Search for RPV SUSY in multijet events

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SUSY WG approval
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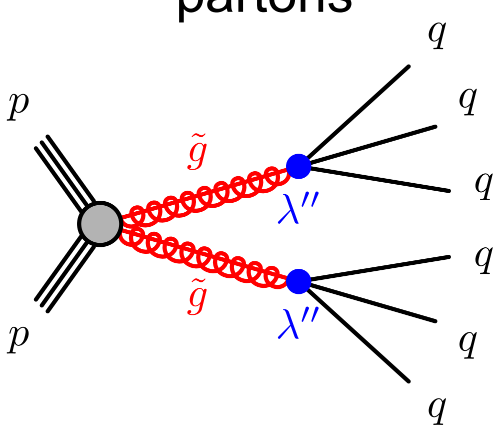
Signal model

The signal model is the same as the one used in the Run-1 analysis.

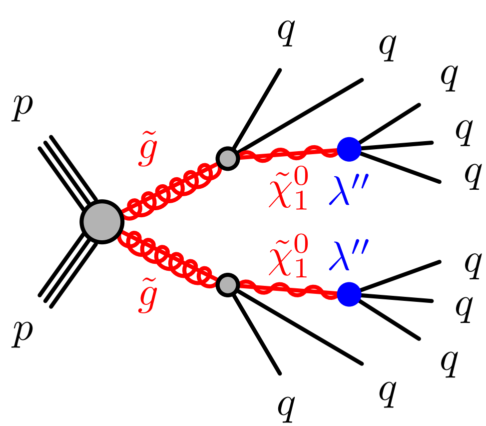
- ***UDD scenario***: λ and λ’ are set to 0.

$$W_{\not{R}_p} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$$

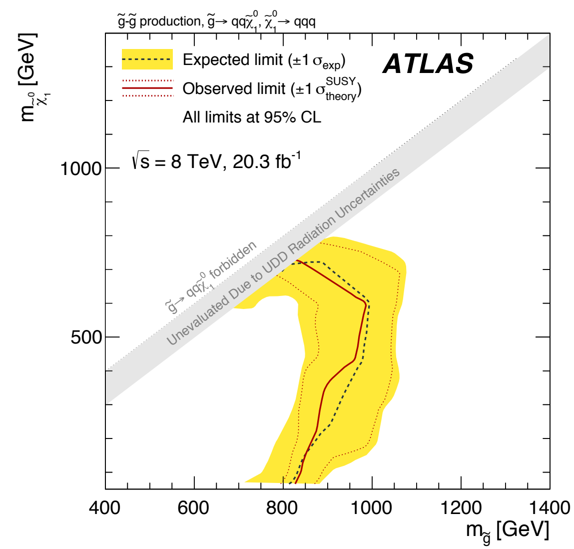
- Equal branching ratio for all possible final states.
- Set the widths of gluino and neutralino to 1 GeV so that decays are prompt.
- Two diagrams considered: gluino direct decay and gluino cascade decay
- Madgraph is used to generate signals with up to 2 additional partons



gluino direct decay
(6-quark)



gluino cascade decay
(10-quark)



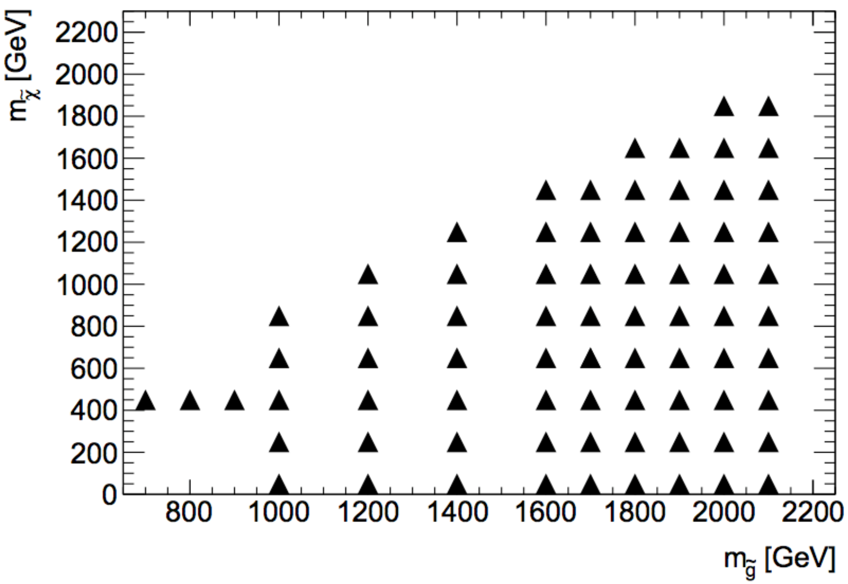
Samples

RPV10 (10-quark model)

Gluino decays to 1st and 2nd generation quarks + neutralino

RPV6 (6-quark model), 0.9 TeV to 1.8 TeV with a step of 0.1 TeV

Equal decay BR to 18 allowed final states



Background Monte Carlo samples

Pythia8, Herwig++, Sherpa multijet samples are used to test background estimation method; no quantitative info derived from MC used in the analysis

Powheg ttbar sample; always combined with the multijet MC sample in the study of background estimation method

