



### Maurizio Pierini CERN













### • 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



![](_page_4_Picture_0.jpeg)

![](_page_4_Picture_1.jpeg)

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)

![](_page_4_Figure_7.jpeg)

![](_page_5_Picture_0.jpeg)

![](_page_5_Picture_1.jpeg)

• 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

![](_page_5_Picture_6.jpeg)

![](_page_5_Picture_7.jpeg)

![](_page_6_Picture_0.jpeg)

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.

![](_page_6_Picture_6.jpeg)

### THE BG PCTURE

![](_page_6_Picture_8.jpeg)

![](_page_6_Picture_10.jpeg)

![](_page_7_Picture_0.jpeg)

![](_page_7_Picture_1.jpeg)

• 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	$E_{\tau}^{miss}$	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 <sup>4</sup> <sub>1</sub> )<200 GeV, m(1 <sup>4</sup> gen q)m(2 <sup>14</sup> 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 <sup>0</sup> 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 <sup>0</sup> 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 <sup>1,0</sup> scale 865 GeV	n(G)>1.8 × 10 <sup>-4</sup> 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 <sup>0</sup> )×600G∢V 1.97 TeV n(k <sup>0</sup> )×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 <sub>1</sub> 960 GaV	n( <sup>2</sup> )×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( <sup>20</sup> )-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 <sup>n</sup> <sub>1</sub> )=0GeV	705.03986
4. 2 B. R. 1-108	2 ε,μ	U	Yes	36.1	7 80-500 GEV	n(2 <sup>0</sup> )=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
$\hat{x}_1^{\dagger}\hat{x}_1^{\dagger}/\hat{x}_2^{0}, \hat{x}_1^{\dagger} \rightarrow \bar{x}_1(z)$	), $\tilde{k}_{3}^{l} \rightarrow \tilde{r}s(r^{5})$ $2\tau$		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 <sub>L</sub> ℓ(ν) 3 ε,μ	0	Yes	36.1	大式 1.13	<b>TOY</b> $m(\mathcal{X}_1) = m(\mathcal{X}_2), m(\mathcal{X}_1) = 0, m(\ell, i) = 0.5(m(\mathcal{X}_1) + m(\mathcal{X}_1))$	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 <sup>0</sup> <sub>1</sub> -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(( <sup>2</sup> )/m(( <sup>2</sup> )/m(( <sup>2</sup> )/m))/m(( <sup>2</sup> )/m))/m(( <sup>2</sup> )/m)/m(( <sup>2</sup> )/m)/m(( <sup>2</sup> )/m)/m)/m(( <sup>2</sup> )/m)/m(( <sup>2</sup> )/m)/m(( <sup>2</sup> )/m)/m)/m(( <sup>2</sup> )/m)/m)/m(( <sup>2</sup> )/m)/m(( <sup>2</sup> )/m)/m)/m(( <sup>2</sup> )/m)/m)/m)/m(( <sup>2</sup> )/m)/m)/m)/m(( <sup>2</sup> )/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 <sub>1</sub> )=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 <sup>a</sup> 440 GeV	'<'(₹j)<3 ts, SPS3 model	1400.0046
23 X <sup>0</sup> ren/ep/hp	g-W90.X 2.F displ.ee/eu/		13 <sup>-</sup>	203 203 TeV	2 440 GeV 2 1.0 TeV	<sup>1</sup> <<(ℓ <sub>i</sub> )<3 1s, S <sup>2</sup> S3 model 7 α <sub>i</sub> ν <sub>i</sub> <sup>2</sup> ℓ <sub>1</sub> <sup>1</sup> <740 mm, m(2)=1.3 TeV <sup>2</sup> 10.11, λ <sub>20,10000</sub> at 0.07 m(2), cr <sub>257</sub> <1 mm >400 GeV, λ <sub>151</sub> ≠0 (k = 1,2) > 0.2×m <sub>i</sub> <sup>2</sup> ℓ <sub>1</sub> <sup>1</sup> , λ <sub>20</sub> ≠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 <sup>-</sup>	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
