An overview of recent LHC searches for the supersymmetric partners of gluons and (light) quarks

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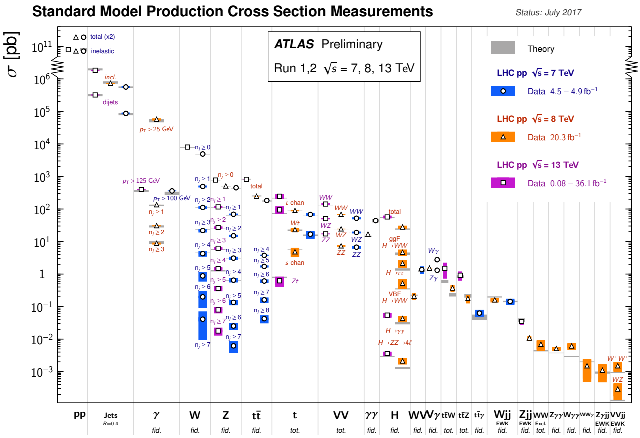
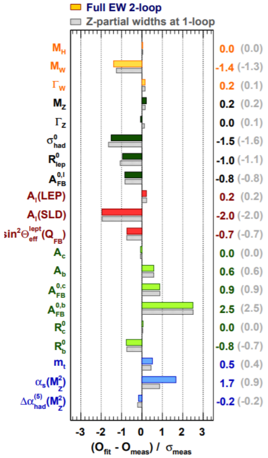
Montreal,
January 25, 2018

The Standard Model: accuracy up to the TeV scale





ATLAS (left), Eur. Phys. J. C **74** (2014) 3046 (right)

But many open questions...

- Gravitational interactions?
- Neutrino oscillations / masses?
- Nature of Dark Matter?
- Baryogenesis?

- Unification of strong and electroweak interactions?
- Hierarchy between electroweak and Planck scales?
- No CP violation in strong interactions?
- Number of fermion generations?
- Origin of the 19 free parameters?

What is Supersymmetry?

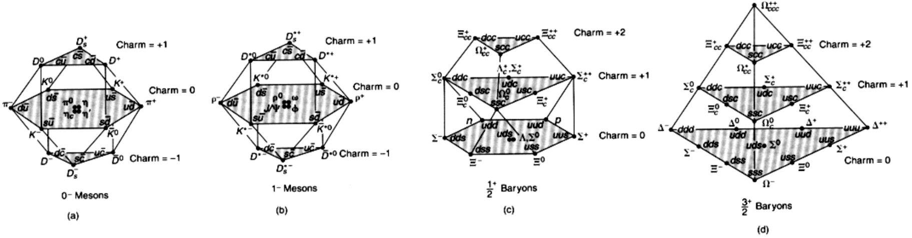
- A superalgebra generated by infinitesimal transformations swapping fermions and bosons while preserving the action for interacting fields:

SM fermion chiral projection scalar superpartner auxiliary field without dynamics	$\begin{pmatrix} \psi_{L/R} \\ \phi \\ F \end{pmatrix}$	$\xrightarrow{\epsilon}$	$\begin{pmatrix} -i(\sigma^\mu \epsilon^\dagger)\partial_\mu \phi + \epsilon F \\ \epsilon \cdot \psi_{L/R} \\ -i\epsilon \cdot (\bar{\sigma}^\mu \partial_\mu \psi_{L/R}) \end{pmatrix}$
SM vector gauge field gaugino superpartner aux. field without dynamics aux. scalar field, gauged away aux. scalar field, gauged away aux. Weyl spinor, gauged away	$\begin{pmatrix} A^\mu \\ \lambda \\ D \\ a \\ b \\ \xi \end{pmatrix}$	$\xrightarrow{\epsilon} \frac{1}{\sqrt{2}}$	$\begin{pmatrix} i\epsilon\partial^\mu \xi - i\epsilon^\dagger \partial^\mu \xi^\dagger + \epsilon\sigma\mu\lambda^\dagger - \epsilon^\dagger \bar{\sigma}^\mu \lambda \\ \epsilon D + \frac{i}{2}(\sigma^\mu \bar{\sigma}^\nu \epsilon)(\partial_\mu A_\nu - \partial_\nu A_\mu) \\ -i\epsilon\sigma^\mu \partial_\mu \lambda^\dagger + \epsilon^\dagger \sigma^\mu \partial_\mu \lambda \\ \epsilon \cdot \xi + \epsilon \dagger \cdot\xi\dagger \\ \epsilon^\dagger \lambda^\dagger - i\epsilon^\dagger \bar{\sigma}^\mu \partial_\mu \xi \\ 2\epsilon b - (\sigma^\mu \epsilon^\dagger)(A_\mu + i\partial_\mu a) \end{pmatrix}$

- But why?

(notation from S. Martin, hep-ph/9709356)

While trying to figure out strong interactions. . .



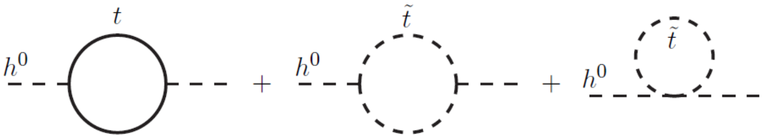
- Historically (Miyazawa, 1966), to try merging the separate classifications of mesons and hadrons into representations of SU(6), into a single structure
- Later to understand connections between fermionic *s*- and bosonic *t*-channel amplitudes in S-matrix program
- Further on superstrings, reason for parity violation, for massless neutrinos. . .

