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• Lecture 1: SETTING UP A SEARCH AT THE LHC

- Searching for SUSY in practice: strategy, trigger, reconstruction
- Designing a search: Simplified Models
- tools

• Lecture 2: R-PARITY **CONSERVING SUSY**

- DM direct production
- DM cascade production

• Building a search: signal region, control regions, statistics











• I don't intend to give you the status-of-theart picture of searches @LHC

• what is excluded in which final state up to which mass

• You have a full conference coming soon for that, hopefully with new results

WHAT THESE LECTURES ARE NOT







I would like to give you an idea of how a search is built

• I will use SUSY for practical reasons, but I will touch other searches too

• What I will say applies in general, not just to SUSY searches

• For experimentalists, it might be useful to design the strategy towards your next discovery

• For theorists, it might be useful to understand experimental results (i.e., where the assumptions come in, to which level results generalise, etc)







• The slides are CMSbiased, for obvious practical reasons

• I am in CMS, I know CMS more, and it costs me less time to prepare lectures this way

• The large part of what I will say applies also to ATLAS

• If not, I will make it clear to you







By Joseph Lykken and Maria Spiropulu

Supersymmetry and the CPISIS PARTICLE PHYSICS DIVISIOS

Supersymmetry postulates that every known parti- Physicists hoped to find evidence of supersymmetry cle has a hidden superpartner. Physicists love super- in experiments at the Large Hadron Collider (LHC). To symmetry because it solves a number of problems date, they have not. If no evidence arises in the next that crop up when they try to extend our under- run of the LHC, supersymmetry will be in trouble. standing of quantum mechanics. It would also poten- The failure to find superpartners is brewing a crisis in tially solve the mystery of the universe's missing physics, forcing researchers to question assumptions dark matter.

from which they have been working for decades.



THE BG PCTURE









• Extensively searched in all possible directions

Done more than expected, with new ideas and original approaches to data taking

• Our new-physics target evolved towards more complicated scenarios

• EXAMPLE: the SUSY we search for today is very different than what is in the ATLAS/CMS TDRs

EGHT YEARS OF SEARCHES...