Selection

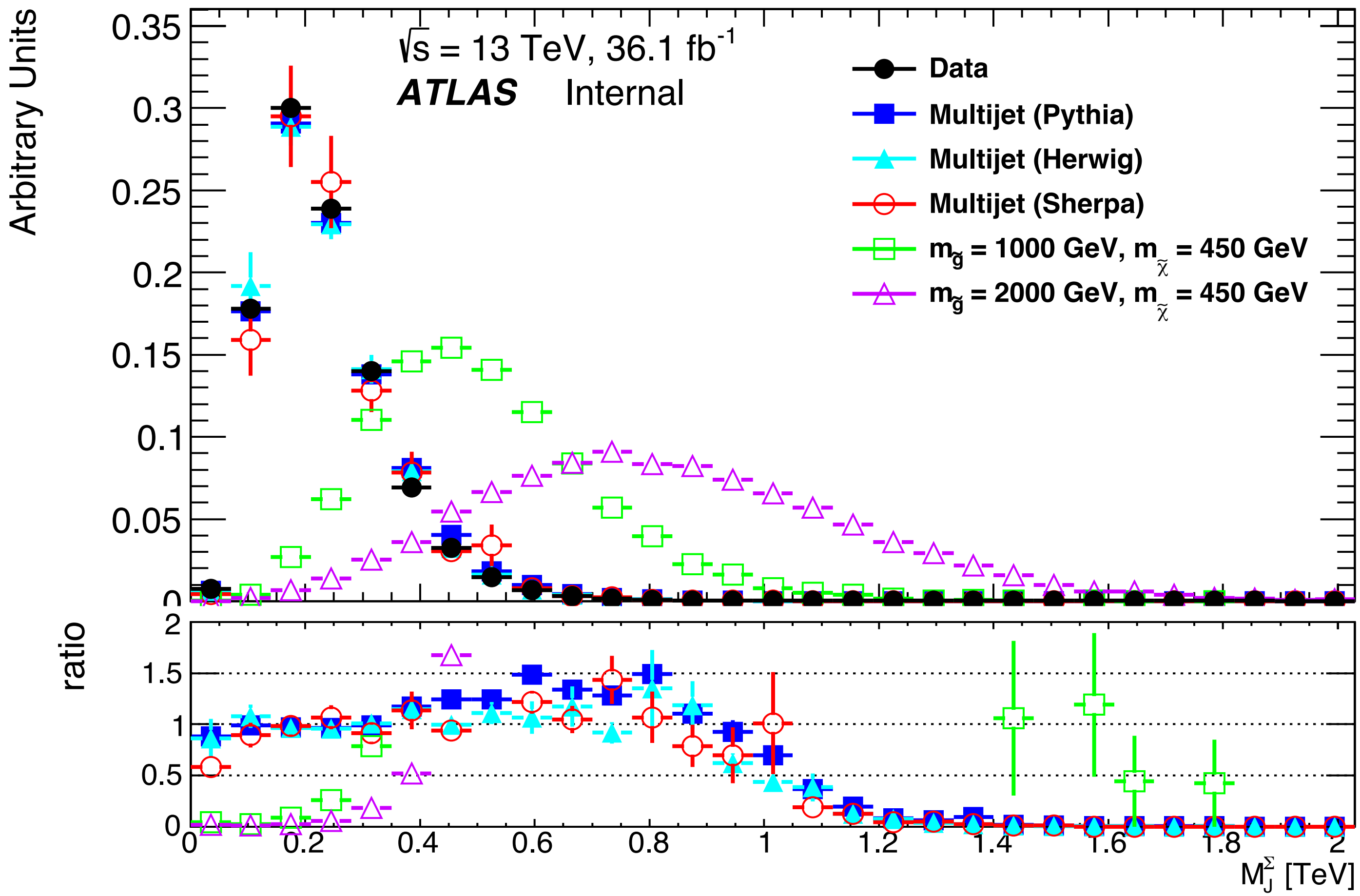
ALL_GOOD GRL; standard event quality flags
Trigger: HLT_ht1000_L1J100