28         31         rem/epr/up           28         31         rem/epr/up           (β=0.5         30,0         32           (10,0) x2         (10,0         32           (10,0) x2         (10,0         32           (10,0) x2         (10,0         32	Leptoo	quark	13 <sup>-</sup>	203 203 TeV	#40 GeV           1.0 TeV           Coloron/(ii) x2           coloron/(ii) x2           gluino(3) x2	1<(ξi)<3 15, SPS3 model 2 ≪r(ξi)<3 16, SPS3 model 2 ≪r(ξi)<3 16, SPS3 model 2 ≪r(ξi)<3 16, SPS3 model 2 ≪r(ξi)<3 16, SPS3 model with the second secon	14040546 564.05162 667.08679 1404.2300 ATLAS-CONF-2016-075 1405.5086 SUIST12016-02 1704.08493 1794.08493 1794.09493 17.0.0717 17.0.05544
28         31         consignation           28         31         consignation           (a)         x2         x2           (b)         x2         x2           (b)         x2         x2           (c)         x2         x2	Leptor	quark	13 <sup>-</sup>	203 203 TeV	#40 GeV           1.0 TeV           coloron()) x2           coloron()) x2           gluino(3) x2           gluino(3) x2	$ultijet = \frac{1}{2} $	504.05162 504.05162 607.08079 1404.2500 ATLAS-CONF-2016.075 1405.5086 SUSY-2016-22 704.08493 704.08493 704.08493 704.08493 70.0717 71.0.05544 501.01325
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 <sup>-</sup>	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 <sup>+</sup> 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)&lt;/td" mm,="">       *     10.11, k_{25,13823mld,07       m(g), cr_{SPS1} mm       &gt;&lt;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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identity     identity       identity     i	2 3 RS Gro	quark 4 avitor	13 -	203 20.3 TeV	Image: String Scole (i)     440 GeV       Image: String Scole (i)     1.0 TeV       Image: String Scole (i)     1.0 TeV	$\frac{1 < (\xi_{1}) < 3 \ rs, S > S 3 \ model}{2 < \sin(\xi_{1}) < 740 \ mm, m(g) = 1.2 \ TeV}$ $\frac{2 < \sin(\xi_{1}) < 740 \ mm, m(g) = 1.2 \ TeV}{(mg), \cos(g > 1 \ mm)}$ $\approx 400 \ GeV, \ \xi_{131} \neq 0 \ (\xi = 1, 2)$ $\approx 0.2 \times m(\xi_{1}^{2}), \ \xi_{132} \neq 0$ $\approx 176V, \ \xi_{232} = 1000$	564.05162 687.08874 1404.2500 ATLAS-CONF-2016-075 1405.5088 SUST-2016-022 1704.08493 1704.08493 1704.08493 170.0717 17.0.05544 1501.01225
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ist ist in the second seco	2 3 RS Gro	quark 4 avitor	13 - - - - - - - - - - - - - - - - - - -		#40 GaV       8 TeV       coloron/(ii) x2       coloron/(ii) x2       gluino(3i) x2       gluino(3i) x2       gluino(3i) x2       D       1       ADD (j), xiEDx4, MB       H, rED=6, MD=4 TeV       String Scole (i)       (j, xiED=4, MD	1<(ξi)<3 15, SPS3 model 2 ser(ξi)<740 mm, m(g=1.2TeV * 10.11. λ <sub>25,135620</sub> m0.07 m(g), cr <sub>157</sub> ×1 mm > 4000kV, λ <sub>131</sub> ±0 (k = 1,2) > 0.22m(ξi), λ <sub>132</sub> ±0 + 17V, λ <sub>25</sub> ±0	14003542 564.05162 667.08874 1404.2500 ATLAS-CONF-2016-075 1405.5086 SUST-2016-22 1704.08493 1704.08493 170.4.08493 170.4.08493 170.0171 17.0.05544 1501.01325
