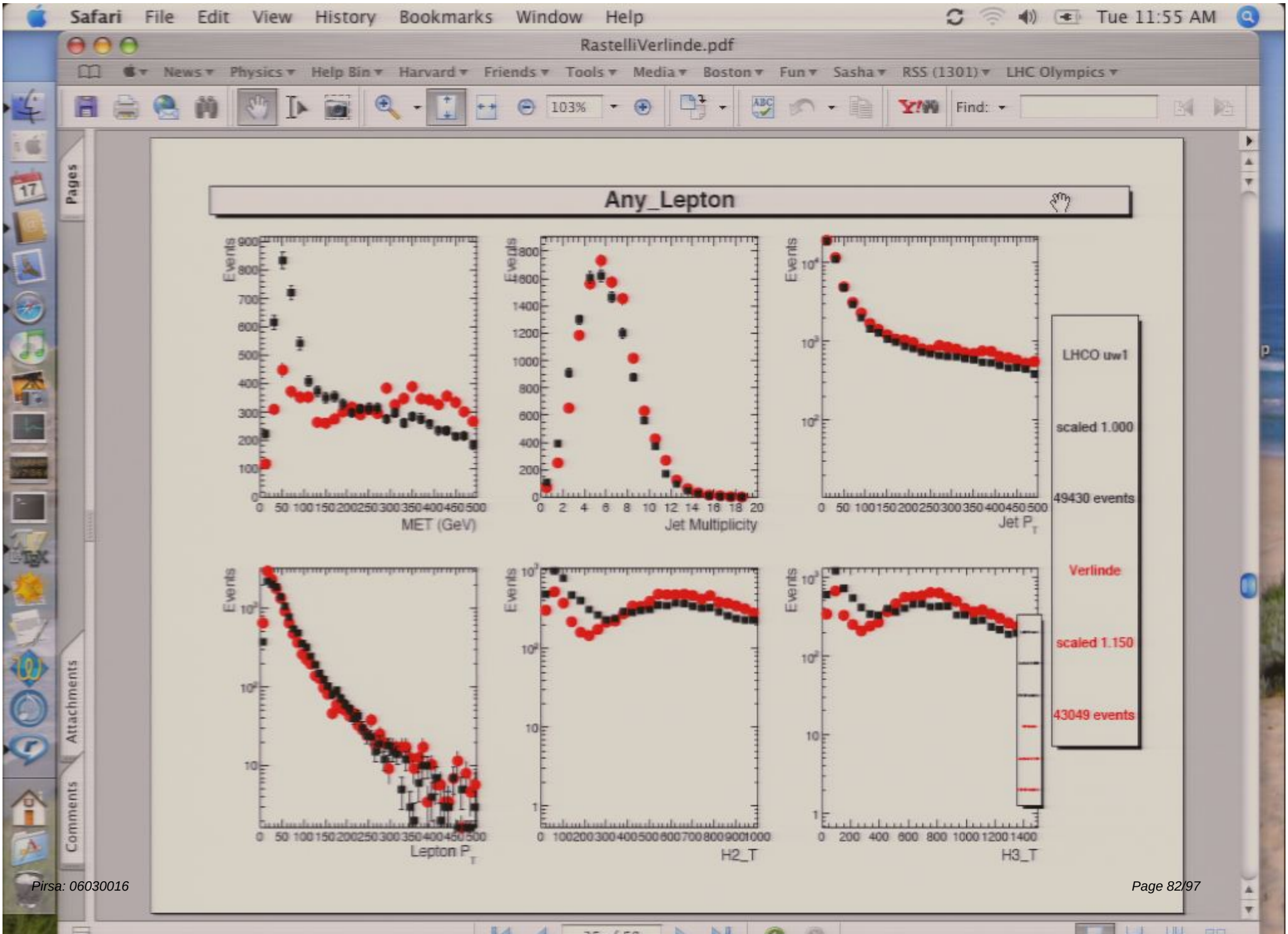
Mpt>30
Meff
Mpt>150
2L invMass
BJet pt
2L + 1Jet invMass
1L + 1Jet invMass
13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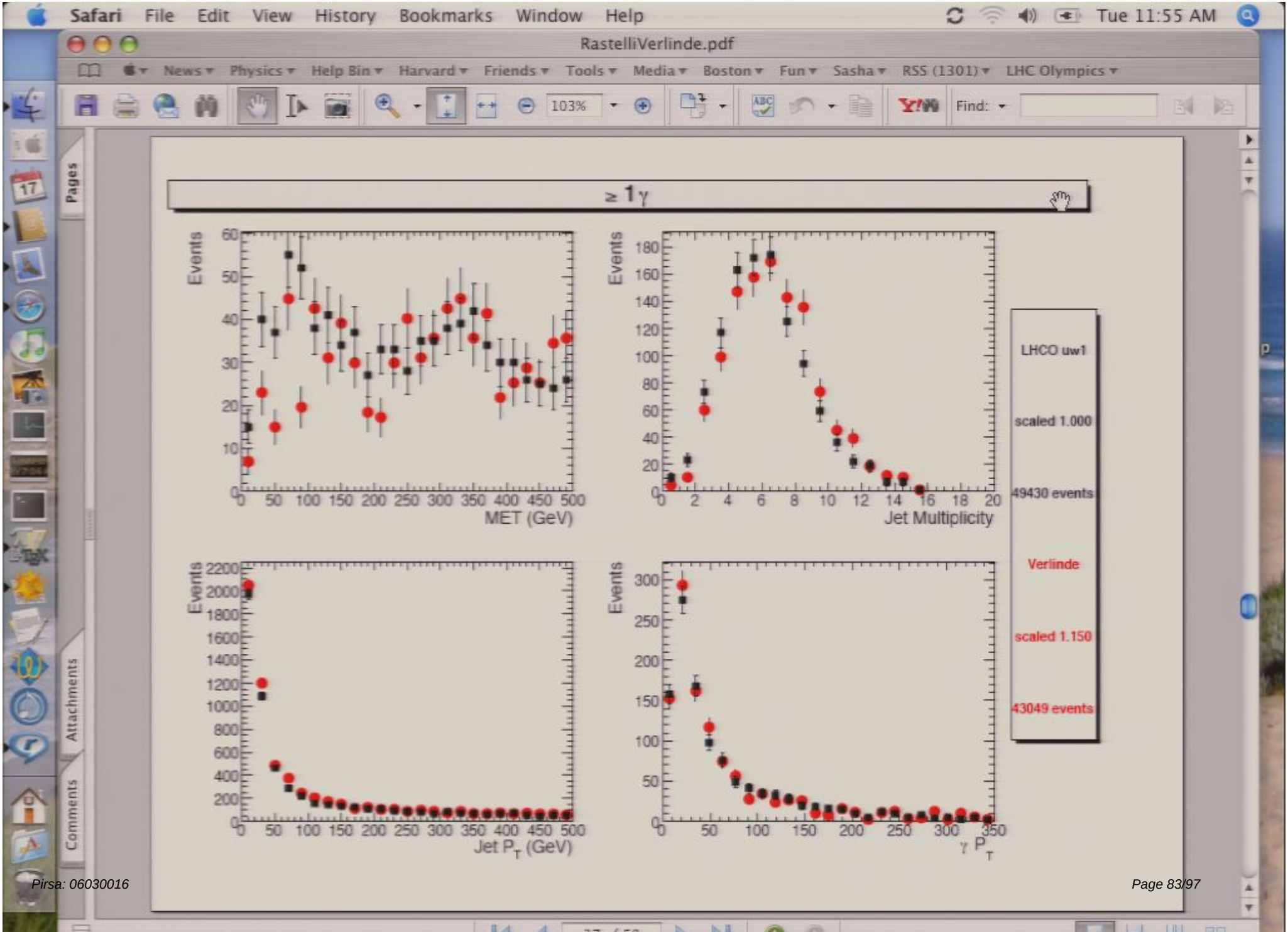
RastelliVerlinde.pdf
Any_Lepton
MET (GeV)
Jet Multiplicity
Jet P_T
Lepton P_T
H2_T
H3_T
Events
LHCO uw1
scaled 1.000