(P. Ramond and P. Fayet, Eur. Phys. J. C **74** (2014) 2841)

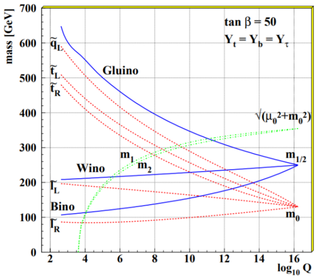
Nowadays, to solve the hierarchy problem

- In SM, natural Higgs mass = Planck scale due to large radiative corrections $\Rightarrow$ huge fine-tuning required to obtain $m_h = 125$ GeV instead

$\Delta(m^2_{h^0}) =$

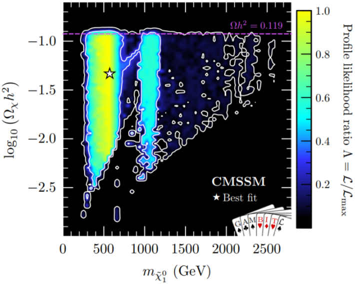


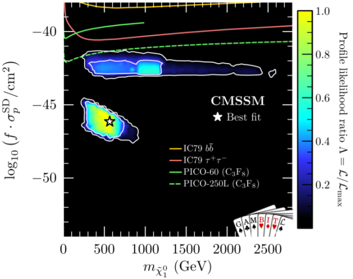
- In SUSY models, cancellation of $\mathcal{O}(\Lambda^2)$ terms $\Rightarrow$ residual $\Delta m_h^2 = \mathcal{O}(\log \Lambda)$
- Higgs potential not arbitrary but given by the superpotential
- Mechanism for radiative electroweak symmetry breaking

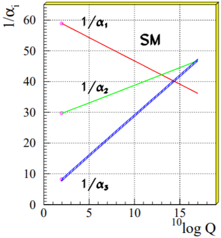


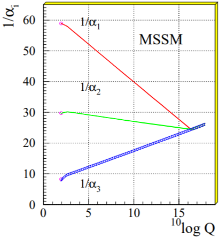
(Figures from S. Martin, hep-ph/9709356, and D. Kazakov, hep-ph/0012288)

Other nice features!









also, local SUSY = supergravity!

Eur. Phys. J. C **77** (2017) 824 (top), and D. Kazakov, hep-ph/0012288 (bottom)

The Minimal SuperSymmetric Model

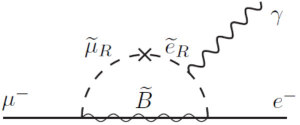
- Two Higgs doublets needed, to cancel axial anomalies $\rightarrow$ 5 massive Higgs bosons
- One scalar partner for each fermion chirality: **squarks** $\tilde{q}_\mathrm{L}$, $\tilde{q}_\mathrm{R}$, **charged sleptons** $\tilde{\ell}_\mathrm{L}$, $\tilde{\ell}_R$, **sneutrinos** $\tilde{\nu}$
  $\Rightarrow$ R and L scalars mixing controlled by Yukawa coupling $\rightarrow$ mostly relevant for **stops** $\tilde{t}_1$, $\tilde{t}_2$, **sbottoms** $\tilde{b}_1$, $\tilde{b}_2$, **staus** $\tilde{\tau}_1$, $\tilde{\tau}_2$
- Eight **gluinos** $\tilde{g}$, Majorana fermions partners of the gluons
- Other vector gauge and Higgs boson partners mix and result in four massive **neutralinos** $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, $\tilde{\chi}^0_4$ and four massive **charginos** $\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_2$
- A **gravitino** (if it exists), mixing with the Goldstone fermion coming from the spontaneous SUSY breaking to acquire a mass
- No superpartners observed so far! $\Rightarrow$ SUSY broken spontaneously at a higher energy scale

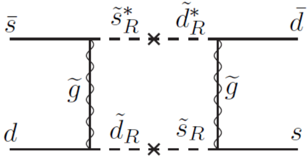
Soft SUSY breaking

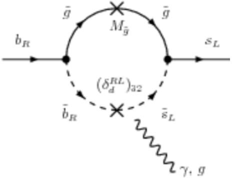
- Breaking in a hidden sector, mediated to SUSY sector via e.g. gravity or gauge interactions; effect parametrized at low energy:

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\; & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.
\end{aligned}
$$

- 105 unknown parameters! But very constrained (“flavor diagonality”) by absence of B or L violation, FCNC, hadron decay and mixing rates. . .

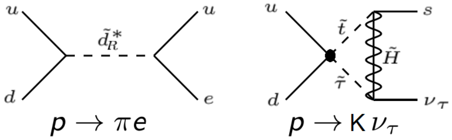






R-parity

- MSSM potential may contain terms violating B or L numbers conservation
- Couplings must be very weak, otherwise can mediate e.g. fast proton decay:



- More radical: enforce conservation of R-parity $= (-1)^{3(B-L)+2s}$

$\Rightarrow$ "dangerous" couplings are no longer allowed in the models

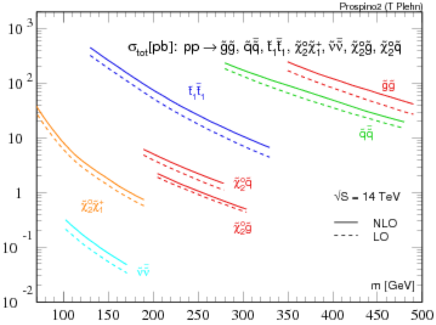
$\Rightarrow$ SUSY particles always produced in pairs, decay into a lighter SUSY particle + SM

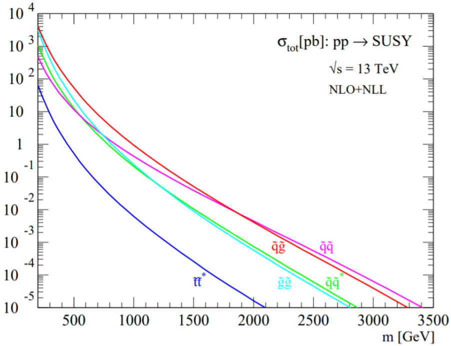
$\Rightarrow$ Lightest (LSP) is stable! If neutral and weakly-interacting, suitable DM candidate