(in x2 (in x2	Leptor	quark	13 -		#40 GeV       8 TeV       coloron(ii) x2       coloron(ii) x2       gluino(iii) x2       gluino(iiii) x2       0     1       2       (y+MET) nED=4, MD       ADD (j), nED=4, M2       H, nED=6, MD=4 TsV       String Scole (j)       (j), nED=4, MD       D       (j), nED=4, MD       (j), nED=4, MD       (j), nED=4, MD	1 <c(ki)<3 15,="" model<br="" sps3="">2 <u (ki)<3="" 15,="" <="" model<br="" sps3="">2 <u <="" ul=""> <sup>1</sup> <ul> <li>(ki)</li> <li>(ki)<td>14005042 564.05162 667.06874 1404.2500 ATLAS-CONF-2016-075 1405.5088 SUSY-2016-022 1704.08493 1704.08493 170.0717 17.0.05544 1501.01225</td></li></ul></u></u></u></u></u></u></c(ki)<3>	14005042 564.05162 667.06874 1404.2500 ATLAS-CONF-2016-075 1405.5088 SUSY-2016-022 1704.08493 1704.08493 170.0717 17.0.05544 1501.01225
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$\begin{array}{c c} c \\ z \\$	2 3 RS Gro 2 3 ninary Heavy	quark quark 4 avitor 4 Gauç	13 - - - - - - - - - - - - - - - - - - -		440 GeV       8 TeV       coloron/(i) x2       gluino(3) x2       gluino(3) x2       gluino(3) x2       gluino(3) x2       0       1       2       (y+MFT), nFD=1, MD       ADD (), nED=4, M2       H, nED=6, MD=4 TeV       String Scole (i)       (), nED=4, M2       D       (), nED=4, M2       Jet Extinction Scale	1<(ki)<3 15, SPS3 model 2 ser(ki)<3 15, SPS3 model 11 1, k_2, serse million 1000, carge s1 mm 94000, ki, stat (k) 1000, ki, stat (k)	564.05162 564.05162 667.08479 1404.2000 ATLAS-CONF-2016-075 1405.5088 SUST-2016-075 1405.5088 SUST-2016-022 1704.08493 1704.08493 170.05544 1501.01325
<sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · corr/spin/hpp     <	2 3 RS Gro 2 3 Ninary Heavy Bos	quark quark avitor 4 Gauç ons	13 - cs TeV 15 TeV		440 GaV       8 TeV       coloron/()) x2       gluino(3) x2       gluino(3) x2       gluino(3) x2       gluino(3) x2       0     1       2       (y+MET). nED=1, MD       ADD (), nED=4, M2       H, nED=6, MD=4 ToV       String Scole (i)       (i), nED=4, M2       D       (i) (MET). nED=4, M2       D       I) (2 3, 4       D       I) (2 3, 4	1<({k})<3 15, SPS3 model 2 ser(k <sup>2</sup> )<740 mm, m(g=1.2TeV     "	14003042 564.05162 667.08874 1404.2500 ATLAS-CONF-2016-075 1405.5086 SUSY-2016-22 1704.08493 170.408493 170.0717 17.0.05544 1501.01225
<sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap <sup>1</sup> / <sub>2</sub> × <sup>2</sup> / <sub>1</sub> · conv/oper/hap     <	2 3 RS Gro 2 3 Ninary Heavy Bos	quark quark 4 avitor 4 Gaug ons	Yes 13 CS TeV IS TeV		440 GaV         8 TeV         coloron/()) x2         gluino(3) x2         gluino(4)         ADD (3), nED=4, MD         gluino(4), nED=4, MS         gluino(5)         gluino(5)         gluino(5)         gluino(5)         gluino(5)         gluino(5)         gluino(5)         gluino(5)         gluino(5)	1<({k})<3 15, SPS3 model 2 ser(k)<740 mm, m(g=1.2TeV 2 ser(k)<740 mm, m(g=1.2TeV	564.05162 564.05162 667.08474 1404.2500 ATLAS-CONF-2016-075 1405.5086 SUSY-2016-022 1704.08493 1704.08493 170.0717 17.0.05544 1501.01225