49430 events
Verlinde
scaled 1.150
43049 events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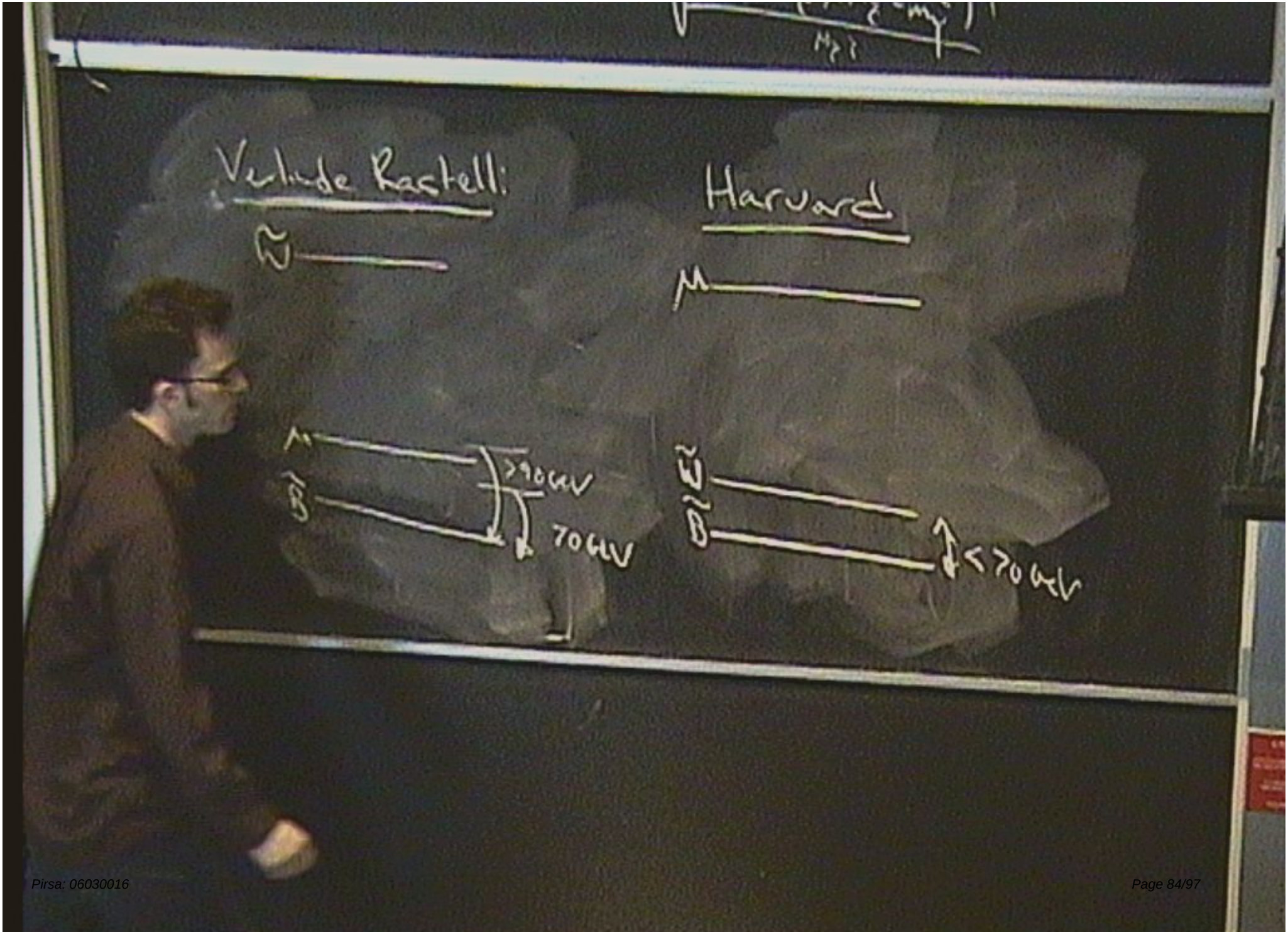
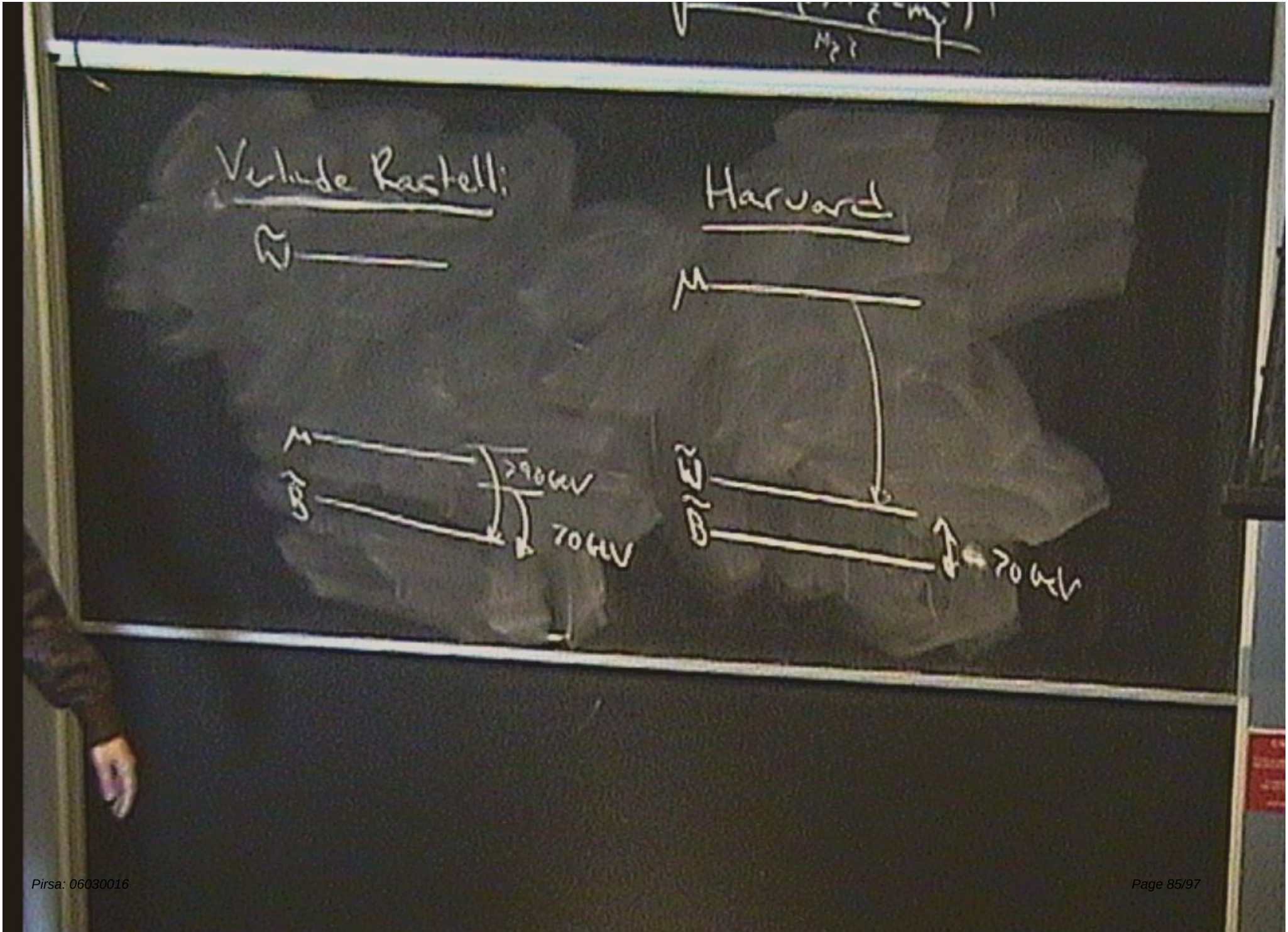
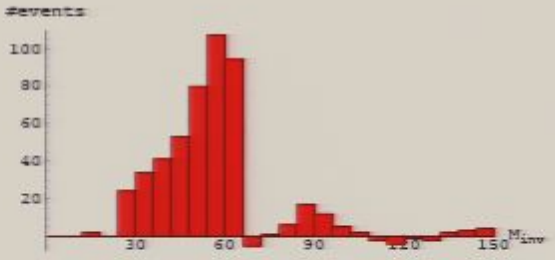
MET (GeV)
Jet Multiplicity
Jet P_T (GeV)
γ P_T
LHCO uw1
scaled 1.000
49430 events
Verlinde
scaled 1.150
43049 events