December 2017 Model	e, µ, τ, γ	Jets	E_{τ}^{miss}	fLagn	Mass limit	√ <i>i</i> = 7, 3 TeV √ <i>i</i> = 13 TeV	$\sqrt{s} = 7, 8, 13$ Reference
$\bar{q}q, \bar{q} \rightarrow q \tilde{\kappa}_{L}^{0}$	0	2.6 jeta	Yes	30.1		1.67 TeV m(ξ ⁴ ₁)<200 GeV, m(1 ⁴ gen q)m(2 ¹⁴ gen q)	1712.42332
à à à →atí (compre	ssec) mono-jat	1-3 jets	Yes	36.1	710 GeV	n(i)-n(?]):5GeV	71.0330
28.8→qqri 30.0→qqri	F ⁰ 0	2-0 jets 2-0 jets	Yes	36.1	1	2.02 TeV m(?;)>20004V	7.2 62332
28 8 4441 - 1444	ee.uµ	2 jets	Yes	14.7	2	1.7 TeV n(2) < 300 GeV	61.0579
D 28.8-199/11/w)20	30.11	4 jets		36.1	1	1.87 TeV m(2)=0GeV	1706.03731
28.8→9qWZR1	0	7-11 jets	yes yes	36.1	1	1.3 TeY n(l ⁰ 1) <+01 GeV	705.02794
GMSB (/ NLSP)	1-2 + 0-1	¿ 0-2 jets	Yes	32	1	20 TeV	607.05979
SGM (birb NLSP)	NLCO Y	2 jets	Yes	36.1	2	2.15 TeV POINT SPIRIT PM	AT LAS-CONF-2017-080
Gravitino LSP	0	mono-jei	t Yes	20.3	7 ^{1,0} scale 865 GeV	n(G)>1.8 × 10 ⁻⁴ eV, n(g)=n(c)=1.5 TeV	502.01518
2 28 8 → ahr	0 0-1 <i>e.p</i>	3b 3b	Yes Yes	36.1 36.1	2 2	1.92 TeV n(k ⁰)×600G∢V 1.97 TeV n(k ⁰)×600G∢V	1711.01901
$\tilde{\delta}_1 \tilde{\delta}_1, \tilde{\delta}_1 \rightarrow b \tilde{\ell}_1^0$	0	24	Yee	36.1	j ₁ 960 GaV	n(²)×420G/V	1708.09264
2 3 5101. B1-121	2 e.µ (88)	1.0	Yes	36.1	31 275-700 GeV	$m(\ell_1^0) \le 200 \text{ GeV}, m(\ell_1^0) = m(\ell_1^0) + 100 \text{ GeV}$	1706.03731
2 hh.h→bli	0-2 <i>e</i> , µ	1-2.8	Yes 4	47/13.3	1 117-170 GeV 200-720 GeV	$m(\tilde{t}_{1}^{n}) = 2m(\tilde{t}_{1}^{n}), m(\tilde{t}_{1}^{n}) = 55 \text{ GeV}$	1209.2102, ATLAS-CONF-2016-0
$i_1i_1, i_1 \rightarrow Wbk_1 \text{ or } k$	ο 0.2 <i>e</i> ,μ	0-2 002/1-3	2 /0 Yes 2	20.3/35.1	1 60-168 GeV 0.196-1.0 Ter	m(2)=1GcV	1506.06616, 1709.04183, 1711.11
5 5 (natural GMSB)	2 c. a (Z)	1.6	Yas	20.3	in 150-600 GeV	n(() h(t))=0.00V	1403.5222
5 6h. 6 1 1Z	3 e, p (2)	15	Yes	36.1	i 200 700 GeV	m(²⁰)-0GeV	796.03886
$i_2 h_1, i_2 \rightarrow l_1 + h_1$	1·2 e, µ	4.0	Yes	36.1	i2 320-830 G9V	n(2 ⁿ ₁)=0GeV	705.03986
4. 2 B. R. 1-108	2 ε,μ	U	Yes	36.1	7 80-500 GEV	n(2 ⁰)=0	ALLAS-CONF-2017-039
$\tilde{I}_{1}^{+}\tilde{X}_{1}^{-}, \tilde{X}_{1}^{+} \rightarrow \tilde{l}\nu(l\tilde{\nu})$	2 e. µ	0	Yes	36.1	注 750 GeV	$m(\tilde{\ell}_{1}^{0})=0, m(\tilde{\ell}, \tilde{v})=0.5(m(\tilde{\ell}_{1}^{+})+m(\tilde{\ell}^{0}))$	ATLAS-CONF-2017-039
$\hat{x}_1^{\dagger}\hat{x}_1^{\dagger}/\hat{x}_2^{0}, \hat{x}_1^{\dagger} \rightarrow \bar{x}_1(z)$), $\tilde{k}_{3}^{l} \rightarrow \tilde{r}s(r^{5})$ 2τ		Yes	36.1	.行	$m(\hat{r}_1^0)=0, m(\hat{r},\hat{r})=0.5(m(\hat{r}_1^0)+m(\hat{k}_1^0))$	1708.07875
Tix2 + Lillon, i	νℓ _L ℓ(ν) 3 ε,μ	0	Yes	36.1	大式 1.13	TOY $m(\mathcal{X}_1) = m(\mathcal{X}_2), m(\mathcal{X}_1) = 0, m(\ell, i) = 0.5(m(\mathcal{X}_1) + m(\mathcal{X}_1))$	ATLAS-CONF-2017-039
TIN WITH	23e.µ	0-2 jets	Yes	36.1	SED GeV	$\mathbf{n}(\tilde{r}_1^n) = \mathbf{n}(\tilde{k}_1^n), \mathbf{m}(\tilde{k}_1^n) = 0, \tilde{\ell}$ decaupled	ALTER CONE-5012-038
