Deep learning the SUSY search at the LHC

Jinmian Li

Korea Institute for Advanced Study

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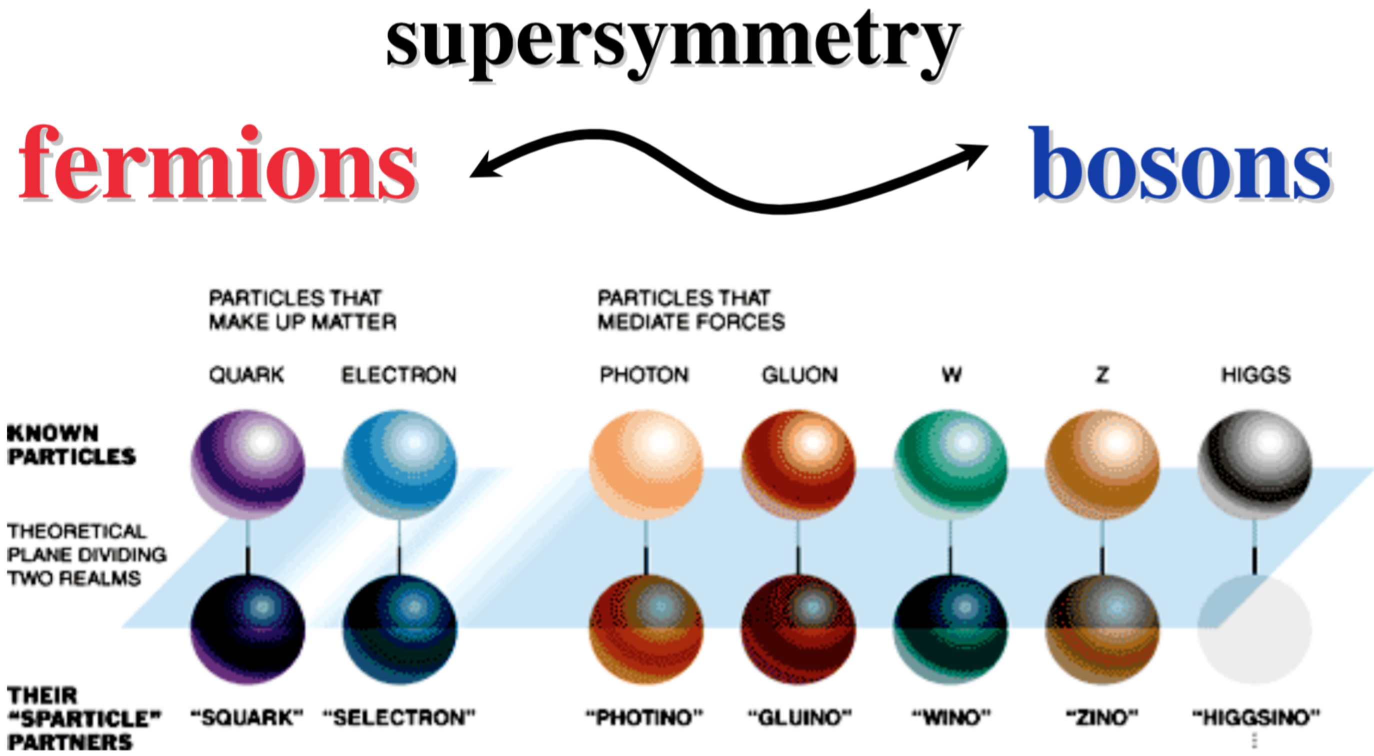
Outline

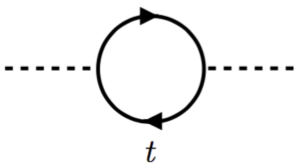
1. Supersymmetric particles at the LHC
   - R-parity violating SUSY
2. Application of CNN in RPV SUSY search - a case study
3. Conclusion


supersymmetry
fermions
bosons
PARTICLES THAT MAKE UP MATTER
PARTICLES THAT MEDIATE FORCES
QUARK
ELECTRON
PHOTON
GLUON
W
Z
HIGGS
KNOWN PARTICLES
THEORETICAL PLANE DIVIDING TWO REALMS
THEIR "SPARTICLE" PARTNERS
"SQUARK"
"SELECTRON"
"PHOTINO"
"GLUINO"
"WINO"
"ZINO"
"HIGGSINO"