Large R jet selection
p_T > 200 GeV, $|\eta|$ < 2.0, combined mass used

Anti-kt4 EMtopo jet selection
p_T > 50 GeV, $|\eta|$ < 2.5, fixed 70% WP

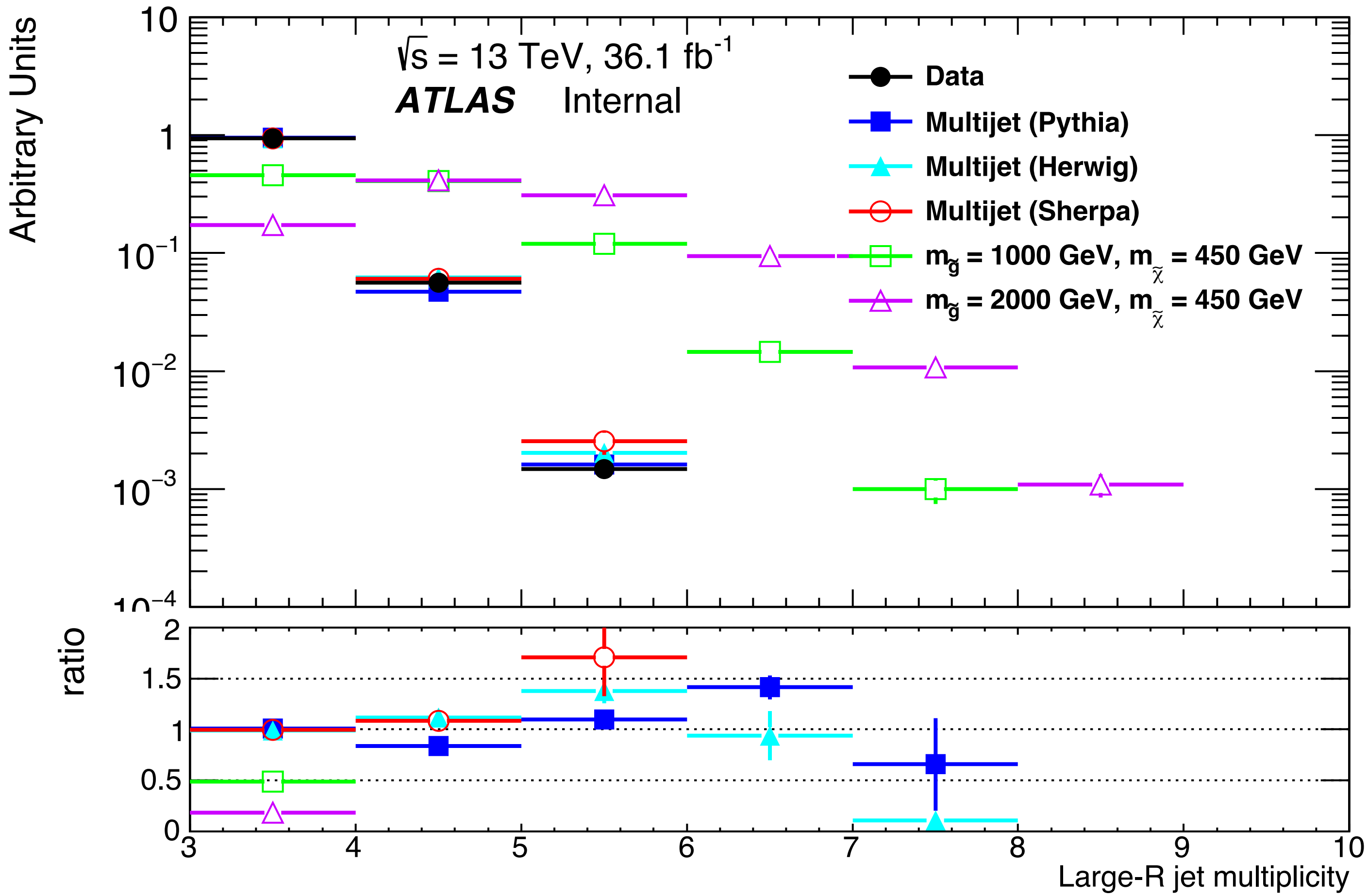
B-tag event: The event has at least one b-jet.
B-matching jet: the large-R jet is matched to a b-tagged jet with ΔR = 1.0

