This lectures are to cover "Special Topics on Advanced Physics", focusing on Collider Physics related to cosmology.

What I wanted you to learn were:

(a) Why I am working on PPC;
(b) You develop your own research agenda after your Ph.D. thesis;
(c) You think of the interconnection between your agenda and others;
(d) If your research topic is to pursue a new physics, then think of guidance by a principle.

LHC in 2011

Data Certification: 2011 pp Dataset

A fantastic result: \( \sim 4.7 \text{ fb}^{-1} \) good for any analysis; \( \sim 4.9 \text{ fb}^{-1} \) for muon only analyses. \( \rightarrow \sim 350 \text{ trillion pp collisions} \)

The LHC: Above and Beyond

2010: \( 10^{27} \) to \( 2 \times 10^{32} \) \( \rightarrow \) 2011: to \( 3.6 \times 10^{33} \)

US Institutions

We may soon find a new physics landscape. Perhaps by 2012!
Both ATLAS and CMS are coping well with larger than expected (at this Stage) and increasing pile-up. Impressive efforts have limited the impact on CPU and event sizes. Today: average over a fill is ~12 interactions per crossing with tails up to ~20. Pile-up could increase by up to ~2 in 2012. Efforts will continue.

Z → μμ event with 20 reconstructed vertices (ellipses have 20 σ size for visibility reasons).

Pile-up

Both ATLAS and CMS are coping well with larger than expected (at this Stage) and increasing pile-up. Impressive efforts have limited the impact on CPU and event sizes. Today: average over a fill is ~12 interactions per crossing with tails up to ~20. Pile-up could increase by up to ~2 in 2012. Efforts will continue.

Low mass: H → ZZ → 4leptons

Challenge to go as low as possible in p, and keep the highest possible geometrical acceptance.

CMS SM Higgs Combination

Disfavored mass region for minimal SM Higgs:
- Expected Exclusion: 130 – 440 GeV
- Observed Exclusion: 145-216, 226-288, 310-400 GeV

Higgs in Summer

All channels together → combined constraints

- Excluded by ATLAS at 95% CL: 146-466 GeV, except 232-256, 282-296 GeV
- Expected if no signal at 95% CL: 131-447 GeV

- LHC: direct exclusion (95% CL) of a large mass range until now unexplored
- The best-motivated low-mass region (EW fit: mH < 161 GeV 95% CL) still open to exploration
- Data within ±2σ of expectation for no signal → no significant excess

On March for the Higgs in December

<table>
<thead>
<tr>
<th>Date</th>
<th>Objective</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 21</td>
<td>DONE Higgs Review, Part I</td>
<td>Freeze analysis meeting on 2011A; show improvements w.r.t. LP11 analysis. Start interacting with ARC informally</td>
</tr>
<tr>
<td>Nov 01</td>
<td>DONE Higgs Review, Part II</td>
<td>Final strategy based on 2011B high PU data analysis. Good tension of AN, ARC well engaged</td>
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<tr>
<td>Nov 15-16</td>
<td>Common AN/PAS frozen</td>
<td>Pre-approval preparation based on documentation</td>
</tr>
<tr>
<td>Nov 22-23</td>
<td>Final AN &amp; PAS to ARC</td>
<td>Higgs pre-approval meetings</td>
</tr>
<tr>
<td>Dec 02</td>
<td>ARC green light</td>
<td></td>
</tr>
<tr>
<td>Dec 09</td>
<td>Approval talks</td>
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<tr>
<td>Dec 12</td>
<td>LHC jamboree</td>
<td></td>
</tr>
<tr>
<td>Dec 21</td>
<td>Paper drafts in CWR</td>
<td></td>
</tr>
</tbody>
</table>
A View of SUSY or Other New Physics Searches (Lepton-Photon 2011)

SUSY: More than the CMSSM

• Wide variety of possible SUSY signatures
• Other scenarios (e.g., extra dimensions) may lead to similar signatures