Verlinde Rastelli:
Harvard
>70GeV
70GeV
<70GeV

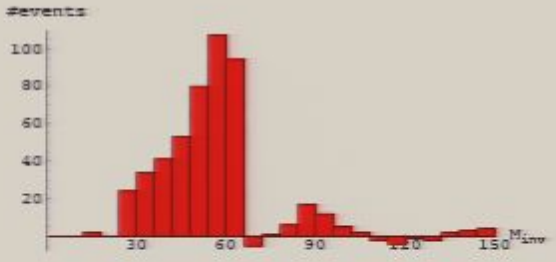

Verlinde Rastell:
Harvard
290kV
70kV
70kV

Key Facts: Dileptons



- There is a very clear kinematic feature in the flavor subtracted OS dilepton invariant mass plot.

Key Facts: Dileptons



- There is a very clear kinematic feature in the flavor subtracted OS dilepton invariant mass plot.
- In the absence of on shell sleptons, this feature is most likely an endpoint arising from $\chi_{high} \rightarrow \chi_{low} Z^*$.

The Pythia Parameter File in computer form

```
MSEL=39
IMSS(1)=1
IMSS(5)=1
RMSS(1)=170
RMSS(2)=250
RMSS(3)=1500
RMSS(4)=380
RMSS(5)=34


RMSS(8)=900
RMSS(9)=700
RMSS(10)=1875
RMSS(11)=1925
RMSS(12)=1850


RMSS(15)=00
RMSS(26)=0.0
RMSS(27)=0.0

PMAS(6,1)=175.
CKIN(1)=150.0
```