Observable : total jet mass

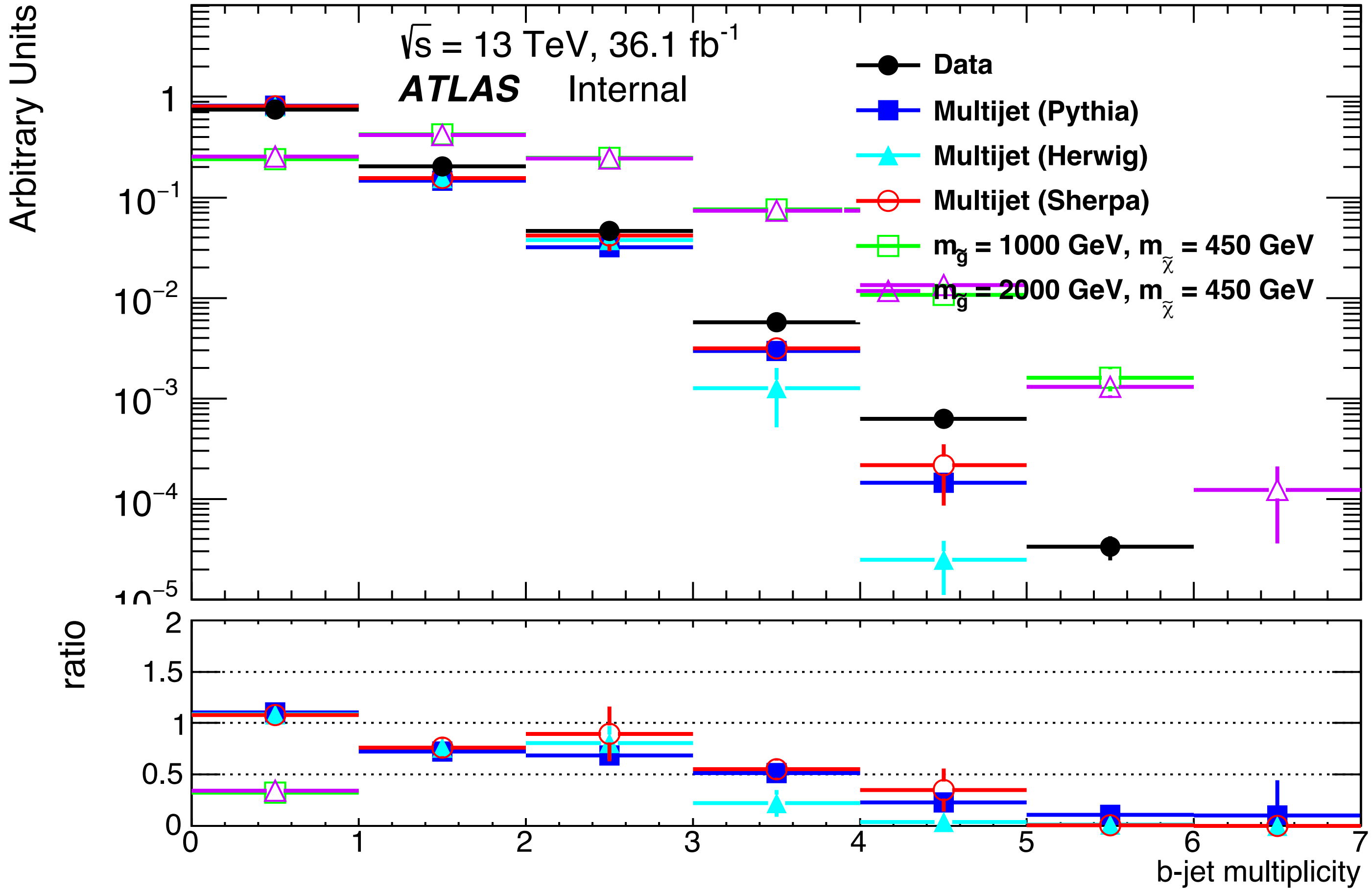


Sum of masses of four leading jets in the event
Data driven method to estimate background shape