Putting it all Together in mSUGRA/CMSSM

Dilepton Resonance Search (1.1 fb⁻¹)

Search for new gauge bosons or new symmetries (Eds) yielding high mass narrow dilepton resonances (ee, μμ)

Extending the kinematic reach further and further into the TeV region

Searches for New Physics in di-jet final states (1 fb⁻¹)

Jet pT spectrum

Events with M > 3.5 TeV

P_T(j1) ~ 1.9 TeV
P_T(j2) ~ 1.7 TeV

Jet pT spectrum

Z' SSM
Z' ψ
RS G⁺ k = 0.05
RS G⁺ k = 0.1

1.94 TeV
1.62 TeV
1.45 TeV
1.78 TeV

SUSY Results of New Physics Searches

SUSY: mass limits on in the range 0.5-1 TeV (within constrained models)

Limits on Massive Exotic New States. Some to Several TeV

CMS Results of New Physics Searches

heavy Bosons
W, Z, G_KK

4th Generation
Quarks b', t'

HSCP

Compositeness
Contact Interact.

Leptoquarks

G. Tonelli
**LHCb: 1st Observation of $B_s \rightarrow J/\psi f_0(980)$**

- In $B_s \rightarrow J/\psi \phi$ the S-wave predicted (& now observed) under the $\phi$ could manifest itself as a $0^+ \pi^+\pi^-$ system, the $f_0(980)$ [Stone & Zhang PRD 79, 074024 (2009)]. As a CP eigenstate can be used to measure $\phi$, without angular analysis

\[
\frac{\Gamma(J/\psi f_0 \rightarrow \pi^+\pi^-)}{\Gamma(J/\psi \phi \rightarrow K^+K^-)} = 0.25
\]

- $m(J/\psi \pi^+\pi^-)$ within $90$ MeV of $B_s$ mass
- $m(\pi^+\pi^-)$ within $30$ MeV of $980$ MeV

---

**SUSY Overview**

When one wants to pick a new physics topic, list the problems in the SM and check the theories that give us solutions with a minimal framework.

**SUSY is more or less a complete framework:**

(a) solution for structural defect in the SM (e.g., Higgs),
(b) indication of unification,
(c) precision data,
(d) flavour physics,
(e) cosmology, etc.

**SUSY may be not the true theory, but one guiding principle answers many questions. So I am enjoying with SUSY.**

---

**Probe Metric**

We test a "minimal" case first, followed by "non-minimal" cases.

A model with the best $\chi^2$ doesn’t mean a correct model.

---

**Additional prediction based on a principle.**

We test a "minimal" case first, followed by "non-minimal" cases.

A model with the best $\chi^2$ doesn’t mean a correct model.
J. Lykken’s Note (I)

**SUSY Philosophy**

- Many parameters
  - MSSM – more than 100 parameters
  - Impossible to have more than 100 measurements at the LHC
  - Let’s consider a way to test a minimal scenario, first. Then, expand to non-minimal scenarios.

- Few parameters
  - Minimal scenario

J. Lykken’s Note (II)

**SUSY Philosophy (II)**

- Many parameters
  - MSSM – more than 100 parameters
  - Impossible to have more than 100 measurements at the LHC
  - Let’s consider a way to test a minimal scenario, first. Then, expand to non-minimal scenarios.

- Few parameters
  - Minimal scenario = Guiding Principle
  - Grand Unification = universality
  - Dark matter = stable LSP

J. Lykken’s Note (III)

**BSM Frameworks at the TeV scale**

- MSSM
  - In practice, the CMSSM, pMSSM, RGI-MSSM
  - SUSY with extended Higgs and/or other particle content
  - NMSSM, nMSSM, SUSY+Z’, SUSY+extra vectorlike fermions

- “Little” Higgs
  - The Higgs is light because it is a pseudo-Nambu-Goldstone

- New strong dynamics
  - Composite Higgs, or no Higgs but a bunch of resonances

- Flat or warped extra dimensions
  - If warped, dual to new strong dynamics

- Hidden valleys
  - Generic name for weird stuff weakly coupled to the SM

J. Lykken’s Note (IV)

**High-Energy Physics Vision Eqs.**

- Standard Model, SUSY/Higgs & Cosmology

- **Unification:**
  - Why $g_80$?
  - Why $g_80$?