(iq) x2       (j=0,5)       (j=0,5)       (j=0,5)       (j=0,5)       (j=0,5)       (i) x2       (j=0,5)       (i) x2       (i) x2       (i) x2       (i) x2       (ii) x2       (iii) x2       (iii) x2       (iii) x2       (iiii) x2<	2 3 RS Gro 2 3 Ninary Heavy Bos	quark quark 4 avitor 4 Gaug ons	Yes 13 CS TeV 1S TeV		440 GaV         8 TeV         coloron(ii) x2         gluino(3i) x	rge Extra 7 8 9 10 7 8 9 10 7 8 9 10	564.05162 564.05162 667.08474 1404.2500 ATLAS-CONF-2016-075 1405.5086 SUSY-2016-22 1704.08493 1704.08493 170.0717 17.0.05544 1501.01225
(init) x2       (jac) x2	2 3 RS Gro 2 3 ninary Heavy Bos	quark quark 4 avitor 4 Gauç ons	Yes 13 CS TeV IS TeV		#40 GaV         8 TeV         coloron(ii) x2         gluino(ii) x2         gluino(iii) x2         gluino(iiii) x2         gluino(iiiii) x2         gluino(iiii) x2         gluino(iiii) x2         gluino(iiii) x2         gluino(iiiii) x2         gluino(iiii) x2         gluino(iiiiiiiiiii) x2 <td>rge Extra 7 8 9 10 7 8 9 10 7 8 9 10 7 8 9 10</td> <td>14003044 564.05162 607.08074 1404.2300 ATLAS-CONF-2016-075 14055086 SUSY/2016-22 1704.08493 1704.08493 1704.08493 170.0717 1710.05544 1501.01325</td>	rge Extra 7 8 9 10 7 8 9 10 7 8 9 10 7 8 9 10	14003044 564.05162 607.08074 1404.2300 ATLAS-CONF-2016-075 14055086 SUSY/2016-22 1704.08493 1704.08493 1704.08493 170.0717 1710.05544 1501.01325
(in) x2     (in) x2       (ja=0,5)     (in) x2       (ja=0,5)     (in) x2       (in) x2     (in) x2       (in) x3     (in) x3       (in) x3     (in) x3       (in) x3     (in) x3 <td>2 3 RS Gro 2 3 ninary Heavy Bos</td> <td>quark quark 4 avitor 4 Gauç ons</td> <td>тем 13 - сс тем 15 тем</td> <td></td> <td>440 GeV         8 TeV         coloron(ii) ×2         gluino(3i) ×2         gluino(3j) ×2         gluino(jb) ×2         gluino(jb) ×2         0       1         ADD (j), ==D=4, MD         ADD (j), ==D=4, M2         k;===4, M2 = 4, M2         k;====4, M2 = 4, M2         k;====4, M2 = 4, M2         k;=====4, M2 = 4, M2         &lt;</td> <td>1<c(ki)<3 15,="" model<br="" sps3="">2 <ur>         2 &lt;<ur>         2 &lt;<ur>         2 &lt;</ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></c(ki)<3></td> 2 <	2 3 RS Gro 2 3 ninary Heavy Bos	quark quark 4 avitor 4 Gauç ons	тем 13 - сс тем 15 тем		440 GeV         8 TeV         coloron(ii) ×2         gluino(3i) ×2         gluino(3j) ×2         gluino(jb) ×2         gluino(jb) ×2         0       1         ADD (j), ==D=4, MD         ADD (j), ==D=4, M2         k;===4, M2 = 4, M2         k;====4, M2 = 4, M2         k;====4, M2 = 4, M2         k;=====4, M2 = 4, M2         <	1 <c(ki)<3 15,="" model<br="" sps3="">2 <ur>         2 &lt;<ur>         2 &lt;<ur>         2 &lt;</ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></ur></c(ki)<3>	1404.05162 607.08079 1404.2200 ATLAS-CONF-2016-075 1405.5086 SUSY/2016-22 704.08403 70.0717 710.05544 1501.01325