$\Rightarrow$ LSPs produced in pp collisions escape the detector $\to$ source of missing momentum

Production cross-sections at LHC

- Access to a wide range of colored superpartners ($\tilde{g}$, $\tilde{q}$) masses at LHC:

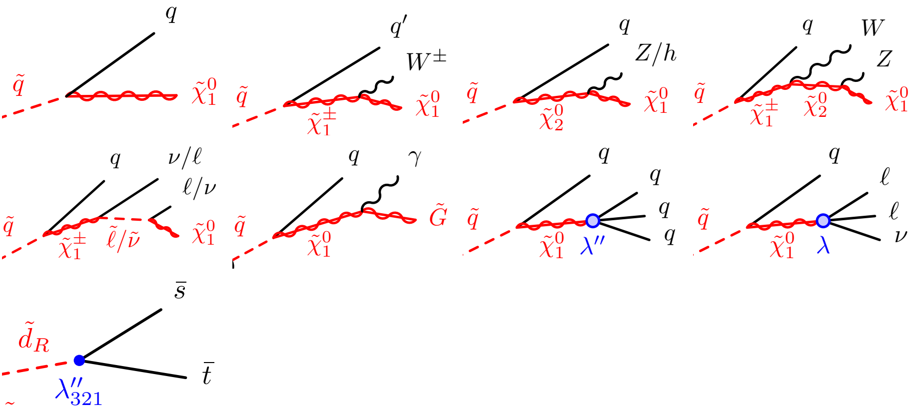




Borschensky et al, Eur. Phys. J. C **74** (2014) 12 (right)

Squark decay modes (non exhaustive!)

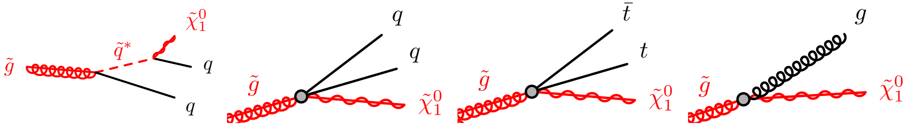
- Dominant mode = $\tilde{q} \to q\tilde{g}$ if kinematically allowed; otherwise decay via electroweak / Yukawa / RPV coupling:

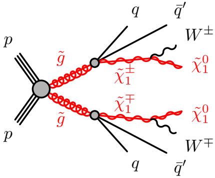


(diagrams taken from various ATLAS publications)

Gluino decay modes (non-exhaustive!)

- Gluinos couple only to squarks → similar decay modes, with 1 additional quark
- Decay mediated by virtual squark if $m(\tilde{q}) + m(\text{LSP}) > m(\tilde{g})$

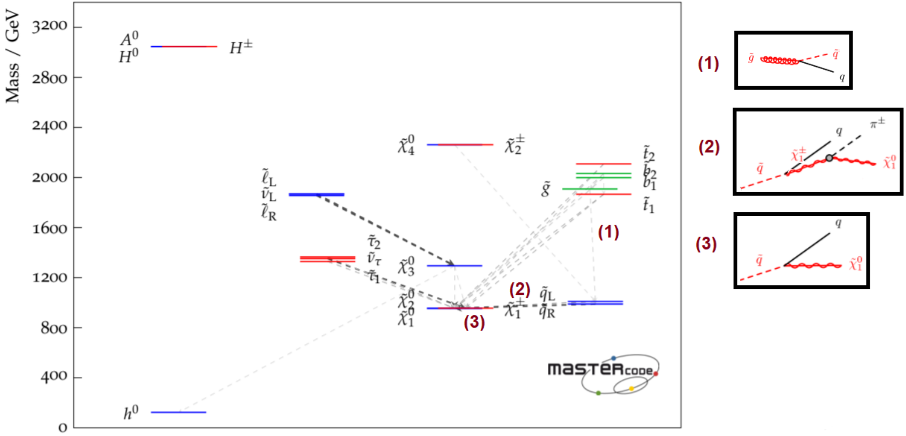




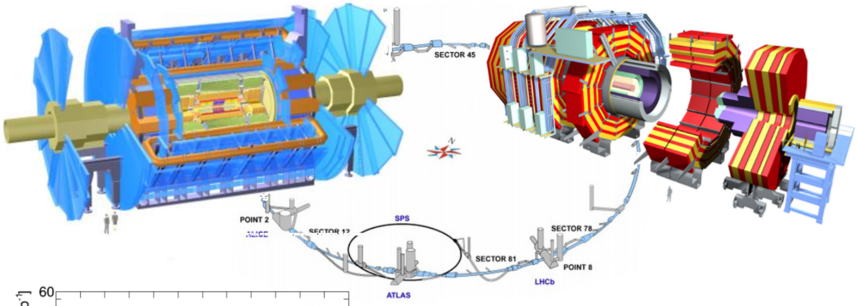
→ same probability for $W^\pm W^\mp$ and $W^\pm W^\pm$ final states

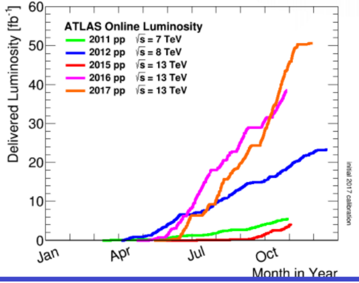
Example of recent "realistic" spectrum

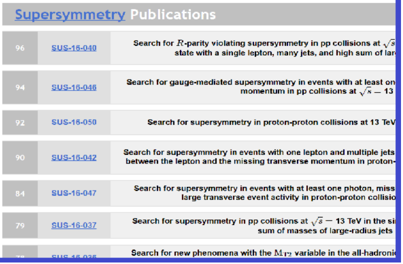
- pMSSM11 best-fit scenario with respect to collider + astrophysical constraints:



Bagnasci et al, 1710.11091 [hep-ph]







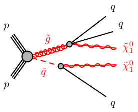
Supersymmetry Publications

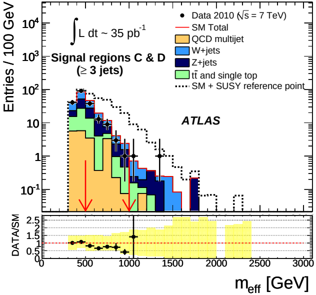
96	SUS-16-040	Search for R-parity violating supersymmetry in pp collisions at $\sqrt{s}$ … state with a single lepton, many jets, and high sum of lar…
94	SUS-16-046	Search for gauge-mediated supersymmetry in events with at least on… momentum in pp collisions at $\sqrt{s}$ = 13
92	SUS-16-050	Search for supersymmetry in proton-proton collisions at 13 TeV
90	SUS-16-042	Search for supersymmetry in events with one lepton and multiple jets … between the lepton and the missing transverse momentum in proton-…
84	SUS-16-047	Search for supersymmetry in events with at least one photon, miss… large transverse event activity in proton-proton collisio…
79	SUS-16-037	Search for supersymmetry in pp collisions at $\sqrt{s}$ = 13 TeV in the si… sum of masses of large-radius jets
78	SUS-16-036	Search for new phenomena with the M_{T2} variable in the all-hadroni…

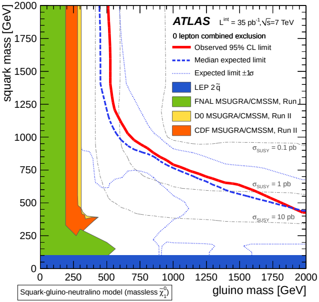
A simple search (7 TeV, 35 pb^{-1})

		A	B	C	D
Pre-selection	Number of required jets	≥ 2	≥ 2	≥ 3	≥ 3
	Leading jet p_T [GeV]	> 120	> 120	> 120	> 120
	Other jet(s) p_T [GeV]	> 40	> 40	> 40	> 40
	E_T^{miss} [GeV]	> 100	> 100	> 100	> 100
Final selection	$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	–	> 0.25	> 0.25
	m_{eff} [GeV]	> 500	–	> 500	> 1000
	m_{T2} [GeV]	–	> 300	–	–

	Signal region A	Signal region B	Signal region C	Signal region D
QCD	$7\ ^{+8}_{-7}$[u+j]	$0.6\ ^{+0.7}_{-0.6}$[u+j]	$9\ ^{+10}_{-9}$[u+j]	$0.2\ ^{+0.4}_{-0.2}$[u+j]
W+jets	50 ± 11[u] $^{+14}_{-10}$[j] $\pm\ 5[\mathcal{L}]$	4.4 ± 3.2[u] $^{+1.5}_{-0.8}$[j] $\pm 0.5[\mathcal{L}]$	$35 \pm\ 9$[u] $^{+10}_{-\ 8}$[j] $\pm 4[\mathcal{L}]$	1.1 ± 0.7[u] $^{+0.2}_{-0.3}$[j] $\pm 0.1[\mathcal{L}]$
Z+jets	52 ± 21[u] $^{+15}_{-11}$[j] $\pm\ 6[\mathcal{L}]$	4.1 ± 2.9[u] $^{+2.1}_{-0.8}$[j] $\pm 0.5[\mathcal{L}]$	27 ± 12[u] $^{+10}_{-\ 6}$[j] $\pm 3[\mathcal{L}]$	0.8 ± 0.7[u] $^{+0.6}_{-0.0}$[j] $\pm 0.1[\mathcal{L}]$
$t\bar{t}$ and t	$10 \pm\ 0$[u] $^{+\ 3}_{-\ 2}$[j] $\pm\ 1[\mathcal{L}]$	0.9 ± 0.1[u] $^{+0.4}_{-0.3}$[j] $\pm 0.1[\mathcal{L}]$	$17 \pm\ 1$[u] $^{+\ 6}_{-\ 4}$[j] $\pm 2[\mathcal{L}]$	0.3 ± 0.1[u] $^{+0.2}_{-0.1}$[j] $\pm 0.0[\mathcal{L}]$
Total SM	118 ± 25[u] $^{+32}_{-23}$[j] $\pm 12[\mathcal{L}]$	10.0 ± 4.3[u] $^{+4.0}_{-1.9}$[j] $\pm 1.0[\mathcal{L}]$	88 ± 18[u] $^{+26}_{-18}$[j] $\pm 9[\mathcal{L}]$	2.5 ± 1.0[u] $^{+1.0}_{-0.4}$[j] $\pm 0.2[\mathcal{L}]$
Data	87	11	66	2







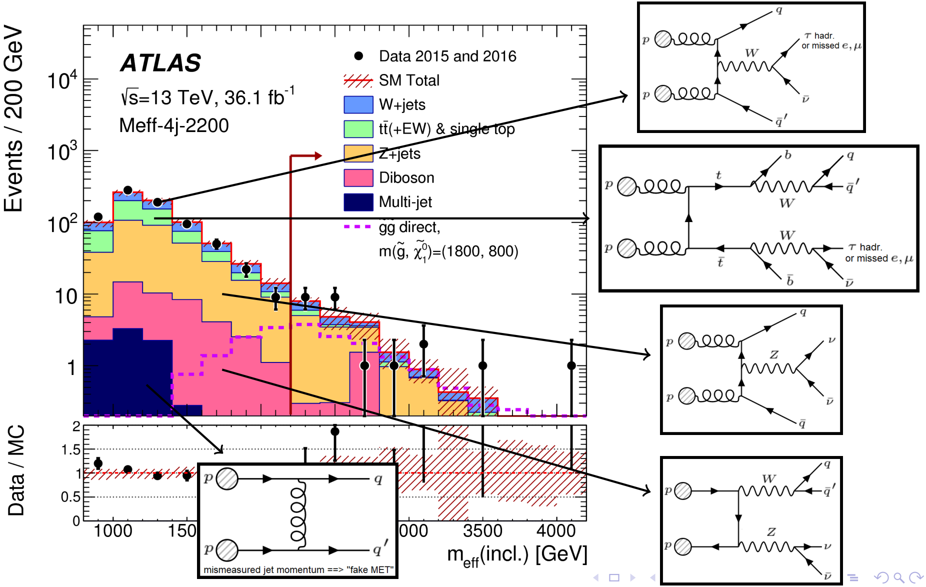
Phys. Lett. B **701** (2011) 186–203

How can these results be improved?