- **Why $g_87$?**
  - **Why $g_87$?**

- **SUSY Philosophy (III)**

- **SUSY who?**
  - SUSY is not a model
    - It is a framework for an infinite number of QFT models whose quantum corrections are suppressed by SUSY
  - SUSY as a framework is “complete”
    - Cosmology, unification, precision data, flavor, strings, etc
  - But at the TeV scale, BSM physics doesn’t have to be SUSY
    - There are at least 5 other competing BSM frameworks
  - SUSY might only show up at higher scales
    - 10 TeV, 100 TeV, 1,000,000,000,000,000,000 TeV

- A modern review: D. Chung et al, hep-ph/0312378
Dark Matter and SUSY

Probing $10^{-7}$ sec. after Big Bang

Now

CMB

$\sim 0.0000001$ seconds

Combination

Excess in Inclusive Searches

Excess in $E_T^{miss} + \text{Jets} + X$

An Excess – Not Good Enough

"Excess in tails of kinematic variables + Masses"

SUSY Mass Techniques

Christopher Lester et al., ICHEP2010, arXiv:1004.2732

Few assumptions

- Missing momentum
- $M_{\text{fin}}$, Razor, $H_T$
- $m_{t\bar{t}}$
- $M_{2\bar{1}}$
- $M_{6\bar{1}}$ (with "kinka")
- $M_{1/2}$ (parallel / perp)
- $M_{0/2}$ ("sub-system")
- "Polynomial" constraints
- Multi-event polynomial constraints
- Whole dataset variables
- Max Likelihood / Matrix Element

Many assumptions

SUSY Mass Techniques

Minimal Supergravity (mSUGRA)

2 Higgs Doublets + Supersymmetrized Standard Model +

$\mu > 0$ and $A_0 = 0$ for simplicity.

$\tan \beta = \frac{<H_u>}{<H_d>}$ at $M_Z$

$\mu$ (spin 0)

$m_{1/2}$ (spin $\frac{1}{2}$)

$m_{0/2}$ = Common gaugino mass at $M_{\text{GUT}}$

$m_\mu$ = Common scalar mass at $M_{\text{GUT}}$

$A_0$ = Trilinear coupling at $M_{\text{GUT}}$

sign($\mu$) = sign of $\mu$ in $H_uH_d$

http://www.damtp.cam.ac.uk/user/gr/public/bb_history.html

Probe Metric at the LHC

We test "mSUGRA" cases first, followed by a "non-universal SUGRA" case.

Precision

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sign($\mu$) = sign of $\mu$ in $H_uH_d$

(We choose $\mu > 0$ and $A_0 = 0$ for simplicity.)
"Universality" allows us to simplify the SUSY world in a 2D plane ($m_0 - m_{1/2}$).

1) $M_{Higgs} > 114 \text{ GeV}$
2) $M_{chargino} > 104 \text{ GeV}$
3) $2.2 \times 10^{-4} < \text{Br}(b \to s \gamma) < 4.5 \times 10^{-4}$
4) $(g - 2)_\mu$ : $3\sigma$ deviation from SM
5) $0.106 < \mu^2 < 0.121$

In the SUSY World

Higgs
Slepton
Gluino &
Squark
m_0
m_{1/2}
Neutralino
& Chargino

Allowed Region

Higgs Mass ($M_h$)
Branching Ratio $b \to s \gamma$
Magnetic Moment of Muon
CDM allowed region?