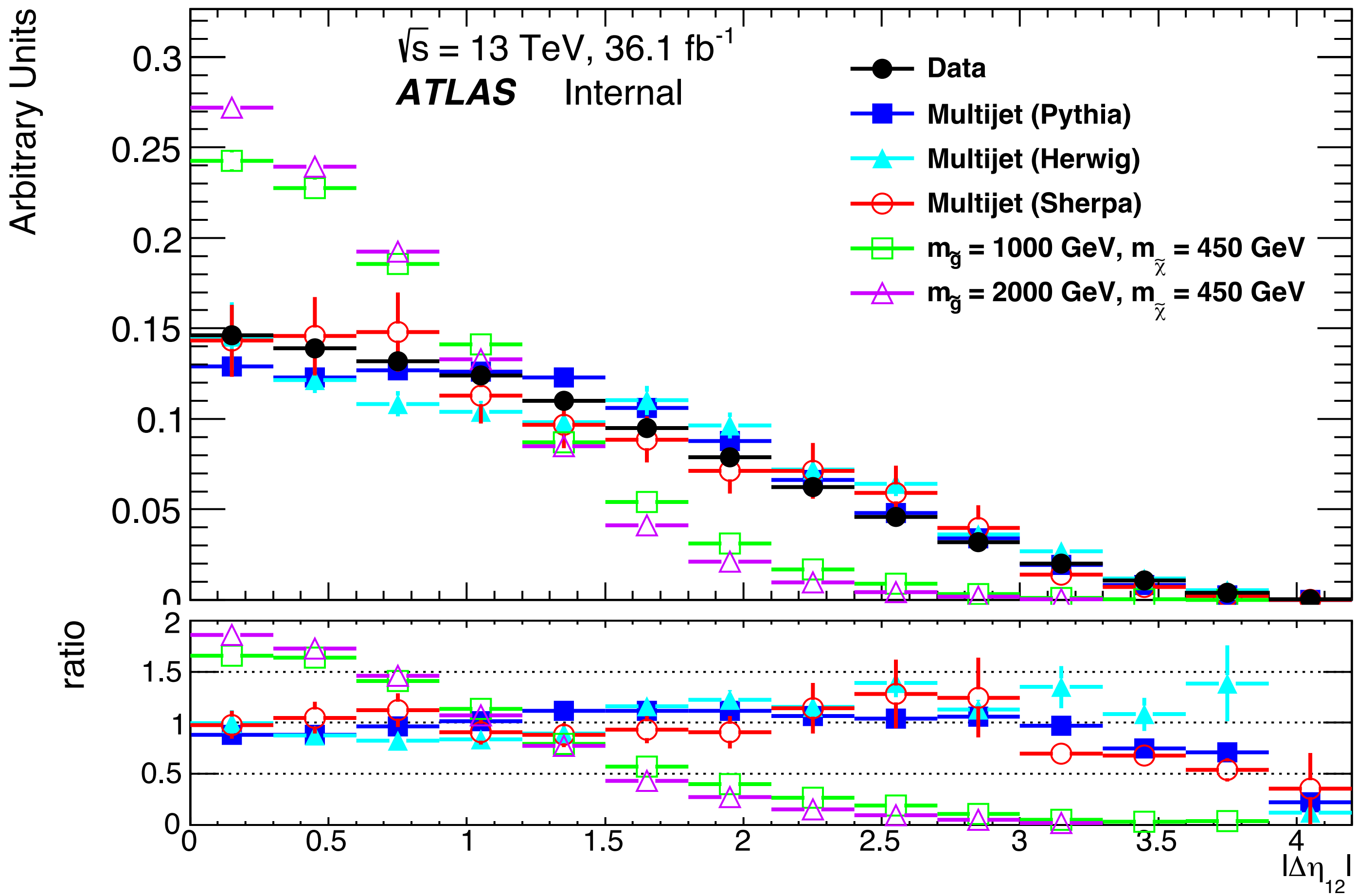
Observable : large-R jet multiplicity



Observable : b-jet multiplicity



Observable : $|\Delta\eta_{12}|$

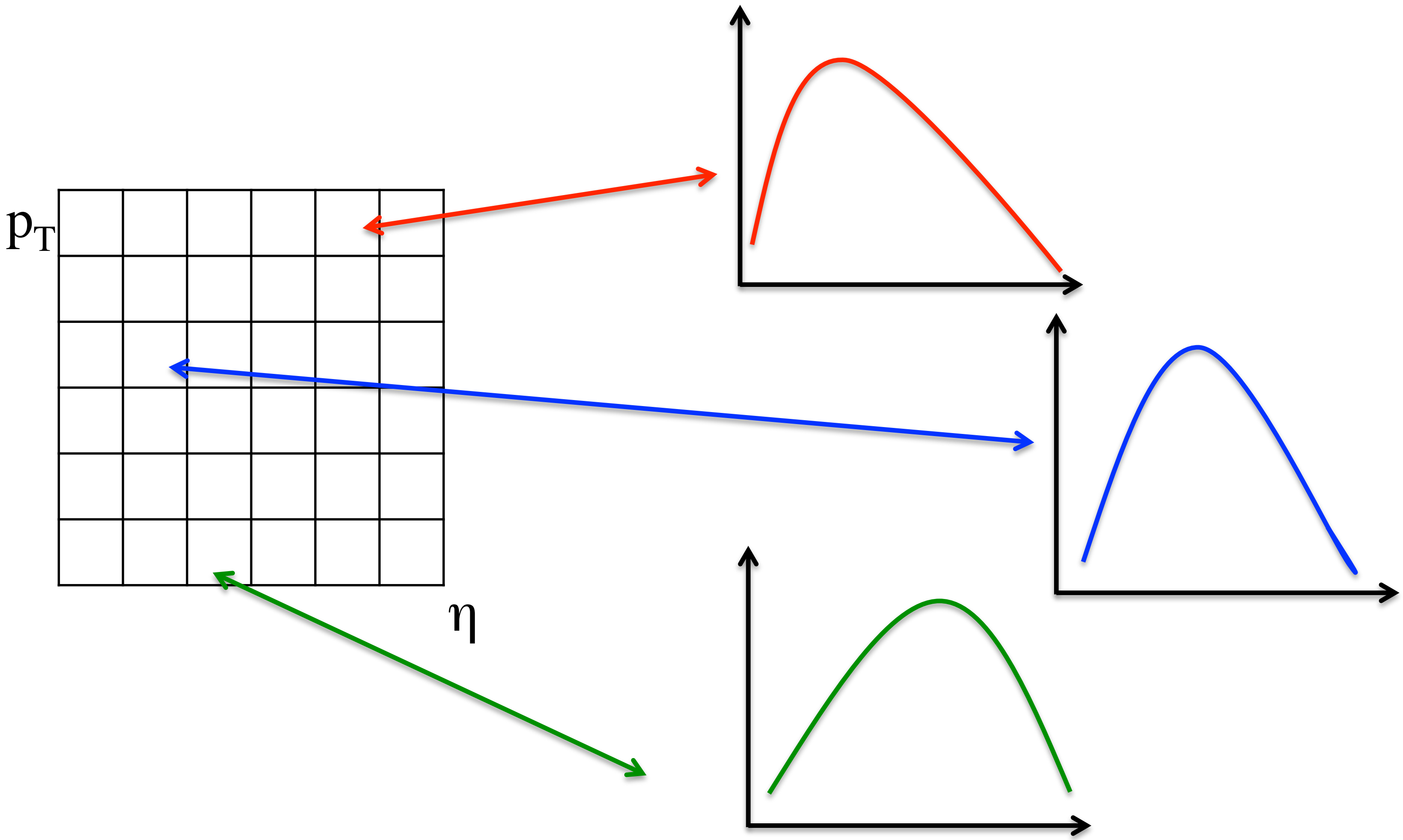


Pseudo rapidity gap between two leading jets
Useful for suppressing signal events