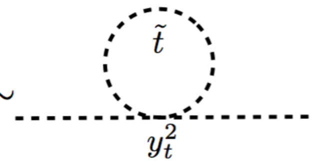
Motivations of supersymmetry

- Hierarchy problem :

$$m^2_{h,\text{phys}} = m^2_{h,\text{tree}} + \delta m^2_h$$

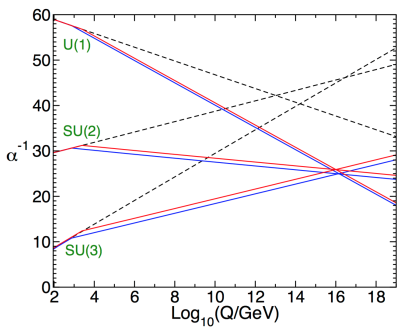
$\delta m_h^2 \sim$ 

$\sim -\frac{3}{4\pi} y_t \Lambda^2_{\text{SM}}$

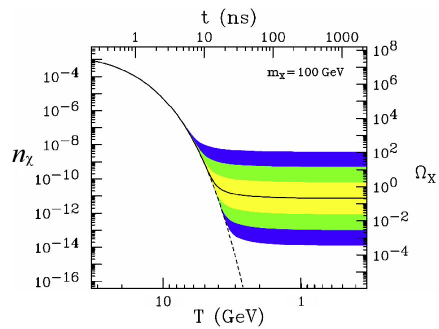
$\delta m_h^2 \sim$ 

$\sim +\frac{3}{4\pi} y_t \Lambda^2$

- Gauge coupling unification



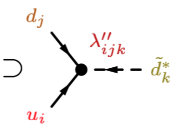
- Cold dark matter candidate (R-parity: $(-1)^{3(B-L)+2s}$)



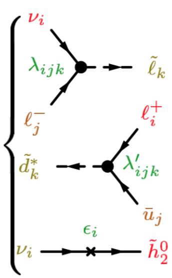
R-parity violating SUSY and its search at the LHC

- Search for RPC SUSY is very efficient, almost reaching the background free region: look for high p_T particles and large missing energy.
- R-parity is not necessary by SUSY theoretical framework, but to avoid proton decay.

$$W_{\mathrm{BNV}} = \lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k \supset$$



$$W_{\mathrm{LNV}} = \lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \epsilon_iL_iH_2 \supset$$



- Proton is stable if only one of the terms is set to non-zero.
- The bounds on RPV SUSY is still relatively weak in same cases. Sufficient signal events for improvement.

Sparticle production and decay in RPV SUSY

- "LQD" (UDD) allows single slepton (squark) production at the hadron collider;
- Decays:

LLE:

- $\tilde{e}_j^- \to \bar{\nu}_i \ell_k^-\,,\ \nu_k \ell_i^-$
- $\tilde{\nu}_j \to \ell_i^+ \ell_k^-$
- $\tilde{\chi}_n^0 \to \bar{\nu}_i \ell_j^+ \ell_k^-\,,\ \nu_i \ell_j^- \ell_k^+$
- $\tilde{\chi}_n^+ \to \ell_i^+ \ell_j^+ \ell_k^-$
- $\tilde{\chi}_n^+ \to \bar{\nu}_i \ell_j^+ \nu_k,\ \nu_i \nu_j \ell_k^+$

LQD:

$\tilde{e}_i^- \to \bar{u}_j d_k$

$\tilde{\nu}_i \to \bar{d}_j d_k$

$\tilde{u}_j \to e_i^+ d_k$

$\tilde{d}_k \to \nu_i d_j,\ \bar{\nu}_j d_i,\ \ell_i^- u_j$

$\tilde{\chi}_n^0 \to \bar{\nu}_i \bar{d}_j d_k,\ \ell^+ \bar{u}_j d_k,\ +\text{c.c.}$

$\tilde{\chi}_n^+ \to \bar{\nu}_i \bar{d}_j u_k,\ \nu_i \bar{d}_k u_j$

$\tilde{\chi}_n^+ \to \ell_i^+ \bar{u}_j u_k,\ \ell_i^+ \bar{d}_j d_k$

UDD:

$\tilde{d}_j \to \bar{u}_i \bar{d}_k$

$\tilde{u}_i \to \bar{d}_j \bar{d}_k$

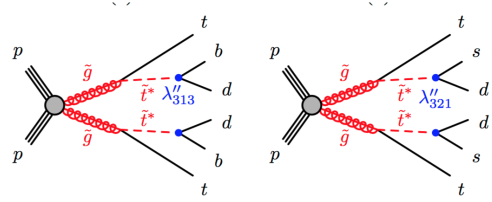
$\tilde{\chi}_n^0 \to u_i d_j d_k,\ +\text{c.c.}$

$\tilde{\chi}_n^+ \to u_i u_j d_k,\ \bar{d}_i \bar{d}_j \bar{d}_k$

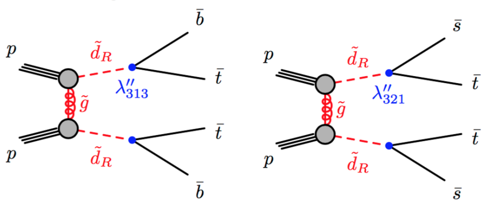
$\tilde{g} \to u_i d_j d_k,\ +\text{c.c.}$

The RPV SUSY searches at the LHC

- Leptonic RPV more constrained due to many leptons in final states.
- Hadronic RPV gives more "jetty" final states and therefore is less constrained.

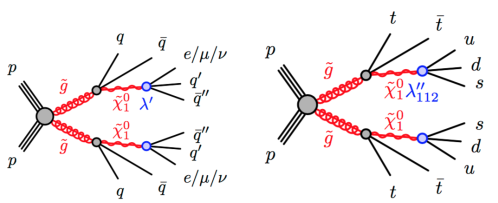


(g) (h)

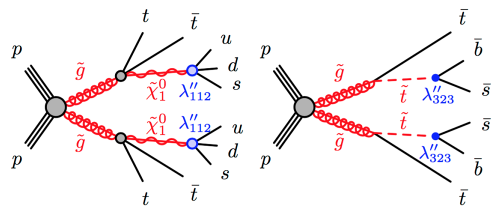


(k) (l)

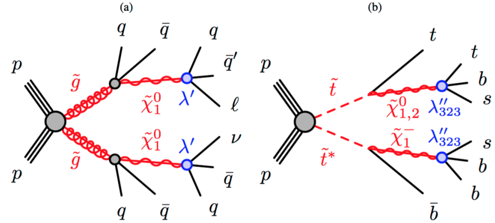
Two leptons:



(i) (j)

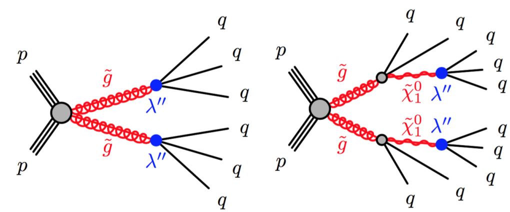


(a) (b)



(c) (d)

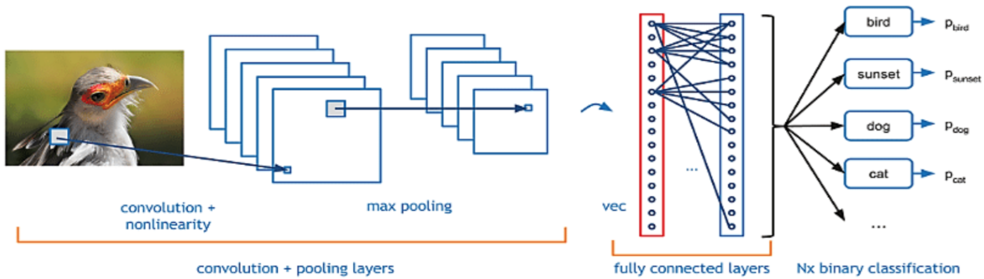
One Lepton:



No lepton:

CNN applications

Image classification:

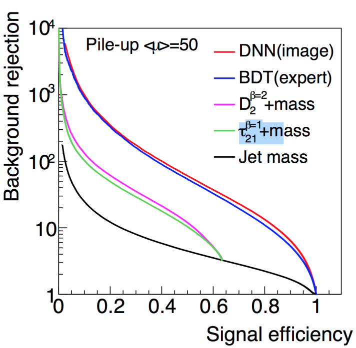


W/Z jet tagging:

J. Cogan, et.al. 1407.5675;

L. de Oliveira et.al. 1511.05190;

P. Baldi et.al. 1603.09349;

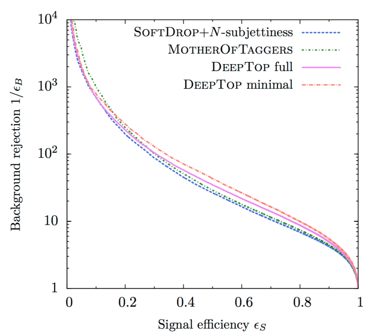


Top quark jet tagging:

L. Almeida et.al. 1501.05968;

G. Kasieczka et.al. 1701.08784;

S. Macaluso et.al. 1803.00107

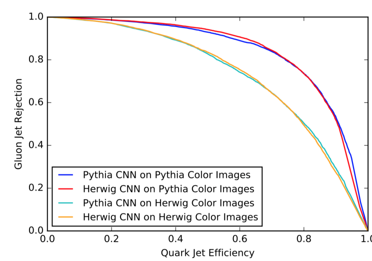


Gluon/quark discrimination:

P. Komiske et.al. 1612.01551;

H. Luo et.al. 1712.03634;

...



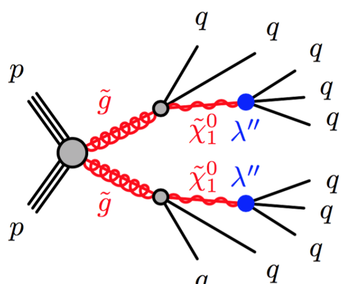
Application of CNN in RPV SUSY search - a case study

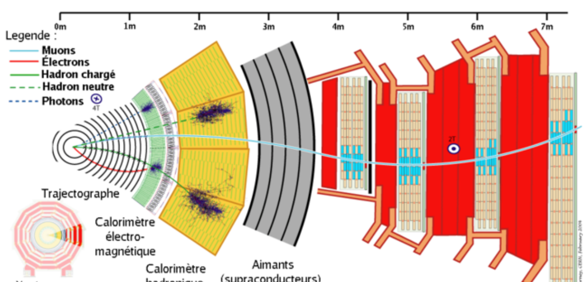
Purpose:

Improve the hadronic RPV gluino search by tagging neutralino jets with CNN

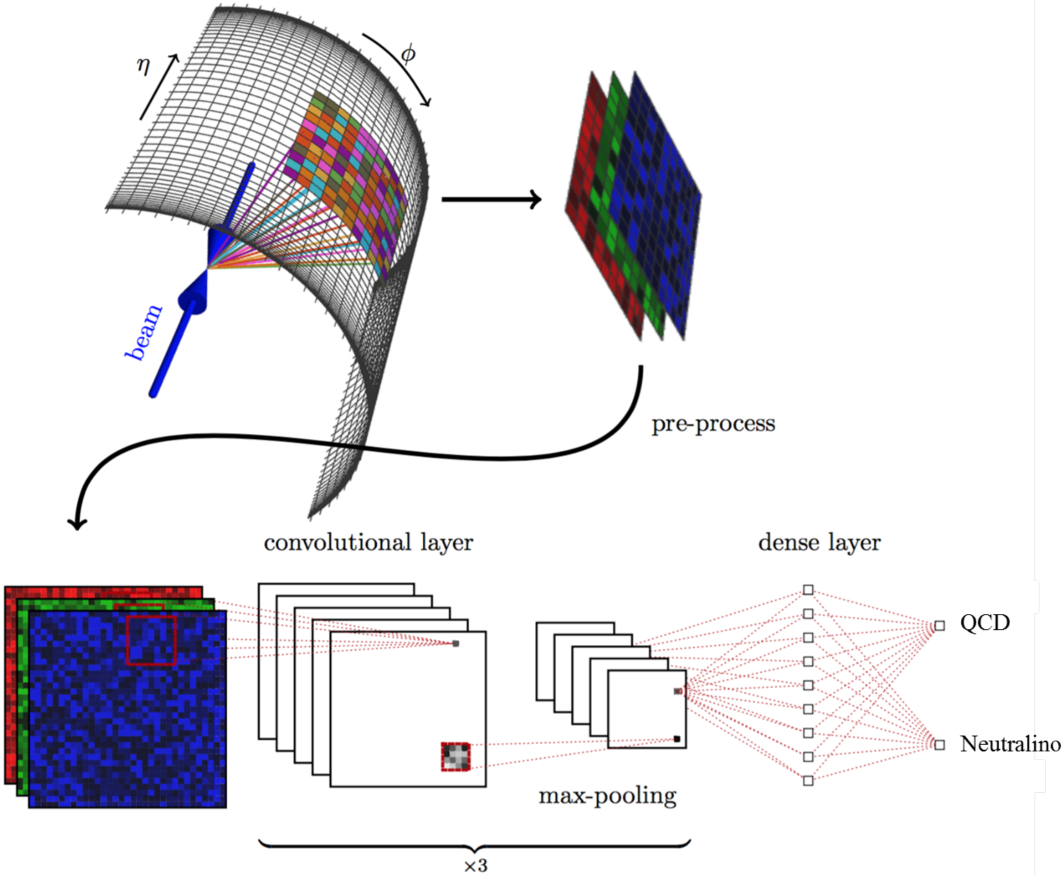
Strategy:

- Information about hadronic activity in an event comes mainly from the hadronic calorimeter (HCAL), with the basic observable being the energy deposited in each of the HCAL cells.
- One can think of the information provided by the HCAL as a digital image, with each cell being identified as a pixel, and with energy deposit in the cell corresponding to the intensity (or grayscale color) of that pixel.
- Neutralino jet identification is simply a classic image-recognition problem: distinguishing the energy-deposit patterns of boosted neutralino from patterns due to other sources, such as QCD jets.



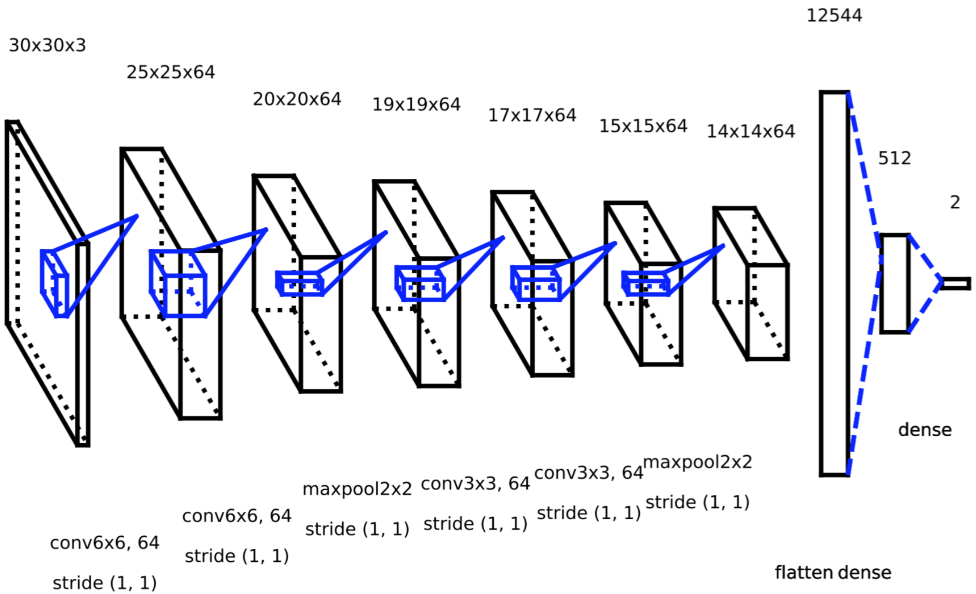


Jet into images



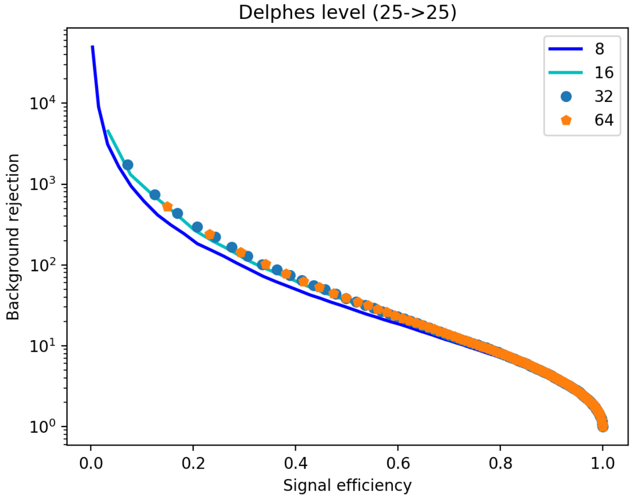
Training the CNN