- Higher energy ($\sqrt{s}$ =7 $\rightarrow$ 13 TeV), larger dataset ($\rightarrow 10^3\times$ 2010 data)
- Improvement of the accuracy of the background estimates
  $\Rightarrow$ control regions, data-driven methods
- More powerful discriminant variables and advanced reconstruction methods
  $\Rightarrow$ razor / RJR, ISR topologies, boosted objects tagging
- Scan of the multi-dimensional MSSM phase space
  $\Rightarrow$ multiple dedicated signal regions
- Advanced statistical analysis of the results
  $\Rightarrow$ combined + binned likelihood fits

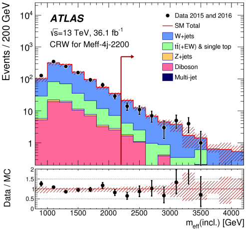
In the following slides, many plots taken from the latest ATLAS 0L+$E_{\mathrm{T}}^{\mathrm{miss}}$+jets search (13 TeV, 36 fb^{-1}), 1712.02332 [hep-ex]

Backgrounds

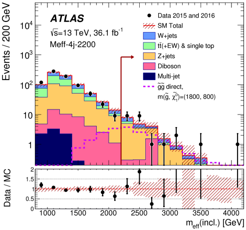


Control regions for $W(\to \tau\nu)$+jets and $t\bar{t}$ backgrounds

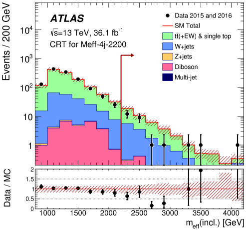
- MC simulation of W+jets and $t\bar{t}$ normalized to observed data in control regions with similar kinematic requirements but signal-free
- Reduces theory uncertainties: simulation only needed to determine the SR/CR "transfer factor", instead of the complete SR fiducial cross-section
- Here, CR→SR extrapolation very minimal ($\tau \leftrightarrow e/\mu$):



$= 1\ell,\ = 0b$
$30 < m_{\mathrm{T}} < 100$ GeV



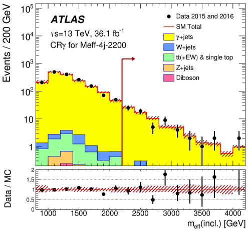
$= 0\ell$

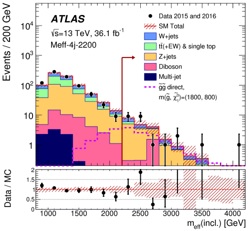


$= 1\ell,\ \geq 1b$
$30 < m_{\mathrm{T}} < 100$ GeV

Control regions for $Z(\to \nu\nu)$+jets and $t\bar{t}$ backgrounds

- Fancier variation: for high boson p_T, $\sigma_\mathrm{fid}(pp \to Z\text{+jets}) \approx K \times \sigma_\mathrm{fid}(pp \to \gamma\text{+jets})$, with $K \sim g^2/e^2$ independent of the fiducial selection
- Thus $Z(\to \nu\nu)$+jets can be estimated from γ+jets data events ($\gamma \leftrightarrow \nu\bar{\nu}$), treating the photon as an invisible particle, and residual MC-based corrections



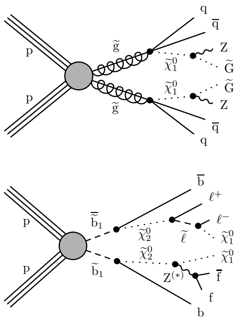


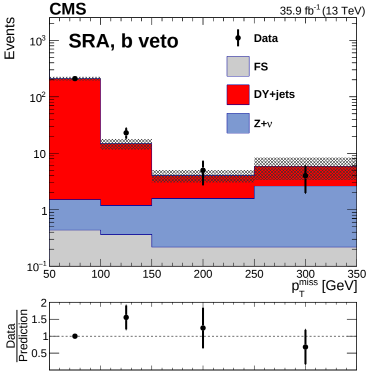
$= 1\gamma$ $\qquad$ $= 0\gamma$

- Cross-check possible with $Z(\to \ell\ell)$+jets data events: much closer to $Z \to \nu\nu$, but lower statistics

More uses of the $Z \leftrightarrow \gamma$ substitution

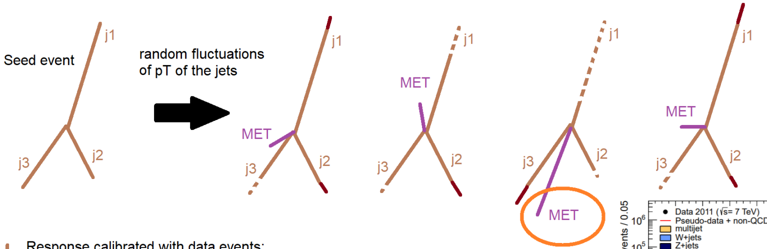
- Used similarly to estimate $t\bar{t}Z/\gamma^*$ with the help of a $t\bar{t}\gamma$ control region
- Or for the $Z/\gamma^*(\to \ell\ell)$+jets background in the SUSY searches looking at the dilepton invariant mass spectrum $\to$ no need to rely on simulation of "fake" E_T^{miss}