Cosmologically Allowed Region

Higgs Mass ($M_h$)
Branching Ratio $b \to s \gamma$
Magnetic Moment of Muon
CDM allowed region

Cosmologically Consistent Signals

Excluded by
- Rare B decay $b \to s \gamma$
- No CDM candidate
- Muon magnetic moment

CDM allowed region

MMCD allowed region?

BR($B_s \to \mu^+ \mu^-$) ~ 3 x 10$^{-4}$

Detection of $B_s \to \mu^+ \mu^-$ at the tevatron Run II and constraints on the SUSY parameter space

R. Anokhina, B. Dutra, K. Kanemura, T. Tanaka, T. Tomita

PRL 107 (2011) 191801

EXO-11-31-PreApproved

KNU-WCU project #3

LHC

KNU-WCU project #2

KNU-WCU project #1

EXO-10-022-PAS

EXO-11-01-PreApproved

PRL 107 (2011) 191801
**Prediction/Result in 2002/2011**

![First 2-side 90%CL Limit](image1)

![SM Expectation](image2)

Fig. 2: Illustrated 95% C.L. Limits on the branching ratio for $B_s \rightarrow \mu^+\mu^-$ at CDF in Run II as a function of integrated luminosity. Solid (Case A) and dashed (Case B) curves are based on different assumptions on the signal selection efficiency and the background rejection power. See the text for details.

---

**SUSY Searches**

- $R_p$ conservation: Stable LSP $\rightarrow$ MET
- $R_p$ violation $\rightarrow$ No MET

---

**Stable LSP and more**

- More distinct final states with quasi-stable LSP and $R_p$ violation

---

**CMS SUSY Strategies**

- Generic searches with inclusive topologies for most possible final states
- Several search regions with multiple approaches
  - Robust data driven background estimates
  - Emphasis on discovery over limit setting
- Public twiki pages contain a full set of results
  
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
CMS SUSY Searches in 2010

URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

- Fully hadronic searches:
  - SUS-10-005: MET + b-jets + τ [JHEP]
  - SUS-10-006: MET + τ + 1 jet [JHEP]
  - SUS-10-007: MET + τ + 3 jets [JHEP]
  - SUS-10-008: MET + τ + 3 jets (JHEP 08 (2011) 157)
  - SUS-10-009: Inclusive search with "Razor" variables [accepted by PRD]

- Searches with leptons:
  - SUS-10-010: MET + b-jets + τ [JHEP]
  - SUS-10-011: MET + b-jets + τ [JHEP]

- Searches with photons:

- Others:
  - EXO-11-001 RPV gluino \( 3j \) [published in PRL]
  - ...

CMS SUSY Searches in 2011

URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

- All hadronic searches (1.1 fb\(^{-1}\))
  - SUS-11-001: all hadronic events with \( \alpha_\text{s} \) [PRL 107 (2011) 221804]
  - SUS-11-002: all hadronic events with MHT

- Searches with leptons (upto 2.1 fb\(^{-1}\))
  - SUS-11-015: single lepton, jets and MET
  - SUS-11-016: same sign di-leptons
  - SUS-11-017: opposite sign di-leptons

- Searches with photons (1.14 fb\(^{-1}\))
  - SUS-11-049: photons, jets and MET

- Others
  - EXO-11-045: RPV in multilepton events (SUS-11-013)
  - EXO-11-069: displaced photon (PAS, Oct 30, 2011)

ATLAS vs. CMS in MET + Jets

- Comparable sensitivities ☺

CMS Combined Results
Determined the dark matter relic density in the Minimal Supersymmetric Stau-Neutralino
Coannihilation Region at the Large Hadron Collider

Richard Arnowitt, Bhaskar Dasgupta, Alvise Gara, Terrel Kenyon, Abram Klevkov, and David Toback
Department of Physics, Texas A&M University, College Station, Texas 77843-4242, USA
(Received 5 March 2008, published 11 June 2008)

We examine the co-annihilation (CA) mechanism of the early Universe. We use the minimal supersymmetric SU(5) model, and show that from measurements at the CERN Large Hadron Collider one can predict the dark matter relic density with an accuracy of 6% with 30 fb⁻¹ of data, which is comparable to the direct measurement by the Wilkinson Microwave Anisotropy Probe. This is done by measuring the h1 (teh1) parameter, mh, in the CA region without requiring direct measurements of the top squark and bottom squark masses. We also provide precision measurements of the penguin, squark, and lighter neutralino in the CA region without assuming any supersymmetry.