arxs-waraxi, n-	4 C. II	0-20	Vec	20.3	210 GeV 635 GeV	m(K)_m(K)_m(K)_m(K)_m(K)_m(K)_m(K)_	1405 5086
GGM (wiro NLSP)	weak prod. 20		Yes	20.3	115-370 GeV	cr<1nn	1507.05490
GGM (biro NLSP)	veak prod., λ ⁰ ₁ -γ/σ 2γ		Yes	30.1	ŵ 1.08 T	e/ extra	ATLN3-CONF-2017-060
Direct $\hat{x}_1^{\dagger} \hat{x}_1^{-}$ prod., i	ong-lived \mathcal{R}_1^d Disapp. trk	1 jot	Yes	06.1	送 600 GeV	m((²)/m((²)/m((²)/m))/m((²)/m))/m((²)/m)/m((²)/m)/m((²)/m)/m)/m((²)/m)/m((²)/m)/m((²)/m)/m)/m((²)/m)/m)/m((²)/m)/m((²)/m)/m)/m((²)/m)/m)/m)/m((²)/m)/m)/m)/m((²)/m)/m)/m)/m)/m)/m)/m)/m)/m)/m)/m)/m)/m)	17-2.02110
Direct $X_1 X_1$ prod., it	org-lived X1 dE/dk t/k		Yes	18.4	21 495 GeV	m(\$1)+m(\$1)~160 NeV, x(\$1)<15 ns	1506.05332
Stable, stopped # R	-hadron ()	1-5 jets	Yes	27.9	7 350 GeV	n(P ₁)=130 G4V, 10µs<+(jj < 1000 +	1310.6584
Metastable 2 E-har	IN HE/dv Hk			32	2	1.58 TeV	604.03 25
Metastable 3 R-had	xtv lapl vtx		Vos	32.8	·	2.37 TeV (2/3/-C.17 m; n(2)) = 100 GeV	17:0 0490
GMSB, stable r, x	+f(e, p)+f(e, p) 1-2 µ			19.1	月 537 0eV	Ostanjik 50	1411.0790
GMSB E made on	- Lord Of Visi						1400.5543
2010/01/01/01/01	0-IV90.X = 7		Yes	20.3	X ^a 440 GeV	'<'(₹j)<3 ts, SPS3 model	1400.0046
23 X ⁰ ren/ep/hp	g-W90.X 2.F displ.ee/eu/		13 ⁻	203 203 TeV	2 440 GeV 2 1.0 TeV	¹ <<(ℓ _i)<3 1s, S ² S3 model 7 α _i ν _i ² ℓ ₁ ¹ <740 mm, m(2)=1.3 TeV ² 10.11, λ _{20,10000} at 0.07 m(2), cr ₂₅₇ <1 mm >400 GeV, λ ₁₅₁ ≠0 (k = 1,2) > 0.2×m _i ² ℓ ₁ ¹ , λ ₂₀ ≠0	544.05.62 647.08479 1404.2300 ATLAS-CONF-2016-075 1405.5088
1(a) ×2 (β=0.5 (u) ×2 (β=0.5	leptor	- -	13 ⁻	203 203 TeV	#40 GeV 1.0 TeV 8 TeV coloron/∰ x2 coloron/∯ x2 M	I <<(ξi) <3 15, SPS3 model	140,00042 1504,05162 1404,2500 ATLAS-CONF-2016-075 1405,5086 SUSY-2016-022 1704,08490 1704,08490 17.0.0717
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1 3 1 1 1 1 1 2 3 3 1 1 1 1 3 2 3 3 1 1 1 3 2 3 3 1 1 1 3 2 3 3 1 1 1 3 2 3 3 1 1 1 3 3 3 3 1 1 1 3 3 3 3 1 1	Lepto	quark	13 ⁻	TeV	#40 GaV 1.0 TeV 0 0 1 0 1 2	$ultijet = \frac{1}{3} = \frac{1}{4} = \frac{1}{16} = \frac$	504.05162 504.05162 607.08079 1404.2500 ATLAS-CONF-2016-075 1405.5086 SUSY-2016-02 704.08493 704.08493 704.08493 70.0717 7 ⁺ 0.05544 501.01325
28 31 rem/epr/up 28 31 rem/epr/up (β=0.5 34,0 82 (β=0.5 34,0 82 (b) x2 1 1 (1) x2 1 1		quark	13 - (S	TeV	#40 Gav 8 TeV coloron(ii) x2 M gluino(3i) x2 M gluino(3i) x2 M 0 1 2 image: transmission of transmissintervite of transmissintervite of transmissintervite	1 <c(k)<3 15,="" model<="" sps3="" td=""> 2 2<c(k)<270 m(g="1.2TeV)</td" mm,=""> * 10.11, k_{25,13823mld,07 m(g), cr_{SPS1} mm ><0006V, k_{15} #0 (k = 1.2)</c(k)<270></c(k)<3>	564.05162 564.05162 667.08874 1404.2500 ATLAS-CONF-2016-075 1405.5086 SUSY-2016-022 1704.08493 1704.08493 1704.08493 170.0717 17'0.05544 1501.01225
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• We started looking for mSugra-inspired models. Thanks to large gluino and squark cross sections, exclusions became soon very strong