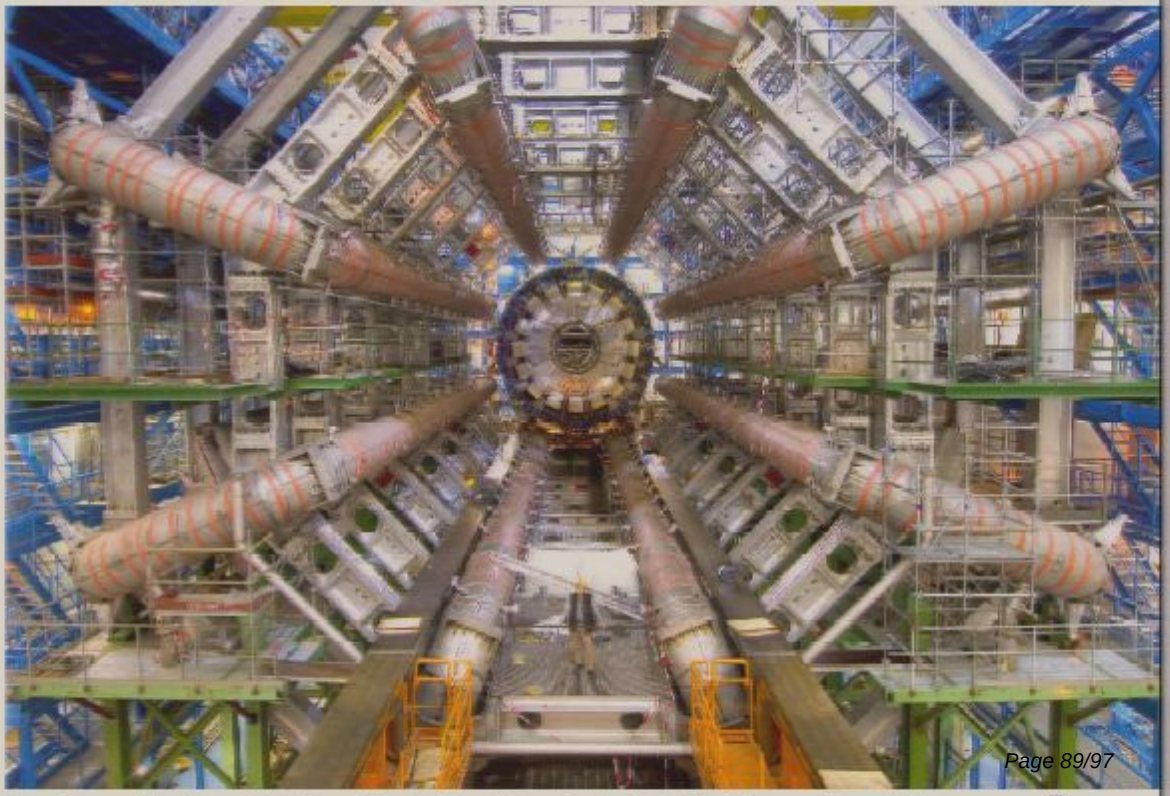
LET THE GAMES BEGIN

A series of mental challenges is helping physicists to prepare for the strange data they may get when the next particle accelerator goes live. **Jenny Hogan** joins the work-out.

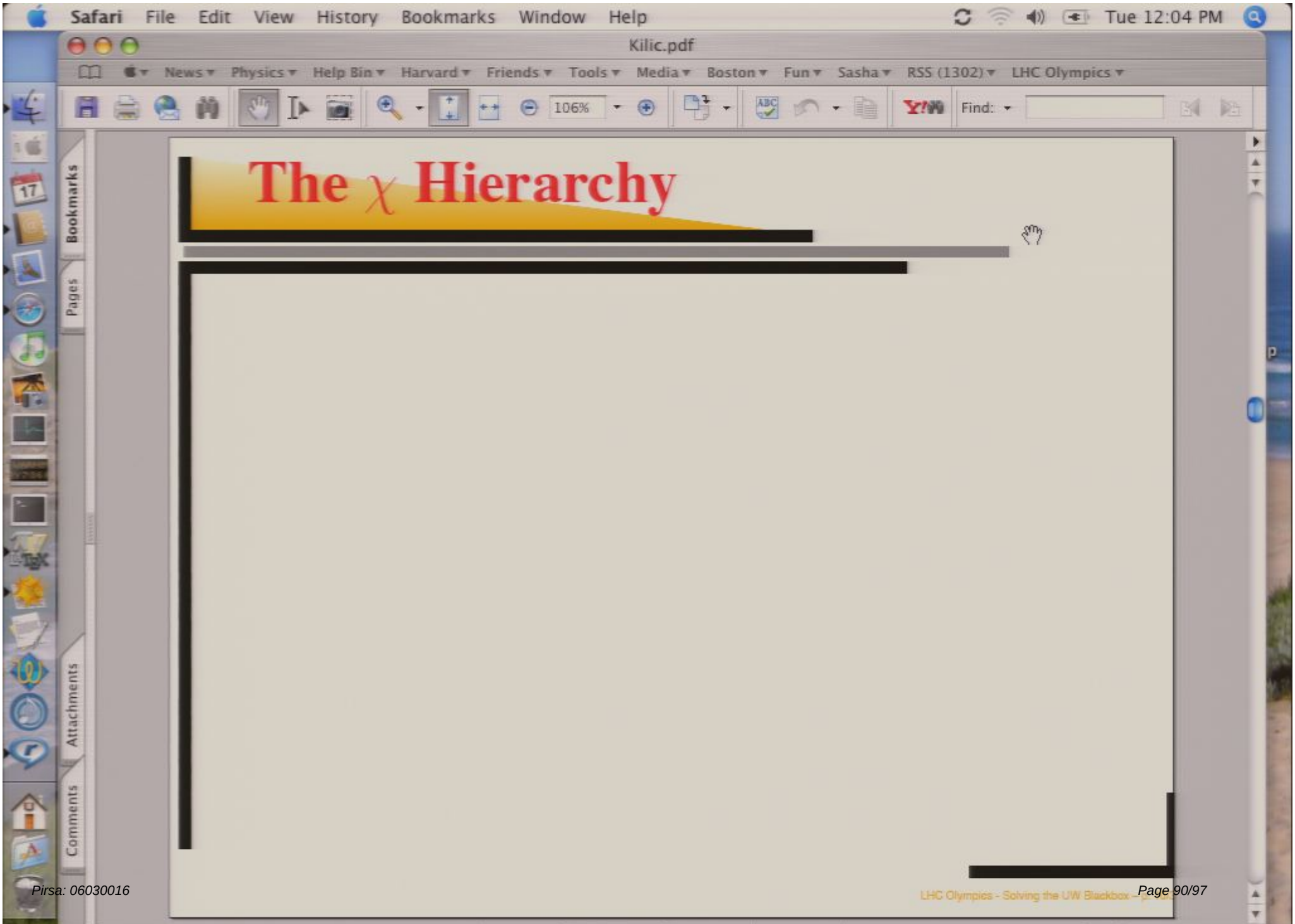
Normally, the trick to learning something at a scientific meeting is to listen to the key lectures. But one afternoon last month, in a conference room at CERN, the European particle-physics lab near Geneva, physicist Matt Strassler managed to convince several researchers that they might learn more if they left the lecture room. He wanted them to avoid hearing the solution to a puzzle they had been working on for months.