CMS-SUS-16-034, 1709.08908 [hep-ex]

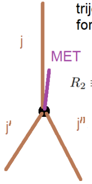
Fake E_T^{miss} in QCD multijets events: jet smearing method



Response calibrated with data events:

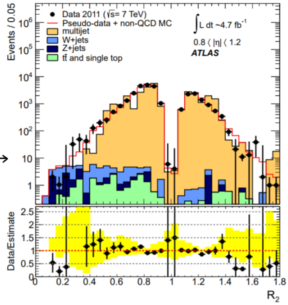
dijet events for the core

$$A = \frac{\Delta p_T}{\langle p_T \rangle} \sim \mathcal{G}\left(\frac{\sigma(p_T)}{p_T}\right)$$



trijet "Mercedes" events
for the low tail

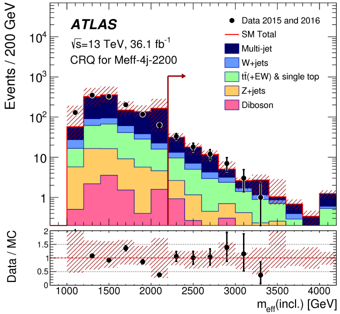
$$R_2 \equiv \frac{\vec{p}_T^{\,J} \cdot (\vec{p}_T^{\,J} + \vec{P}_T^{\,miss})}{|\vec{p}_T^{\,J} + \vec{P}_T^{\,miss}|^2}$$



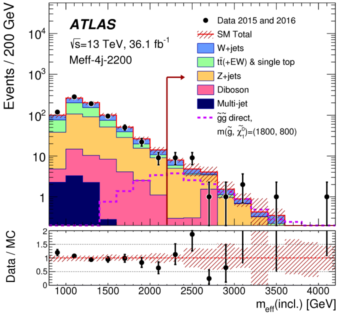
method detailed in Phys. Rev. D **87** (2013) 012008

Jet smearing applied

- In practice, the method is used to obtain shapes and transfer factors
- But the global normalization is set by a dedicated control region:



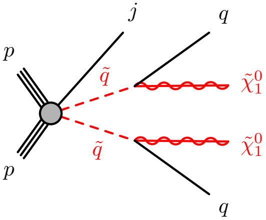
$$\Delta\varphi(j, E_{\mathrm{T}}^{\mathrm{miss}}) < 0.4$$
low $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$



$$\Delta\varphi(j, E_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$$
high $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$

Signal topologies with initial state radiation

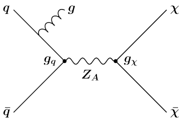
- For smaller $\Delta m(\tilde{q}/\tilde{g}, \text{LSP})$, decay products are softer
- Solution: rely on signal events with a very hard initial-state radiation (ISR):

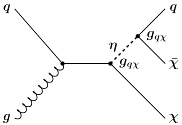


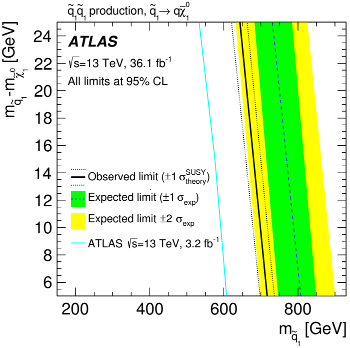
- Recoil of the squark/gluino pair against the ISR + heavy LSP $\rightarrow E_{\mathrm{T}}^{\text{miss}} \sim p_{\mathrm{T}}^{(\text{ISR})}$
- Striking event signature: one hard jet, high $E_{\mathrm{T}}^{\text{miss}}$ in the opposite direction, all other objects (very) soft

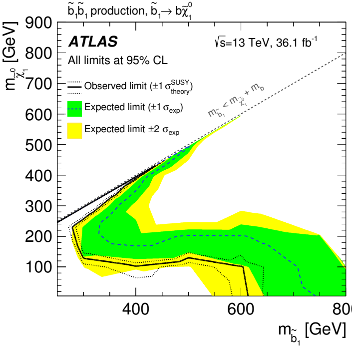
The ultimate ISR topology

- Decay products too soft to be reconstructed → monojet + $E_{\mathrm{T}}^{\mathrm{miss}}$ search
- Same final state as direct search for (non-SUSY) Dark Matter:





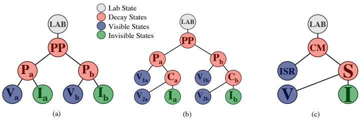


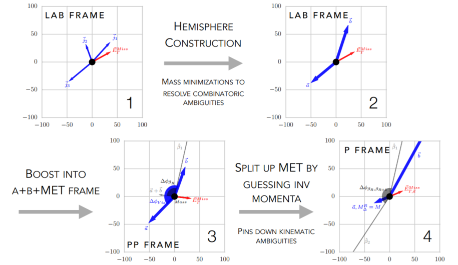


EXOT-2016-27, 1711.03301 [hep-ex]

Recursive Jigsaw Reconstruction

- Set of rules to pair final state objects and reconstruct/guess missing information (split $E_{\mathrm{T}}^{\mathrm{miss}}$ into several invisible particles, reconstruct momenta of intermediate particles in the decay chain. . .)
- Orthogonal constraints used for the different steps $\rightarrow$ provides uncorrelated discriminant variables