Background prediction

Jet mass distribution is modeled by a Probability Density Function

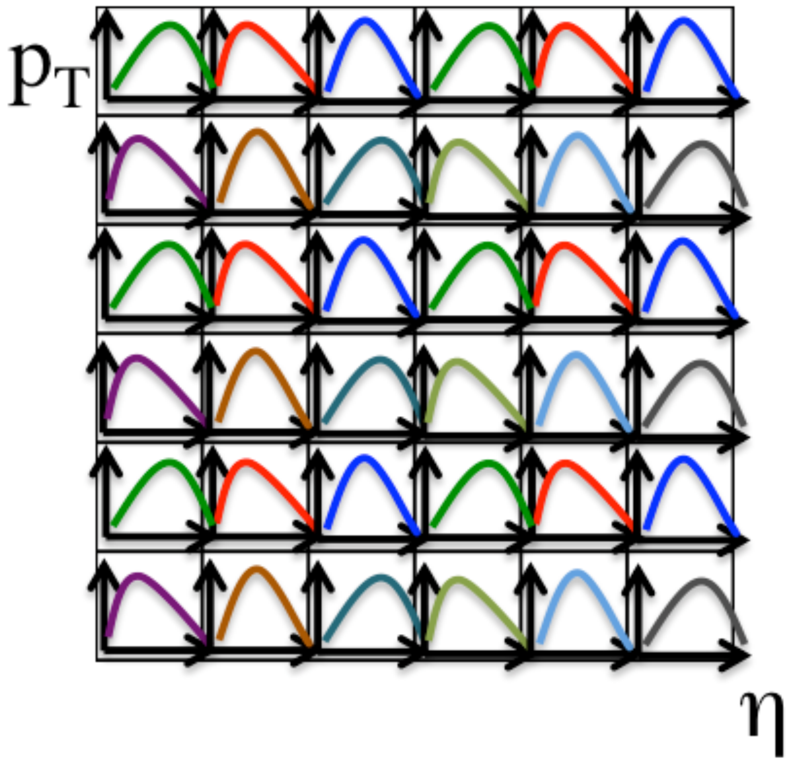
This PDF is pT – η dependent



The jet mass template method

Jet mass distribution is modeled by a Probability Density Function. This PDF is *$p_T - \eta$ dependent*
We can define a *background-only* control region and use jets there to build a library of *the background jet mass PDF*, i.e., the templates.