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$\begin{array}{c} c \\ z \\$	2 3 RS Gro 2 3 RS Gro 2 3 Ninary Heavy Bos	quark quark 4 avitor 4 Gaug ons	TeV TeV	203 20.3 TeV	440 GeV         8 TeV         coloron(ii) x2         gluino(3i) x2         gluino(3i) x2         gluino(3i) x2         gluino(iib) x2         0       1         ADD (j), nED=4, MD         ADD (j), nED=4, MB         Mred=4 TsV         String Scole (j)         (j+MET), nED=4, MD         D (ceuu), nED=4, MB         D (ceuu), nED=4, MB <td><pre></pre></td> <td>14030546 564.05162 687.08078 1404.2000 ATLAS-CONF-2016-075 14055098 SUSTri2016-22 784.08493 794.08493 79.0.0717 7° 0.05544 501.01325</td>	<pre></pre>	14030546 564.05162 687.08078 1404.2000 ATLAS-CONF-2016-075 14055098 SUSTri2016-22 784.08493 794.08493 79.0.0717 7° 0.05544 501.01325
$(a) \times 2 \\ (b) \times 2 \\ (b) \times 2 \\ (b) \times 2 \\ (b) \times 2 \\ (c) $	2 3 RS Gro 2 3 RS Gro 2 3 Ninary Heavy Bos	quark quark 4 avitor 4 Gaug ons	те те те те те те те те те те	203 20.3 TeV	#40 Gav       #10 Gav       8 TeV       coloron(j) x2       gluino(j) x2       gluino(ji) x2       gluino(ji) x2       gluino(ji) x2       gluino(ji) x2       gluino(jii) x2       gluino(jii) x2       gluino(jii) x2       gluino(jii) x2       gluino(jii) x2       gluino(jiii) x2       gluino(jiiiii) x2       glu	1       1	14030546 564.05162 687.08078 1404.2200 ATLAS-CONF-2016-075 14055098 SUSYr2016-22 704.08493 794.08493 79.0717 70.05544 501.01325
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(te) >2 (he) >2 (h	2 3 RS Gro 2 3 RS Gro 2 3 Ninary Heavy Bos 2 3 4 Exo	quark quark 4 avitor 4 Gaug ons	теч теч	203 20.3 TeV	#10 GeV         8 TeV         coloron(#) x2         gluino(#) x2         gluin	1       1	544.05162 687.08879 1404.2300 ATLAS-CONF-2016-075 14055098 SUSY/2016-02 794.08493 794.09493 7 0.0717 7*0.05544 501.01325
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$\begin{array}{c} \text{c} \text{c} \text{c} \text{c} \text{c} \text{c} \text{c} \text$	2 3 RS Gro 2 3 RS Gro 2 3 Aninary Heavy Bos 2 3 4 Exc	quark quark 4 avitor 4 Gaug ons	Yes 13 CS ToW IS ToW IS	203 203 203 TeV	440 GeV 1.0 TeV Coloron(ii) ×2 coloron(ii) ×2 gluino(iib) ×2 gluino(iib) ×2 D 1 2 (++MET) nED=1, MD ADD (j), nED=4, M8 H, nED=6, MC=4 TeV String Scole (i) (), nED=4, MC=4 TeV (), nED=4,	1<<(ki)<3 is, SP33 model	504.05162 607.08078 1404.2000 ATLAS-CONF-2016-075 14055098 SUSYF4016-22 794.08493 794.09493 7 0.0717 7*0.05544 501.01325
$\begin{array}{c} \text{c} \text{c} \text{c} \text{c} \text{c} \text{c} \text{c} \text$	2 3 RS Gro 2 3 RS Gro 2 3 Aninary Heavy Bos	quark 4 avitor 4 Gaus ons	Yes I I I I I I I I I I I I I I I I I I I	203 203 203 TeV	440 GeV 1.0 TeV Coloron(ii) ×2 gluino(iii) ×2 gluino(iii) ×2 gluino(iii) ×2 D 1 2 (++MET) nED=1, MD ADD (j), nED=4, M8 H, nED=6, MC=4 TeV String Scale (i) j(, nED=4, MC=4 TeV String Scale (i) (, nED=4, MC=4 TeV (, nED=4, MC=4 TeV	1<<(ki)<3 is, SP33 model	564.05162 687.0887% 1404.2300 ATLAS-CONF-2016.075 14055088 SUSY12016-22 704.08493 74.08493 70.0717 77.0.05544 501.01325 EU Re Co