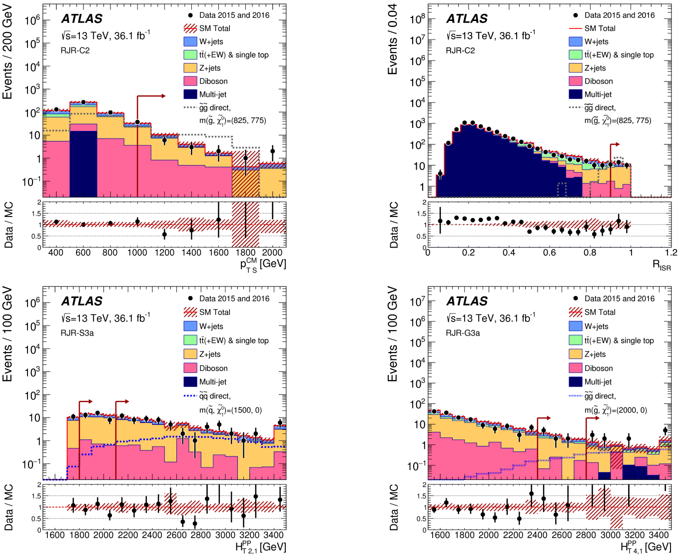




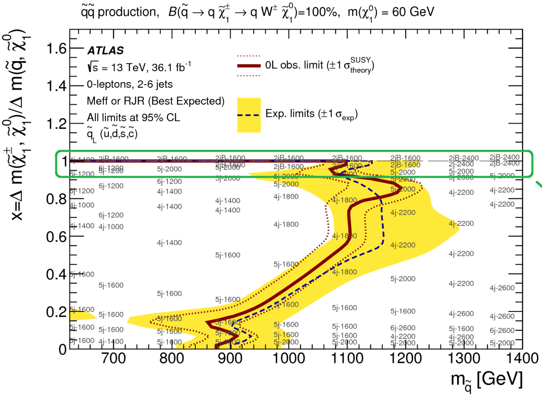
(L. Lee, "Recursive jigsaw", SUSY16, Jul. 2016)

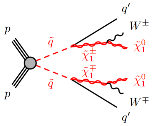
- Then many variables can be built: momenta and scales and ratios, angles, particle counts, at each step of the decay chain

RJR – examples of variables



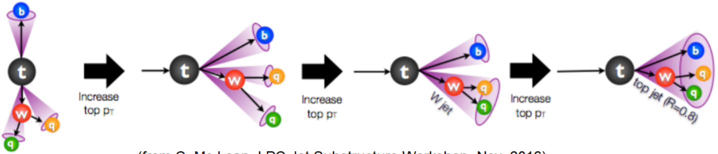
Boosted heavy particles (top, $W/Z/h$ bosons)





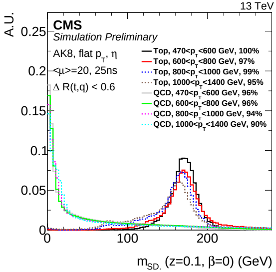
p(W) ~ 500 GeV

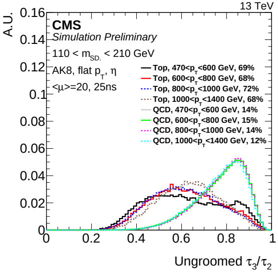
Cut on Large-R jet mass



(from C. Mc Lean, LPC Jet Substructure Workshop, Nov. 2016)

Tagging of boosted top quarks

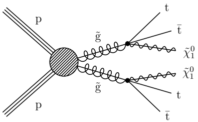


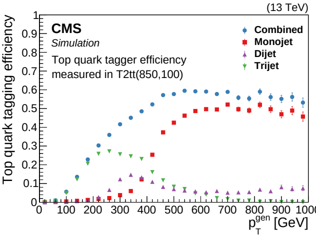


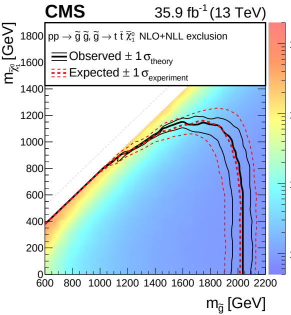
- Large-radius jet
- Drop soft radiations / pile-up / UE

→ Jet mass

→ Jet substructure

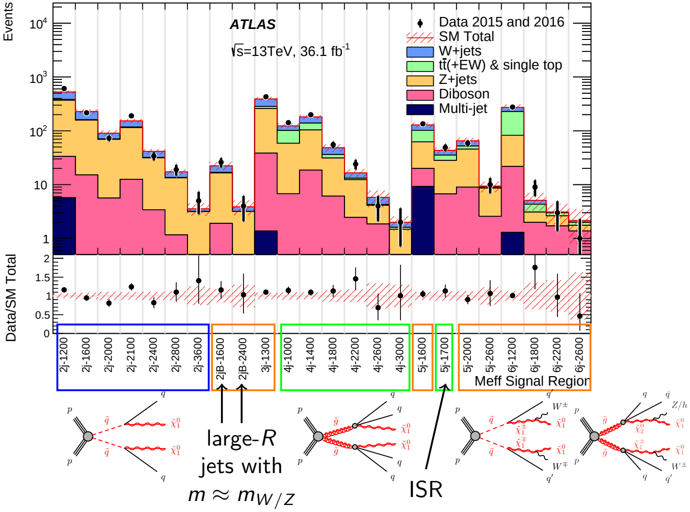






CMS-PAS-JME-15-002 (top) and CMS-SUS-16-050, arXiv: 1710.11188 [hep-ex]

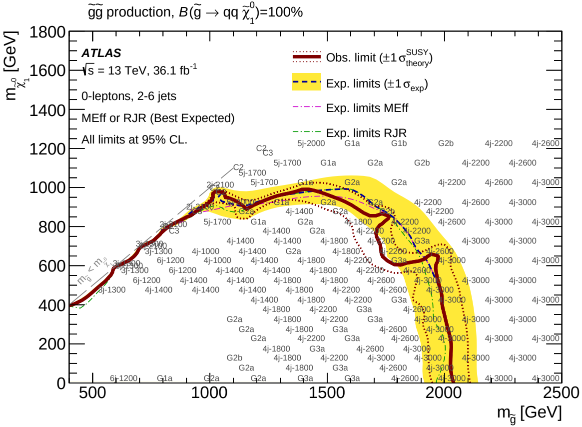
0L: everything together. . .