• We then moved to Natural-SUSY scenarios, with focus on t and b squarks

We moved to simplified models as a generalization of search strategies (with 100% BR assumptions)

• We recently generalized simplified models to BR-independent results

And we extended model interpretation to large-dimensional scans (pMSSM) 9











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models to BR-independent results

Research





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SUSY: A MOVING TARGET











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(a) All LSP types

















• LHC is a proton collider

• whatever you want to produce needs to couple to quarks

• This is basically true for any MSSM particle

 Different production
 mechanisms contribute to determine the production cross section

SGNAL: CHOOSE YOUR TARGET







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- These mechanisms translate into a hierarchy of production cross sections
 - colored particles have larger cross sections
 - gluinos more than quarks, because of color enhancement
 - ewkinos have the smallest cross sections (but with a lot of data we are getting there)

10' 10^{3} 10² 10 10-10⁻²

Cross-section [pb]

 10^{-3} 10-4 10







Council





- Making SUSY particles is only part of the problem
- The next is the decay mode, starting with designing a trigger
 - ewkinos decay to leptons (via W/Z/H) or high-pT y, which are rare in typical LHC collisions
 - squarks and gluons make jets, to which there is a large background
 - Among the squarks, stop
 and sbottom are better to handle, because they come with b-jets and sometimes with W bosons













18













• Too many data, too large data -> need to filter online • Selection done in two stages of reconstruction • Accuracy increases with rate reduction and consequent latency increase • Three main domains Online selection (trigger) • Offline central reconstruction • Offline selection + data analysis 100 KHz 1KHz 1MB/evt 1MB/evt









- 40 MHz in / 100 KHz out
- ~ 500 KB / event
- Processing time: ~10 µs
- Based on coarse local reconstructions
- Not all detectors available (e.g., no tracking in Run I/II)
- FPGAs / Hardware implemented

THE 11 TRUCER













- 100 KHz in / 1 KHz out
- $\odot \sim 500 \text{ KB} / \text{event}$
- Processing time: ~30 ms
- Based on simplified global reconstructions
- Software implemented on CPUs



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- Based on accurate global reconstructions
- Software implemented on CPUs

















• At this stage, anything is possible, with all the time you want (< postdoc contract/PhD duration)</pre>

• But you need to be sure that your interesting data made it up to here

OFFLINE 7ANALYSS

1KHz

1MB/evt

Data Flow

• This is you with your laptop, an ssh connection, a grid





1KHz

30 Kb/evt





Dueruan





A compromise between latency and accuracy, which translates into a compromise between purity and efficiency

















- curve)
- what you use

written for nothing (i.e., resources wasted)





- lot of missing E_T)
- When all you have is jets
- When your signature consists of moderate-pT objects
- (displacement, stopping tracks, large dE/dx, etc)
- very inefficient
 - certain scenarios

• Whenever you don't have rare handles to trigger on (isolated & high-pT leptons or photons, large lepton multiplicity, a

• When your signature consists of track-related features

• Trigger doesn't make things impossible. But can make things

• in which case, you have to wait for A LOT of data to probe





datasets

- Run reconstruction in the trigger farm
- Avoid resource limitations: write less information $2\vdash$

(a few floats) for more events

• Probes <u>unexplored territory</u>, previously left behind

<u>Problem: practical only for specific topologies^{0.5}</u>

<u>No application to SUSY (yet)</u>









• Major trigger upgrades are on the way

- ATLAS introduced tracking capabilities at "L1.5"
- Both experiments planning for
 tracking at 40 MHz for HL-LHC
- Both experiments extending
 scouting usage
- IN RUN III, LHCb & ALICE moving to a real-time reconstruction system that will replace the HLT (i.e., scouting as a default)

LFE WILL BE EASER



Research









• Detectors are designed so that most of the particle is detected by at least one detector

- For jets, you care about the collective objects and not the individual constituents
 - you can use the energy deposits in calorimeters (standard reco)

• you can first reconstruct the individual particles and then cluster them (particle flow)











Neutrinos other neutral stable particles (dark matter etc) don't interact in the detector

Their collective presence can be detected measuring the missing transverse energy













- Two protons with same energy collide
- Actually, the collision is between quarks/gluons in the proton. They carry different fractions of the proton momentum
- As a result, there is a momentum imbalance ~ along the beam axes, but not in the transverse plane
- Transverse momenta should then balance. If some particle escaped undetected, the balance will be broken

MISSING TRANSVERSE ENERGY









- Today's BSM search today expanded in many new directions
 - Better identification of complex objects (e.g., tau leptons, b-jets)
 - New Standard Model candles (e.g.,
 the Higgs boson)
 - New reconstruction strategies (e.g., boosted jets)
 - Better understanding of the detector > better sensitivity to soft particles
 - More and more exotic signatures: displaced vertices, disappearing tracks, heavy stable charged particles, etc









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- As long as you use standard objects (e.g., the kind of jets, leptons, etc used in SM, Higgs, Top analyses) you are ready to go
- Complications may arise with soft or very-hard objects
- Reconstruction more complicated when
 you look into exotic signatures
 - displaced jets/tracks/leptons
 - stopping tracks

•

• The solution there is mainly case dependent, and we will talk about it in the last lecture