DOI: 10.1103/PhysRevLett.100.231802
PACS numbers: 11.30.Qc, 14.60.Lb, 95.35.-d

OS tau pairs: Background Estimations
- Extrapolate from enriched control regions using relative selection efficiencies:

Jet misidentified as τ_{+}:

- Extra background from enriched control regions using relative selection efficiencies:

Table 1: Summary of the selection and signal region definitions.

<table>
<thead>
<tr>
<th>Process</th>
<th>τ_{+} + τ_{−}</th>
<th>τ_{+} + τ_{−}</th>
<th>τ_{+} + τ_{−}</th>
<th>τ_{+} + τ_{−}</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>10.1 ± 1.7 (stat) ± 2.7 (sys)</td>
<td>2.5 ± 1.6 (stat) ± 1.9 (sys)</td>
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</tr>
</tbody>
</table>

Observed: 11 + 8

Figure 1: Event display (I).

Figure 12: Log-plot of the event for the same event in Fig. 9: y_{1} = 54.4 GeV, y_{2} = 10.8 GeV, y_{3} = 54.4 GeV, y_{4} = 10.8 GeV, y_{5} = 10.8 GeV, y_{6} = 10.8 GeV.
Table 6: Summary of model-dependent limits. The efficiency and acceptance are defined in the text; the efficiency uncertainty is dominated by the uncertainty in the hadronic energy scale. The CLs 95% C.L. UL on the cross section is indicated, as well as the value of this quantity for the LM1, LM2 and LM3 scenarios.

<table>
<thead>
<tr>
<th>Model</th>
<th>LM1</th>
<th>LM2</th>
<th>LM3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High $\ell_1$ signal region ((z_1))</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UL_{\sigma_{pT}} [pb]</td>
<td>$3.5^{+1.9}_{-1.8}$</td>
<td>$2.6^{+1.2}_{-1.0}$</td>
<td>$2.1^{+1.5}_{-1.3}$</td>
</tr>
<tr>
<td>UL_{\sigma_{pT}} [pb]</td>
<td>4.2</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>High (E_T) signal region ((\ell_1&lt;z_1))</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UL_{\sigma_{pT}} [pb]</td>
<td>$3.5^{+1.9}_{-1.8}$</td>
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</tr>
<tr>
<td>UL_{\sigma_{pT}} [pb]</td>
<td>5.7</td>
<td>2.5</td>
<td>2.6</td>
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<tr>
<td><strong>High $\ell_2$ signal region ((z_1))</strong></td>
<td></td>
<td></td>
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<tr>
<td>UL_{\sigma_{pT}} [pb]</td>
<td>$3.5^{+1.9}_{-1.8}$</td>
<td>$0.6^{+0.3}_{-0.2}$</td>
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</tr>
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<td>2.9</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>High $\ell_2$ signal region ((z_1, z_2))</strong></td>
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<td></td>
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<tr>
<td>UL_{\sigma_{pT}} [pb]</td>
<td>$2.5^{+1.5}_{-1.2}$</td>
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<td>2.9</td>
<td>2.6</td>
<td>2.5</td>
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<tr>
<td><strong>High (E_T) signal region ((\ell_2&lt;z_1))</strong></td>
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<td>UL_{\sigma_{pT}} [pb]</td>
<td>$2.5^{+1.5}_{-1.2}$</td>
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<td>2.9</td>
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<tr>
<td><strong>UL_{\sigma_{pT}} [pb]</strong></td>
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