8

![](_page_7_Picture_14.jpeg)

![](_page_7_Picture_15.jpeg)

![](_page_8_Picture_0.jpeg)

![](_page_8_Picture_1.jpeg)

• 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

![](_page_8_Figure_7.jpeg)

![](_page_8_Figure_8.jpeg)

![](_page_8_Picture_9.jpeg)

![](_page_9_Picture_0.jpeg)

![](_page_9_Picture_1.jpeg)

We started looking for mSugra-inspired models. Thanks to large gluino and g squark cross sections, exclusions became soon very strong

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We moved to simplified models as a  $\tilde{\chi}^{\circ}$  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)

![](_page_9_Figure_7.jpeg)

![](_page_10_Picture_0.jpeg)

![](_page_10_Picture_1.jpeg)

became soon very strong

• We then moved to Natural-SUSY squarks

(with 100% BR assumptions)

models to BR-independent results

Research

![](_page_11_Picture_0.jpeg)

![](_page_11_Picture_1.jpeg)

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)

## SUSY: A MOVING TARGET

![](_page_11_Figure_8.jpeg)

![](_page_11_Figure_9.jpeg)

![](_page_11_Picture_10.jpeg)

![](_page_12_Picture_0.jpeg)

![](_page_12_Picture_1.jpeg)

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 1000 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)
13

![](_page_12_Figure_7.jpeg)

(a) All LSP types

![](_page_12_Picture_9.jpeg)

![](_page_12_Picture_10.jpeg)

![](_page_12_Picture_11.jpeg)

![](_page_13_Picture_0.jpeg)

![](_page_13_Picture_1.jpeg)

![](_page_13_Picture_2.jpeg)

![](_page_14_Picture_0.jpeg)

![](_page_14_Picture_1.jpeg)

### • 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

![](_page_14_Figure_7.jpeg)

![](_page_14_Figure_8.jpeg)

![](_page_14_Picture_9.jpeg)

15

![](_page_14_Picture_11.jpeg)

![](_page_15_Picture_0.jpeg)

- 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'  $10^{3}$ 10<sup>2</sup> 10 10-10<sup>-2</sup>

Cross-section [pb]

 $10^{-3}$ 10-4 10

![](_page_15_Figure_8.jpeg)

![](_page_15_Figure_9.jpeg)

![](_page_15_Picture_10.jpeg)

Council

![](_page_16_Picture_0.jpeg)

![](_page_16_Picture_1.jpeg)

- 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

![](_page_16_Picture_8.jpeg)

![](_page_16_Figure_9.jpeg)

![](_page_16_Picture_10.jpeg)

![](_page_17_Picture_0.jpeg)

![](_page_17_Picture_1.jpeg)

![](_page_17_Picture_2.jpeg)

18

![](_page_17_Picture_4.jpeg)

![](_page_18_Picture_0.jpeg)

![](_page_18_Picture_1.jpeg)

![](_page_18_Picture_2.jpeg)

![](_page_19_Picture_0.jpeg)

![](_page_19_Figure_1.jpeg)

• 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

![](_page_19_Picture_3.jpeg)

![](_page_20_Picture_0.jpeg)