Welcome to the strange world of the Large Hadron Collider (LHC) Olympics, a workshop held at CERN in which teams of theorists studied fake data in order to explore unproven theories.

Strassler, a theorist from the University of Washington in Seattle, was one of the organizers of the event, which brought together more than 50 theoretical physicists from across Europe and the United States. These 'olympians' have devoted their careers to building mathematical models of the Universe and matter. The LHC Olympics was designed to put their ideas to the test; their challenge was to prepare for the real data expected to emerge



Monster machine: huge detectors will collect and characterize the fall out from proton collisions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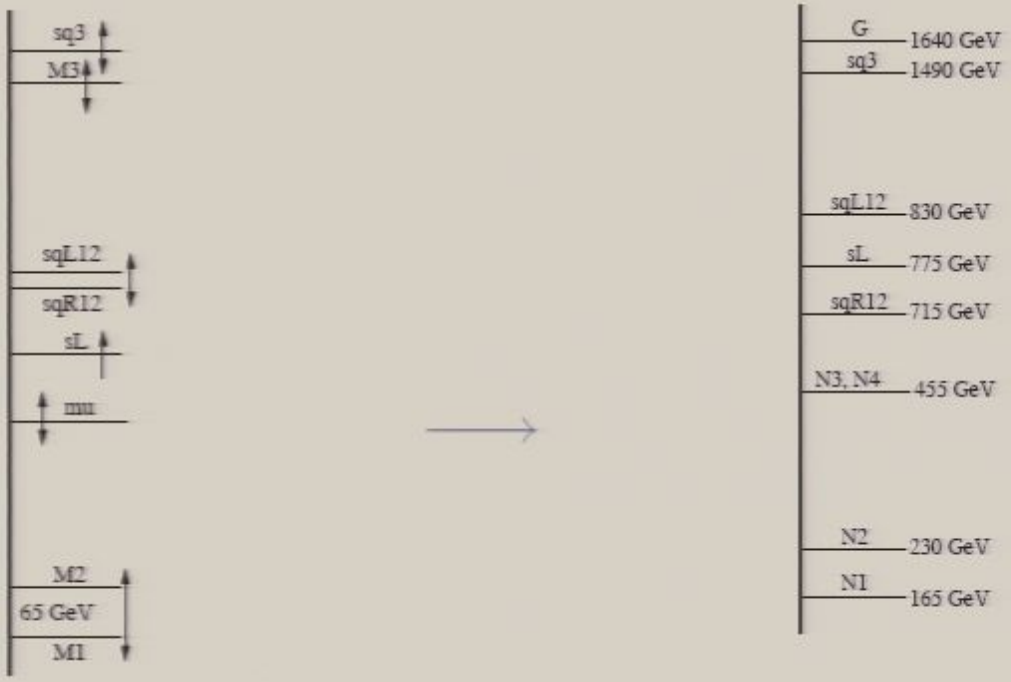
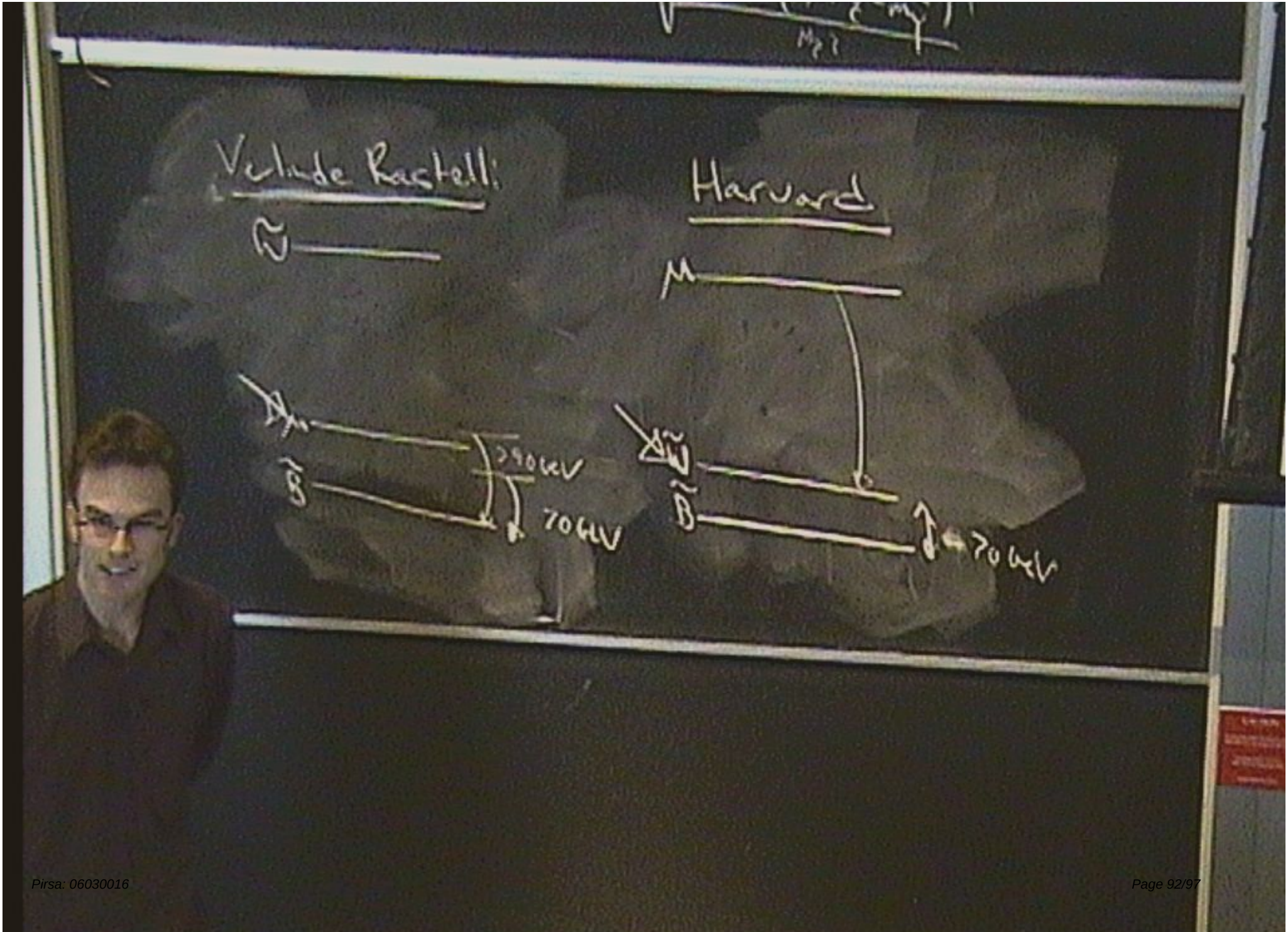
The χ Hierarchy
LHC Olympics - Solving the UW Blackbox