- Based on your signature, you
 signature, should have by now some final state in mind (e.g., jets + 11eptons + missing E_T)
- MC simulation would tell you the list of background processes from the Standard model, among which
 - \odot Z+jets with Z to neutrinos
 - W + jets with $W \rightarrow \ell v$
 - QCD with one lepton from meson decays
 - QCD with one jet faking a lepton (not for muons)
 - tt with at least one $W \rightarrow \ell \nu$







- You need to have some physics motivated quantity that looks different for a signal and a background sample
 - Some kinematic quantity (see Lecture 2)
 - The presence of some special object (see Lecture 3)
 - Multiplicity of objects of some kind, e.g., leptons, b-jets, etc (see Lecture 3)
- Based on these quantities, one can focus the search on a subset of the events for which a signal enhancement is expected











Together with the signal region, a set of control regions are designed, enriched of one kind of background

 Backgrounds can
 ca M_T be measured in these regions and scaled according to transfer factors, predicted with MC simulations

No b-jet +isolated lepton

> 2 b-jets +isolate d lepton













With this MC-assisted data-driven background prediction, you are more robust vs unexpected issues

• Still, keep in mind that our MC simulation is more reliable than this, when far from the tails (template fits are often used for SM measurements)

• At this stage, your analysis translates into a multi-bin counting exercise, where the signal is searched as excess on prediction



















• The full setup of statistical procedure was setup at Higgs discovery time

• (asymptotic) CLs emerged as the limit-setting procedure

• one-sided p-values, converted to number of sigmas, are quoted for evidence of an excess

• These procedures result in plots like these

• In case their meaning is not clear, I will go through the procedure to get them















• Let's say you are looking for the Higgs boson. You have two hypotheses:

• HO: no Higgs

• H1: Higgs somewhere

• Assume a mass value

• For each mass value, assume a cross section and construct the two distributions for some discriminating quantity $\Lambda^{(*)}$ under H0 and H1

• generate toy MC with $\sigma=0$ (H0)

• generate toy MC with $\sigma = \sigma^*$ (H1)





(*) Neyman Pearson lemma says "use the ratio of the likelihood under the two hypotheses

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-2ln(∧)









Research Council

























• Repeat the procedure above for several values of σ/σ_{SM}



 $\sigma(pp \rightarrow H)/\sigma_{SM}(pp \rightarrow H)$







• Each line intercept CLs = 0.05. The intersection gives you

• The expected and observed limit









• Each line intercept CLs = 0.05. The intersection gives you

The expected and observed limit











• Each line intercept CLs = 0.05. The intersection gives you

The expected and observed limit











• Now repeat the procedure for any value of mH and connect the dots









- When you don't know if you have a signal, you first try to exclude it
- If the signal is there, your limit will be poor (and worse than expectation)
- If it is much worse, you might have discovered a signal...
- ... or you might have discovered that your analysis is terrible
- these plots are not the right plots to establish the presence of a signal









• To claim a discovery, you need to exclude the possibility that your background could mimic a signal

- To do so, you measure (with toy experiments) the probability that a bkg-only sample gives a result as signal-like as what you see on data
- The signal is stringer than the conventional 5o threshold so...









observed) signal-like fluctuation in the background









observed) signal-like fluctuation in the background























• Before the LHC, searches were entered on full models

• This changed during Run I. Simplified models became the standard

• Focus on a specific process x decay chain

• Interpret the analysis in this context





- At the beginning of the LHC, many pre-LHC-data analyses were actually found to be too much tailored on the benchmark models
- Simplified models allowed to go beyond certain implicit assumptions
- This new paradigm allowed to discover weakness in the search program and design a nextgeneration set of analyses
- In general, the use of simplified models made our search strategy more robust













• BRs are usually assumed to be 100%. This means that every line in a summary plot is implicitly excluding the others

• Cross sections are sometimes computed under special assumptions (e.g., decoupling limit) and don't hold in general



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MND THE HIDDEN ASSUMPTIONS











BR-independent results

1ike Natural SUSY

worst result



GOING BEYOND ASSUMPTION













BR-independent results

1ike Natural SUSY

worst result



GOING BEYOND ASSUMPTION









• LHC has all it needs to be a SUSY discovery machine

- can produce full spectra of particles
- can observe many final states for any particle
- Practical limitations (e.g., trigger) should come into consideration when designing the analysis
- Data control samples are a key ingredient (a 100% MC-based background prediction would not be considered acceptable at LHC)
- Statistical tools in place from Higgs discovery
- Simplified models great guidance to interpret and improve searches, when taken with a grain of salt





European Research