![](_page_20_Picture_1.jpeg)

![](_page_20_Picture_2.jpeg)

- 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

![](_page_20_Picture_12.jpeg)

![](_page_20_Picture_13.jpeg)

![](_page_20_Picture_14.jpeg)

![](_page_21_Picture_0.jpeg)

![](_page_21_Picture_1.jpeg)

![](_page_21_Picture_2.jpeg)

- 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

![](_page_21_Picture_9.jpeg)

22

![](_page_21_Picture_10.jpeg)

![](_page_21_Picture_11.jpeg)

![](_page_22_Picture_0.jpeg)

![](_page_22_Picture_2.jpeg)

- Based on accurate global reconstructions
- Software implemented on CPUs

![](_page_22_Figure_8.jpeg)

![](_page_22_Picture_10.jpeg)

![](_page_22_Picture_11.jpeg)

![](_page_22_Picture_12.jpeg)

![](_page_23_Picture_0.jpeg)

![](_page_23_Picture_1.jpeg)

![](_page_23_Picture_2.jpeg)

![](_page_23_Picture_3.jpeg)

• 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

![](_page_23_Picture_9.jpeg)

![](_page_23_Picture_11.jpeg)

1KHz

30 Kb/evt

![](_page_23_Picture_12.jpeg)

![](_page_24_Picture_0.jpeg)

**Dueruan** 

![](_page_24_Picture_2.jpeg)

![](_page_24_Picture_3.jpeg)

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

![](_page_24_Picture_5.jpeg)

![](_page_24_Picture_6.jpeg)

![](_page_24_Picture_7.jpeg)

![](_page_24_Picture_8.jpeg)

![](_page_24_Picture_9.jpeg)

![](_page_24_Picture_10.jpeg)

![](_page_25_Picture_0.jpeg)

![](_page_25_Picture_1.jpeg)

- curve)
- what you use

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

![](_page_26_Picture_0.jpeg)

![](_page_26_Picture_1.jpeg)

- lot of missing E<sub>T</sub>)
- 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

![](_page_26_Picture_13.jpeg)

![](_page_27_Picture_0.jpeg)

*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<sup>0.5</sup></u>

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

![](_page_27_Figure_8.jpeg)

![](_page_27_Figure_9.jpeg)

![](_page_28_Picture_0.jpeg)

![](_page_28_Picture_1.jpeg)

• 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

![](_page_28_Figure_8.jpeg)

Research

![](_page_29_Picture_0.jpeg)

![](_page_29_Picture_1.jpeg)

![](_page_29_Picture_2.jpeg)

![](_page_30_Picture_0.jpeg)

• 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)

![](_page_30_Figure_7.jpeg)

![](_page_30_Figure_8.jpeg)

![](_page_30_Picture_10.jpeg)

![](_page_31_Picture_0.jpeg)

![](_page_31_Picture_1.jpeg)

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

![](_page_31_Picture_4.jpeg)

![](_page_31_Figure_5.jpeg)

![](_page_31_Picture_6.jpeg)

![](_page_31_Picture_7.jpeg)

![](_page_32_Picture_0.jpeg)

![](_page_32_Picture_1.jpeg)

- 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

![](_page_32_Figure_11.jpeg)

![](_page_32_Picture_13.jpeg)

![](_page_33_Picture_0.jpeg)

![](_page_33_Picture_1.jpeg)

- 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

![](_page_33_Figure_9.jpeg)

![](_page_33_Picture_11.jpeg)

![](_page_34_Picture_0.jpeg)

![](_page_34_Picture_1.jpeg)

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### 

![](_page_34_Figure_9.jpeg)

![](_page_35_Picture_0.jpeg)

![](_page_35_Picture_1.jpeg)

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![](_page_35_Figure_9.jpeg)

![](_page_35_Picture_10.jpeg)

![](_page_35_Picture_13.jpeg)




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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(∧)









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### • Repeat the procedure above for several values of $\sigma/\sigma_{SM}$



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







### • 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





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