Intuition vs. Simulation



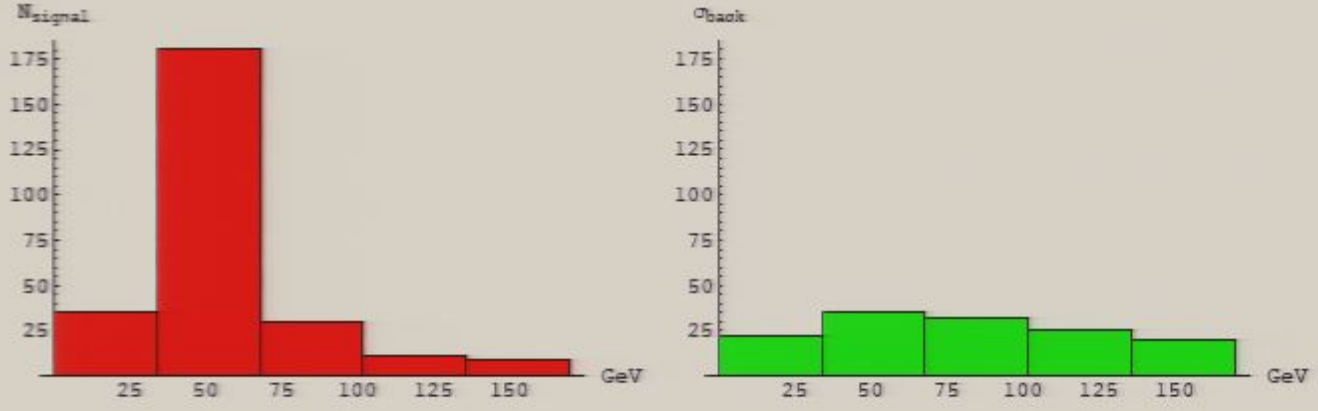
Intuition

Simulation:
3000 CPU hours.