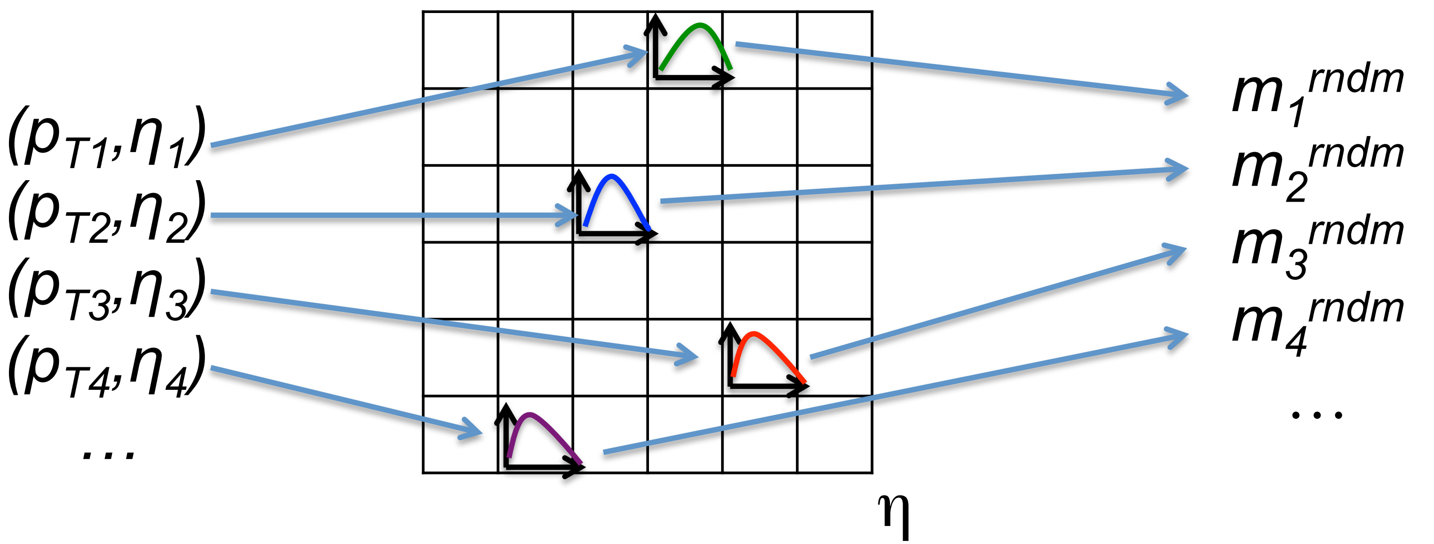
Control region
Three large-R jets



The jet mass template method

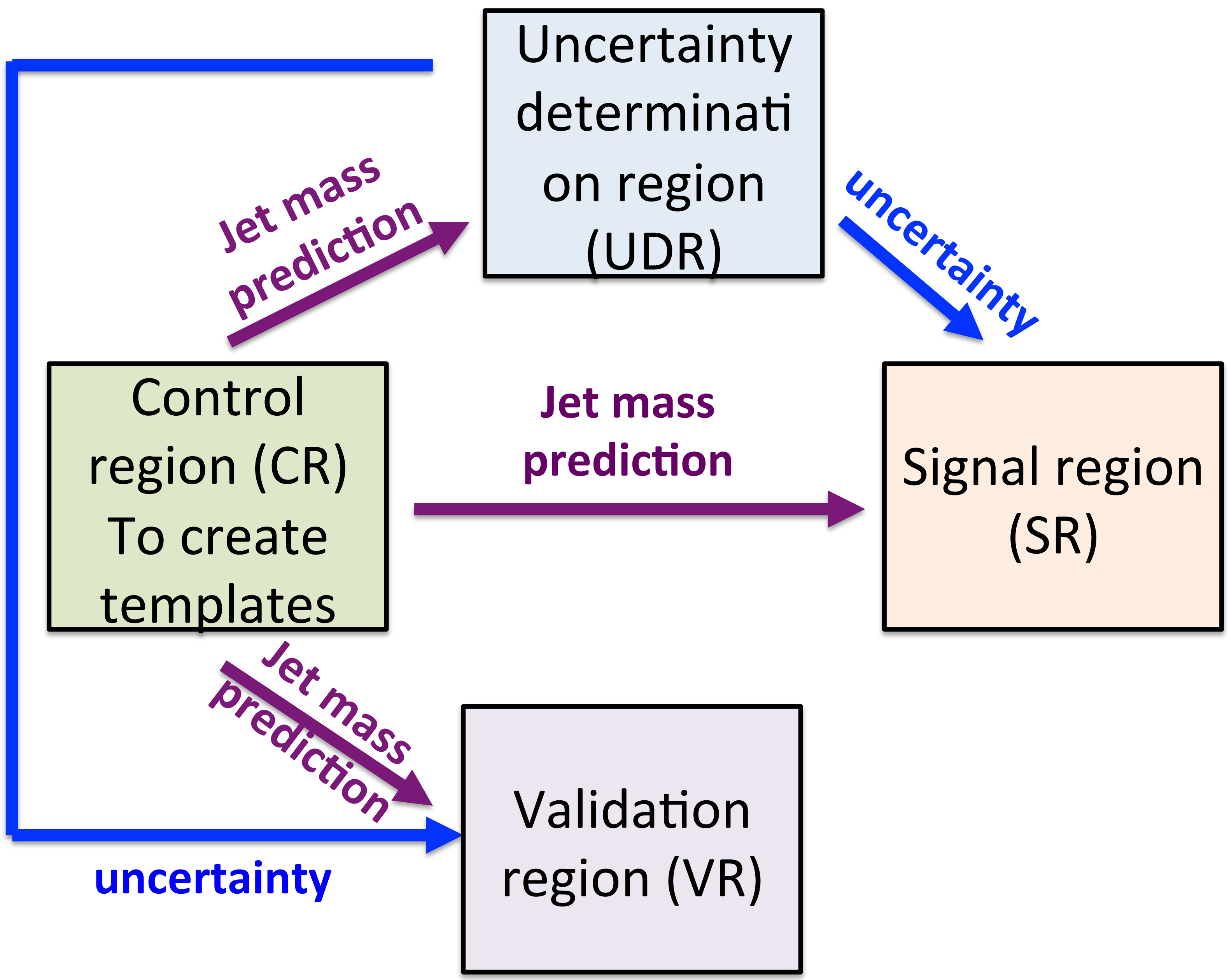
- For every jet in an event in the signal region, its background jet mass PDF can be identified
- A random jet mass can be generated
- A random M_J^Σ can be constructed

Signal regions
≥ 4 jets, ≥ 5 jets
w/wo b-jet



- For a large number of multijet events, the constructed M_J^Σ distribution will be background-like.

Regions



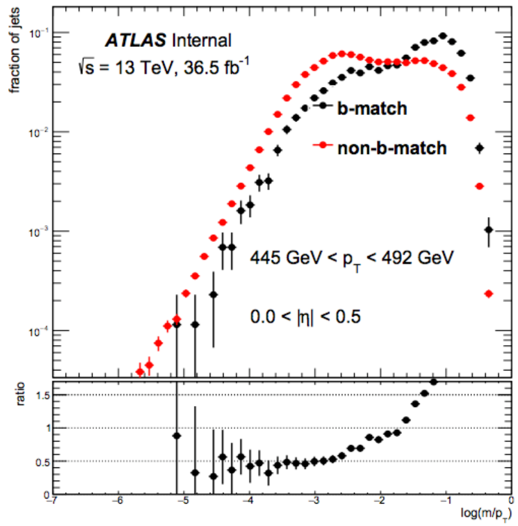
Uncertainty determinati on region (UDR)
Jet mass prediction
uncertainty
Control region (CR) To create templates
Jet mass prediction
Signal region (SR)
Jet mass prediction
Validation region (VR)
uncertainty

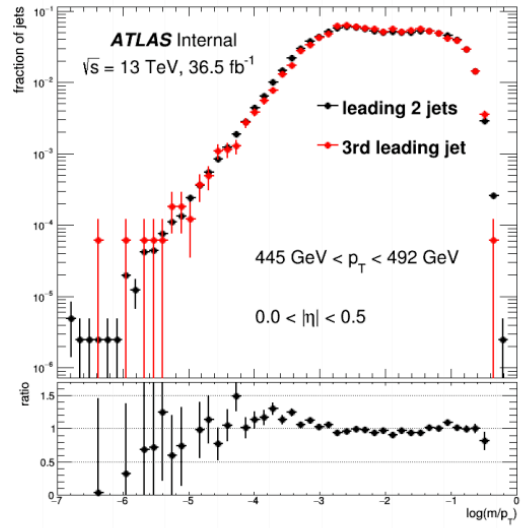
Region definition

		n_{jet}	b-tag	b-match	$p_{T,1}$	$\|\Delta\eta_{12}\|$	M_J^Σ
CR	3jCRb	= 3	-	Yes	-	> 1.4	-
	3jCR	= 3	-	No	-	-	-
UDR	UDR1	= 2	-	-	> 400 GeV	-	-
	UDR2	= 4	-	-	< 400 GeV	-	-
VR	4jVRb	≥ 4	Yes	-	> 400 GeV	> 1.4	-
	5jVRb	≥ 5	Yes	-	-	> 1.4	-
	4jVR	≥ 4	-	-	> 400 GeV	> 1.4	-
	5jVR	≥ 5	-	-	-	> 1.4	-
SR	4jSRb	≥ 4	Yes	-	> 400 GeV	< 1.4	> 1.0 TeV
	5jSRb	≥ 5	Yes	-	-	< 1.4	> 0.8 TeV
		≥ 5	Yes	-	-	< 1.4	> 0.6 TeV
	4jSR	≥ 4	-	-	> 400 GeV	< 1.4	> 1.0 TeV
	5jSR	≥ 5	-	-	-	< 1.4	> 0.8 TeV