- + 19 alternative RJR-based SRs, with comparable performance

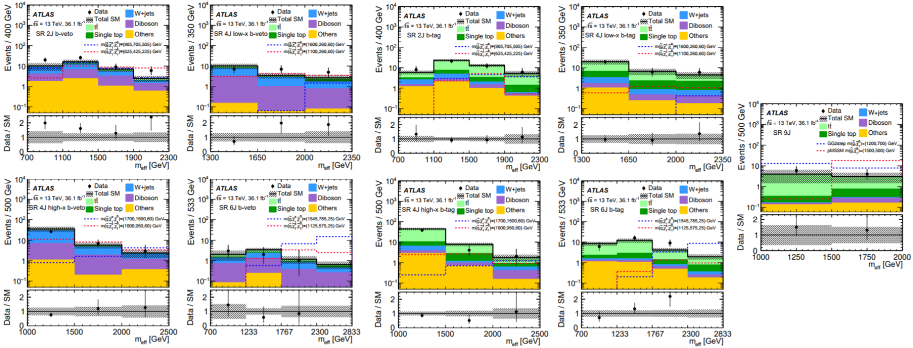
Statistical interpretation of the results

- Combined SR+CRs fit of signal+backgrounds strengths/nuisance parameters
- 0L search uses "simple" approach: only one SR included in the fit
  $\Rightarrow$ chosen for each signal scenario:



Statistical combination of signal regions

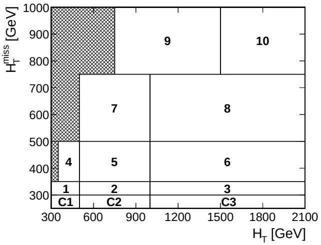
- 1L+$E_{\mathrm{T}}^{\mathrm{miss}}$+jets search relies on a simultaneous fit of up to 9 orthogonal binned SRs
  + 2 CRs for each set of 2 SRs
  + bin-by-bin background normalization to bypass MC mismodelling

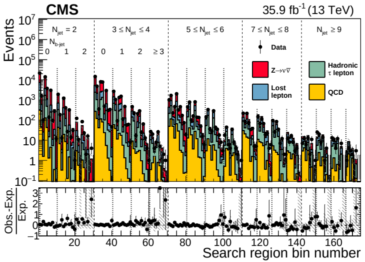


Phys. Rev. D **96** (2017) 112010

ATLAS vs CMS approaches

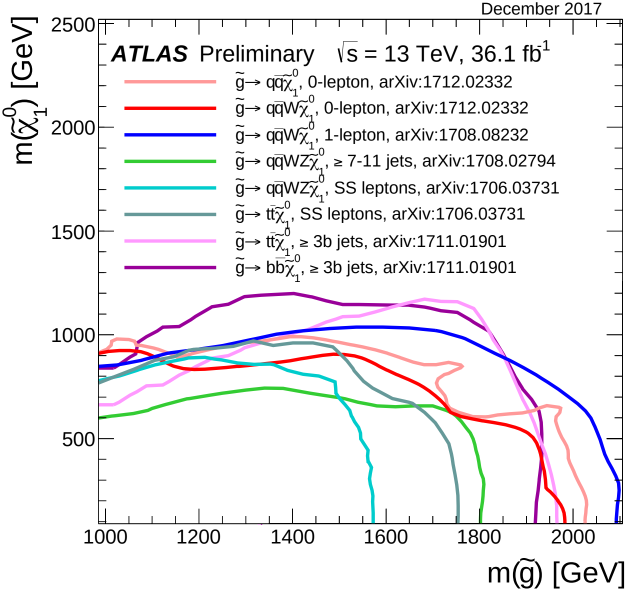
- CMS often performs fine-granularity scans of the phase space
- ATLAS often tries to use fewer, more targeted, SRs
- Complementary approaches!





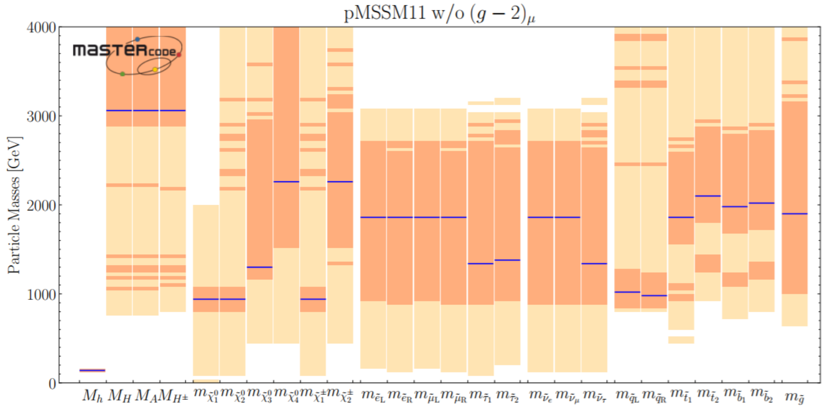
Phys. Rev. D 96 (2017) 032003

Gluino exclusion limits for various decay modes



source

How do these limits impact realistic models?



Bagnasci et al, 1710.11091 [hep-ph]

Conclusion

- ATLAS and CMS have published most of their results with 36 fb^{-1}, preparing for the analysis of the full Run-2 dataset ($\sim 3\times$ integrated luminosity)
- Experimental searches have become quite complex over the years...
- What's the way forward?
  - continued effort in improving signal selection in "difficult" corners of the phase space: machine learning?
  - tests of realistic models (e.g. pMSSM scans) to identify weak spots of the searches (mass gaps, decay modes...). Being done both by the phenomenology community, and within the experiment collaborations.

Backup

Squark limits in simplified models