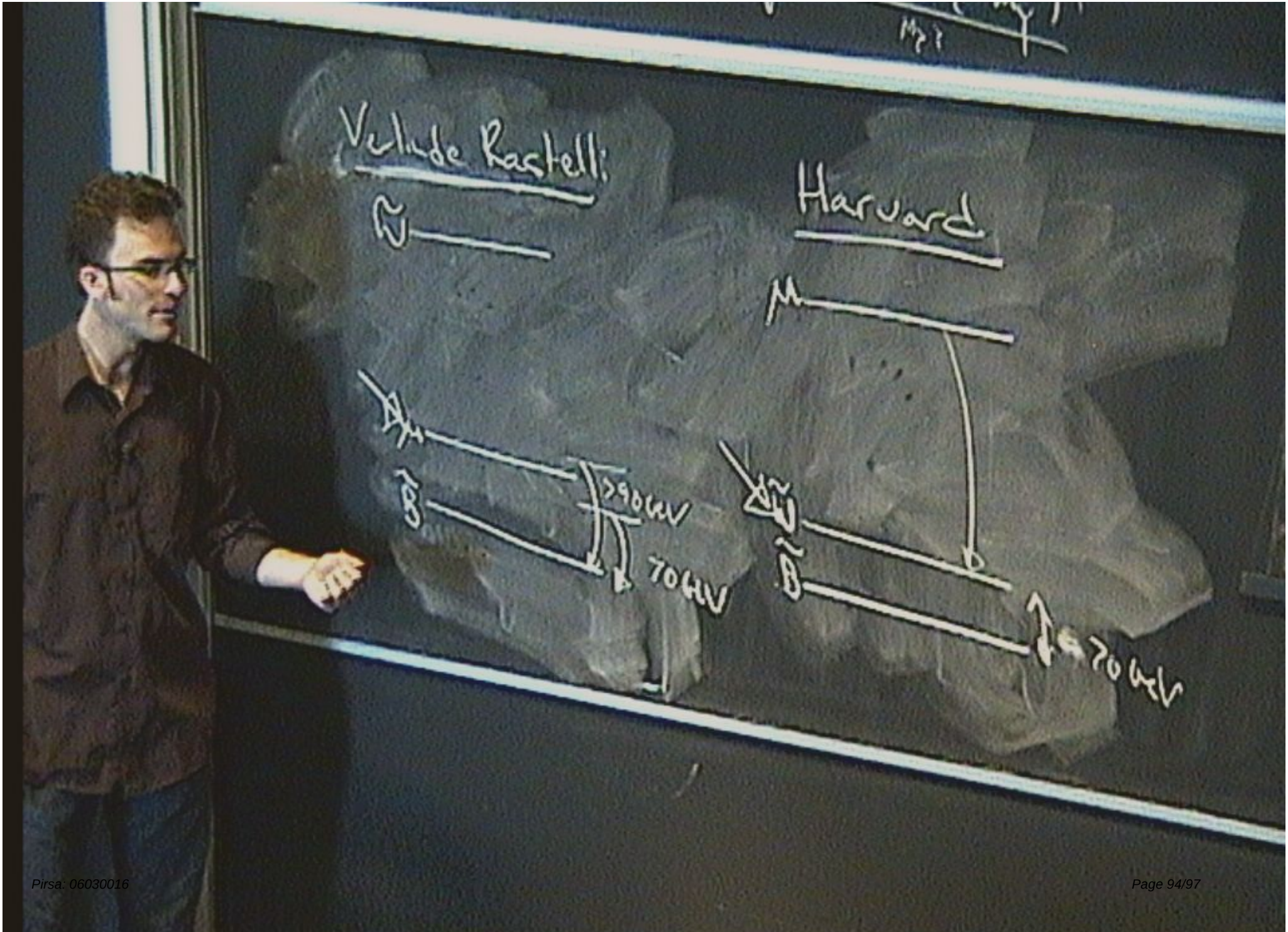

Verlinde Rastall:
Harvard
290 keV
70 keV
70 keV

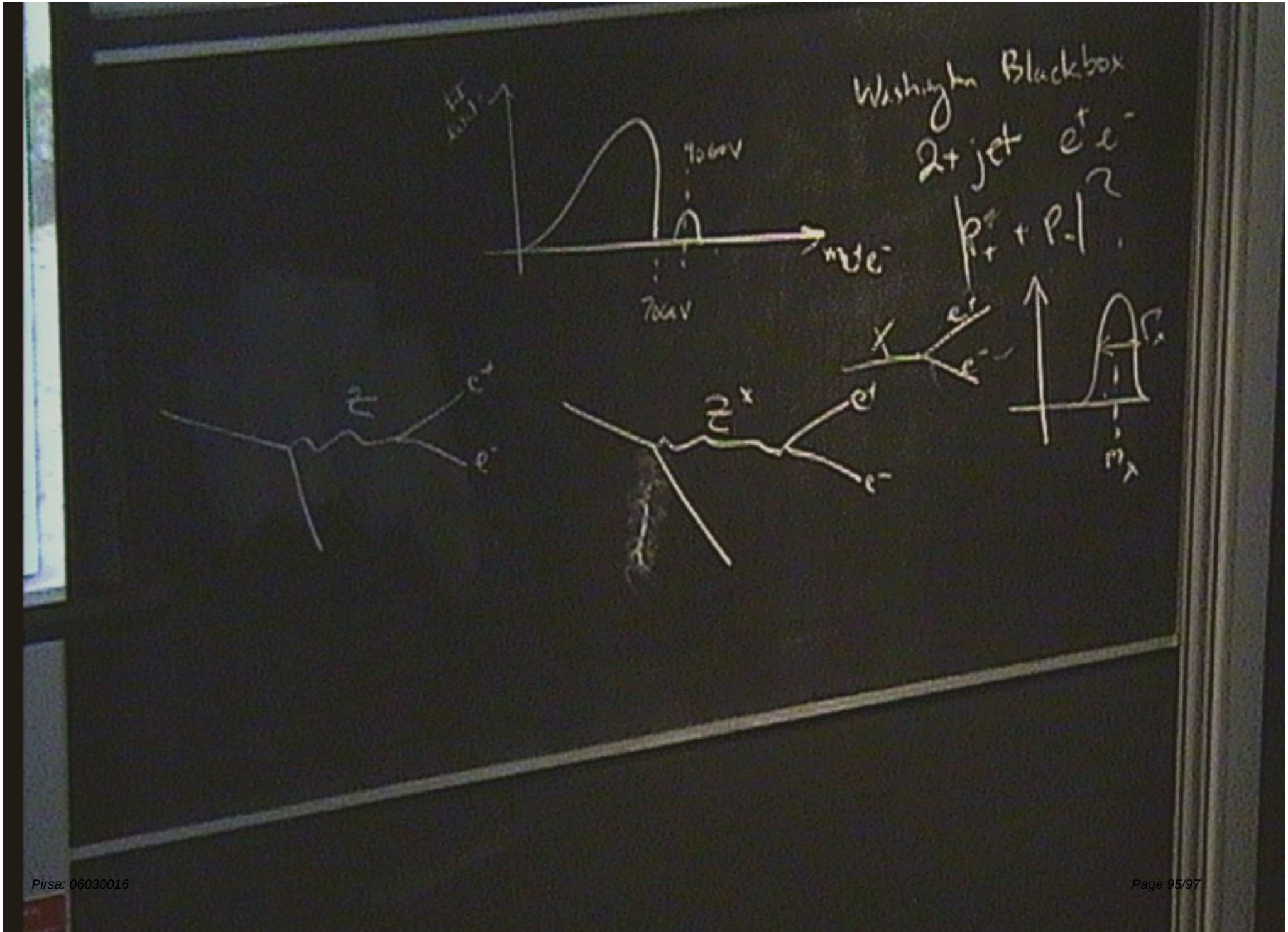
Dileptons

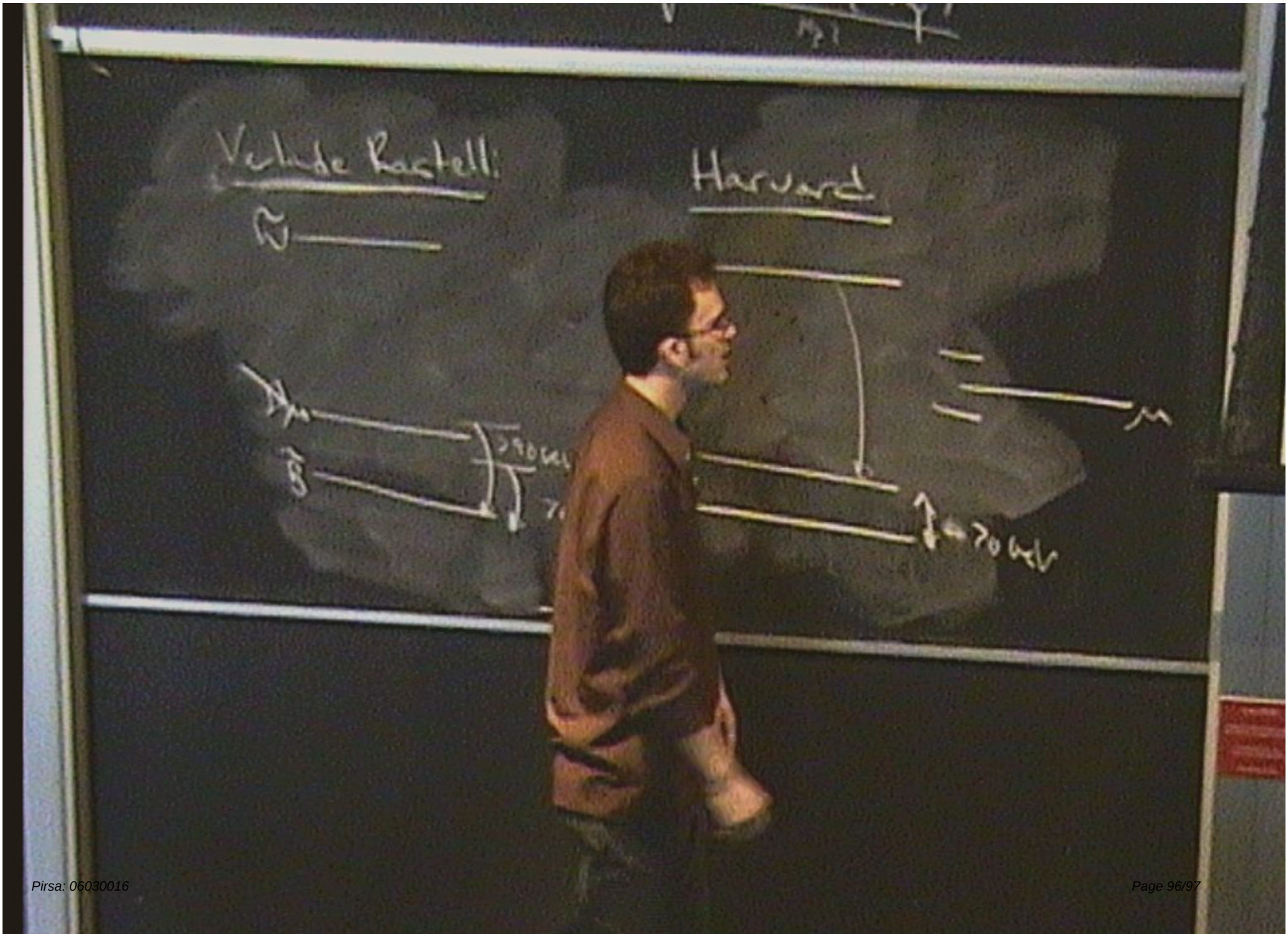
How about the flavor subtracted dilepton invariant mass plot from which we were able to extract so much information?