- Singal: Events with only $\tilde{\chi}^0 \to jjj(bjj)$, $m_{\tilde{\chi}^0} = 100$ GeV, $p_T(\tilde{\chi}^0) > 200$ GeV
  - $|\eta(\tilde{\chi}^0)| < 0.1$
  - $|\eta(\tilde{\chi}^0)| < 2.5$
- Background: QCD jet with the same cuts.
- CNN parameters

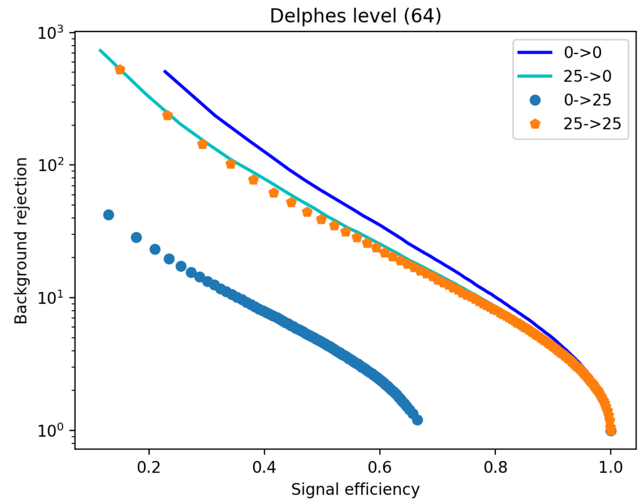


Sensitivity to CNN parameters and jet direction

- Not sensitive to CNN parameters: size and number of convolutional kernels, dropout rates, learning rate, ...

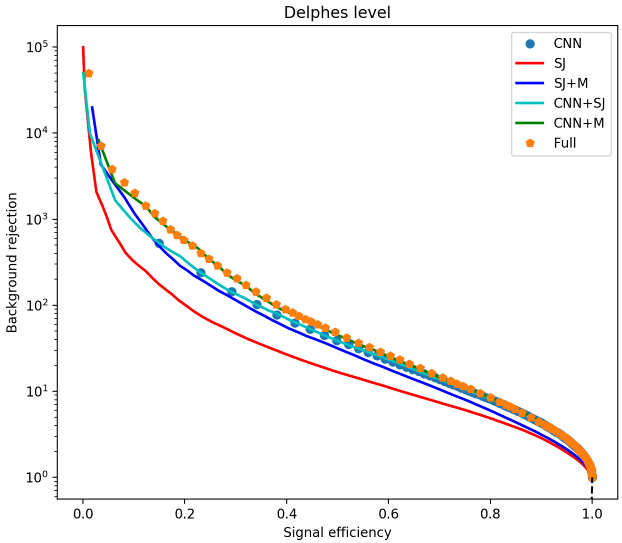


- The identification is best for fixed jet angle ($|\eta| \sim 0$)
- Feature captured by CNN in $|\eta| \sim 0$ sample are not useful for $|\eta| < 2.5$ sample.
- CNN trained on $|\eta| < 2.5$ sample works well also on $|\eta| \sim 0$ sample.



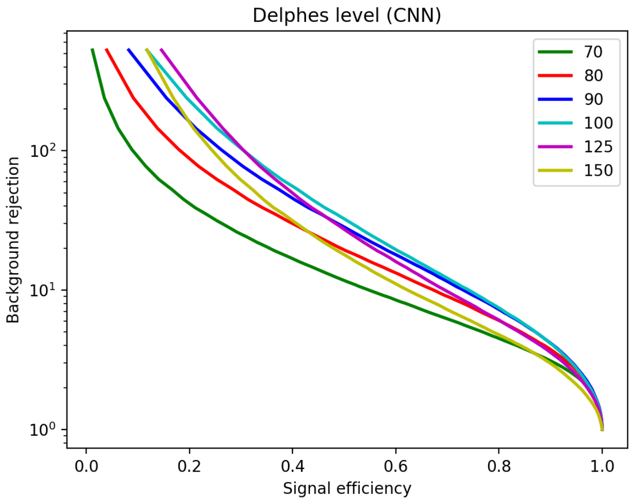
Comparing with jet substructure variable

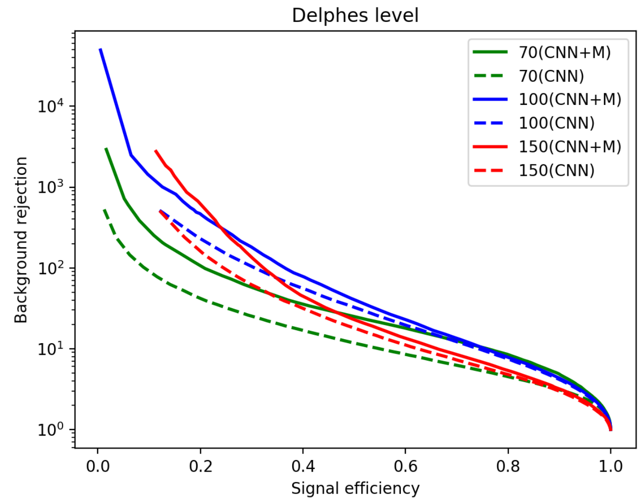
- N-subjettiness: $\tau_N = \frac{\sum_k \min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}}{\sum_k p_{T,k} R_0}$
- jet invariant mass, for signal $m_{\rm neu} \sim 100$ GeV.



- CNN can be improved by adding the jet mass information.

Different neutralino masses

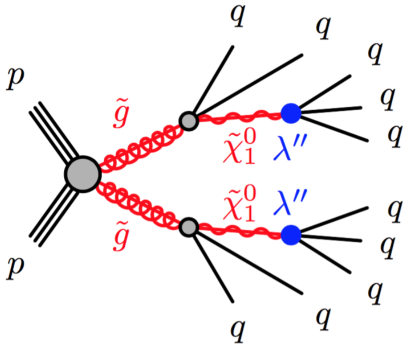




- CNN trained on a given neutralino mass loses some sensitivities when applying to different masses
- CNN + M scenario works better.
- Idea for general signal search: define signal regions with CNN trained on a few chosen masses and used together with the invariant mass information.

LHC search for multi-jet (gluino)

ATLAS-CONF-2016-057



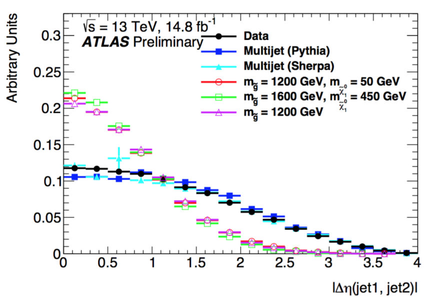
$N_{\rm jet}$	b-tag $\lvert\Delta\eta_{12}\rvert > 1.4$	b-tag $\lvert\Delta\eta_{12}\rvert < 1.4$	b-veto -	inclusive $\lvert\Delta\eta_{12}\rvert > 1.4$	inclusive $\lvert\Delta\eta_{12}\rvert < 1.4$
= 3	3jCRb1_4j	-	3jCRb0_4j	3jCR_5j	
≥ 4	4jVRb1	4jSRb1	-	4jVR	4jSR
≥ 5	5jVRb1	5jSRb1	-	5jVR	5jSR

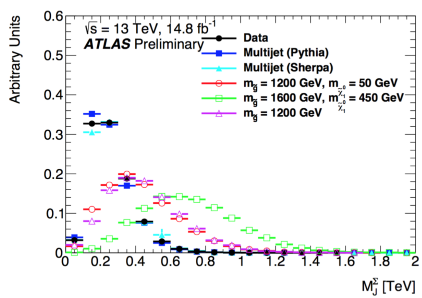
Table 1: Control (CR), validation (VR), and signal (SR) regions used for the analysis.