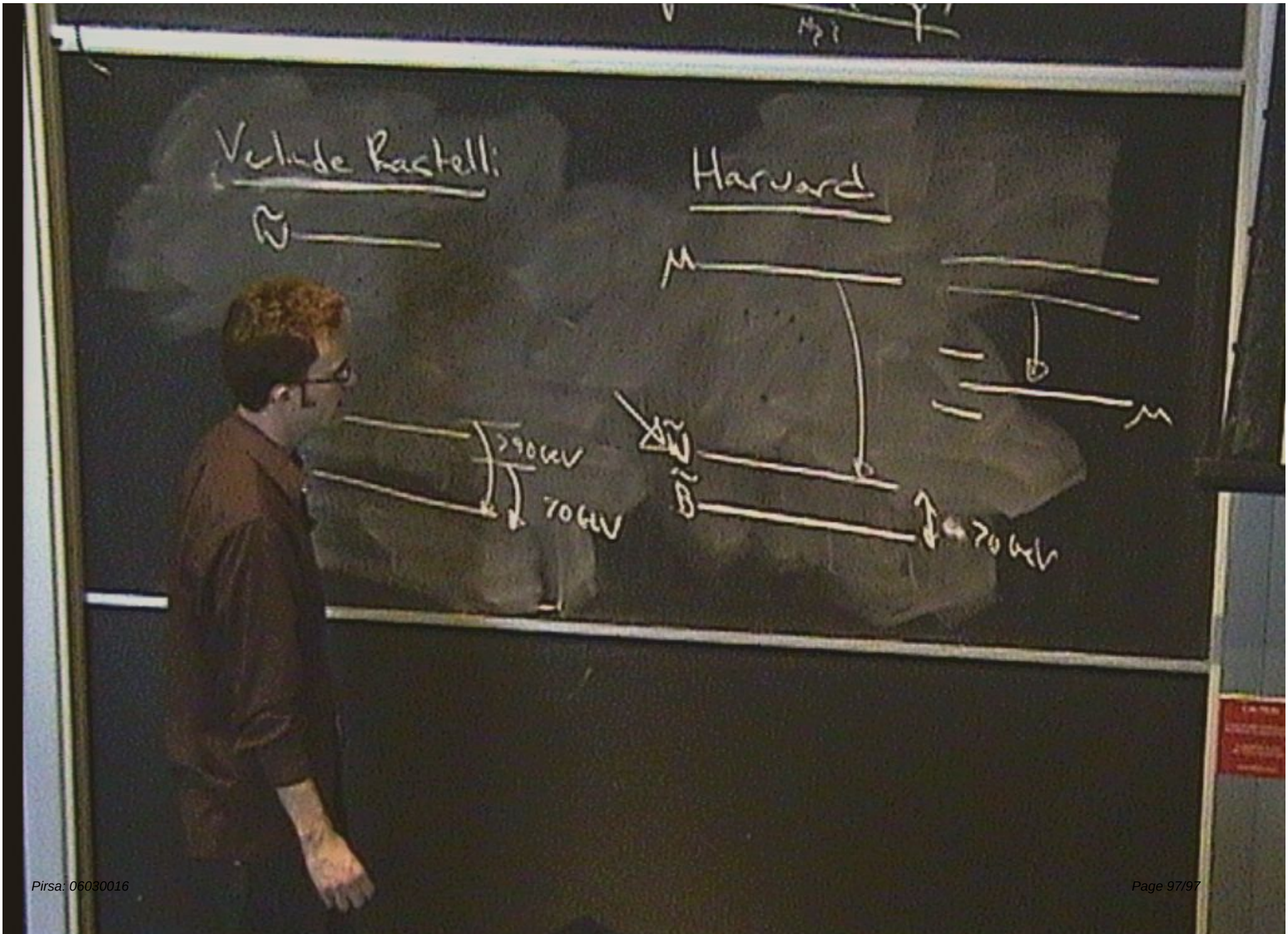


When we preselect events with $\not{E}_T \geq 200$ GeV and at least one jet with $p_T \geq 250$ GeV we can find the Z^* at a 5σ level and the absence of Z consistent with $\pm\sigma$.


Vulnde Rastelli
Harvard
290kV
70kV
70kV


Washington Blackbox
2+ jet e+e-
90 GeV
70 GeV
Z
Z*
e+
e-


Verde Rachell
Harvard


Velade Rastelli
Harvard
290 keV
70 keV
70 keV