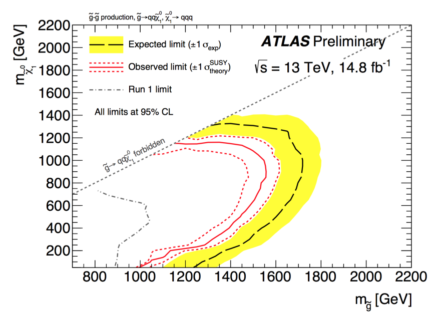
Selections:

- Jets have $p_T > 200$ GeV and $|\eta| < 2.0$
- Leading jet $p_T > 440$ GeV

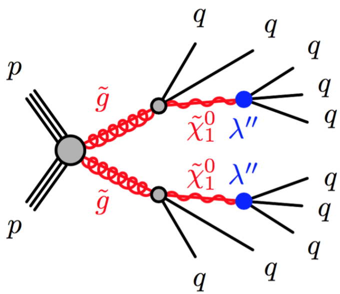
Region	M_J^Σ cut	observed	SM predicted	Expected limit (fb)	Observed Limit (fb)
4jSRb1	> 0.8 TeV	46	61 ± 10 ± 6 ± 12	$2.50^{+1.22}_{-0.74}$	1.76
4jSR		122	151 ± 15 ± 17 ± 20	$4.40^{+2.16}_{-1.29}$	3.11
5jSRb1	> 0.6 TeV	30	18.2 ± 4.2 ± 2.5 ± 3.0	$1.08^{+0.47}_{-0.30}$	2.00
5jSR		64	51.4 ± 7.7 ± 7.2 ± 6.5	$2.03^{+1.12}_{-0.57}$	2.94

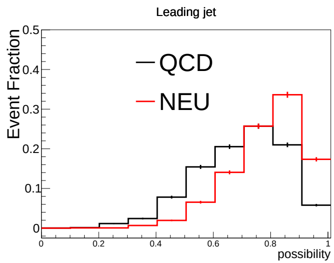


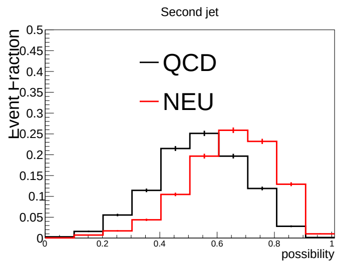


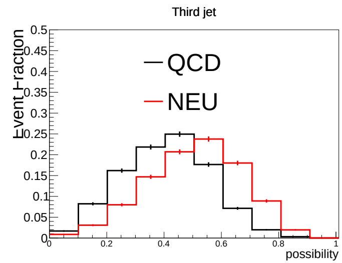


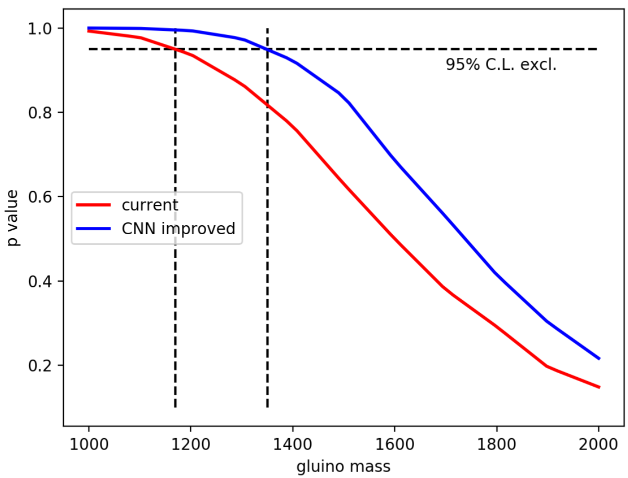
Apply to the realistic gluino search











- The power of neutralino jet identification decreases with increasing number of jets.
- Visible differences in jets score for gluino events and QCD events.
- The current bound can be improved by ~ 200 GeV.

Conclusion

- Some RPV SUSY searches are not so optimized, have sufficient signal events for possible improvement.
- CNN is helpful in RPV searches, increase the bound on gluino by $\sim$200 GeV.

Possible issues:

- Not fully learning the jet mass information?
- Identification power suppressed by the number of jets?