- Control region : jet mass templates created separately for b-matched and non-matched jets

Control region and jet binning





Larger difference between b-matched and non-matched than between two leading and third leading

jet |η| \ jet p_T [GeV]	200	221	244	270	293	329	364	402	445	492	544	600	644	733	811
1.5–2.0	310991	312273	324091	262699	366800	307415	286488	274450	248782	210702	147823	73618	82441	32681	29966
1.0–1.5	381433	390698	411827	337737	481878	411154	391523	386731	360090	309094	223993	117822	140917	63415	78314
0.5–1.0	443522	457305	484691	402010	571735	491281	471409	467609	437163	376084	274803	146756	180824	85115	121264
0.0–0.5	476094	492143	522848	432080	622032	531025	509624	507749	471904	401582	294509	157806	197421	94207	141696

jet |η| \ jet p_T [GeV]	200	221	244	270	293	329	364	402	445	492	544	600	644	733	811
1.5–2.0	7348	7819	9233	8468	12951	10617	9754	8580	6987	5174	3628	1926	2124	911	962
1.0–1.5	9862	10657	11270	9933	14964	12940	11757	10845	9128	7157	5073	2845	3406	1556	1999
0.5–1.0	13599	14005	14428	11237	16407	13462	12010	11218	9275	7112	5287	2705	3431	1548	2150
0.0–0.5	16024	15899	15845	12664	16750	13352	11370	10232	8729	6655	4913	2574	3169	1325	1647

Number of jets in each pt-eta bin

- Left: non-matched Right: b-matched
- Uniform binning in log(p_T)

Region definition

		n_{jet}	b-tag	b-match	$p_{T,1}$	$\lvert\Delta\eta_{12}\rvert$
CR	3jCRb	= 3	-	Yes	-	> 1.4
	3jCR	= 3	-	No	-	-
UDR	UDR1	= 2	-	-	> 400 GeV	-
	UDR2	= 4	-	-	< 400 GeV	-
VR	4jVRb	≥ 4	Yes	-	> 400 GeV	> 1.4
	5jVRb	≥ 5	Yes	-	-	> 1.4
	4jVR	≥ 4	-	-	> 400 GeV	> 1.4
	5jVR	≥ 5	-	-	-	> 1.4
SR	4jSRb	≥ 4	Yes	-	> 400 GeV	< 1.4
	5jSRb	≥ 5	Yes	-	-	< 1.4
	4jSR	≥ 4	-	-	> 400 GeV	< 1.4
	5jSR	≥ 5	-	-	-	< 1.4

- 4j regions now require leading p_T > 400 GeV
  - Fully efficient with trigger
  - Orthogonal to the UDR2 (njet = 4 , p_T < 400 GeV)

Uncertainties of the background estimation method

- ***Jet mass randomization and template statistical uncertainties.*** Evaluated with Pseudo Experiment where bin-by-bin Poisson fluctuation is introduced to jet mass PDFs.

- ***Fundamental assumptions of the method***
  - ***Jet mass PDFs depend on a number of observables***
  - ***Jets in the same event are independent***

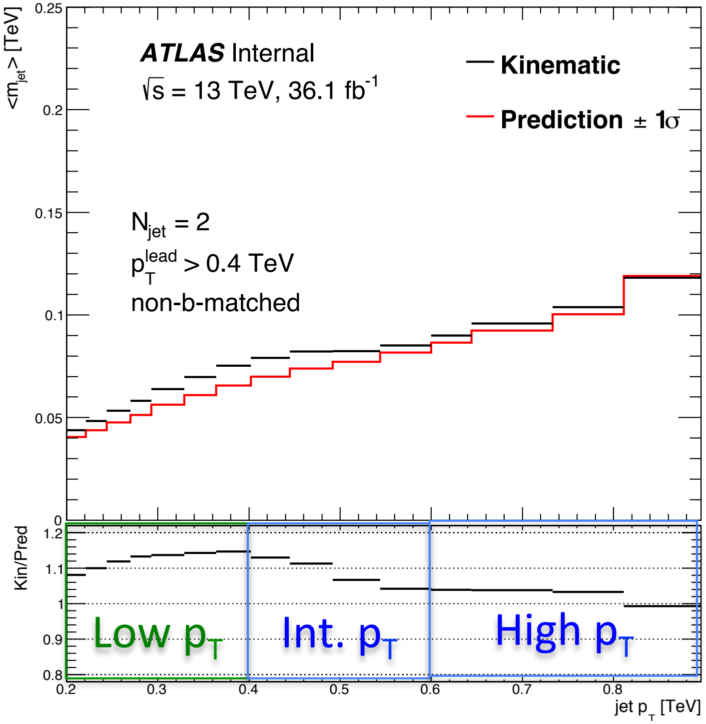
  - Use jets in data to estimate the jet mass prediction uncertainty
  - Samples need to be signal free; contain different types of jets and/or events

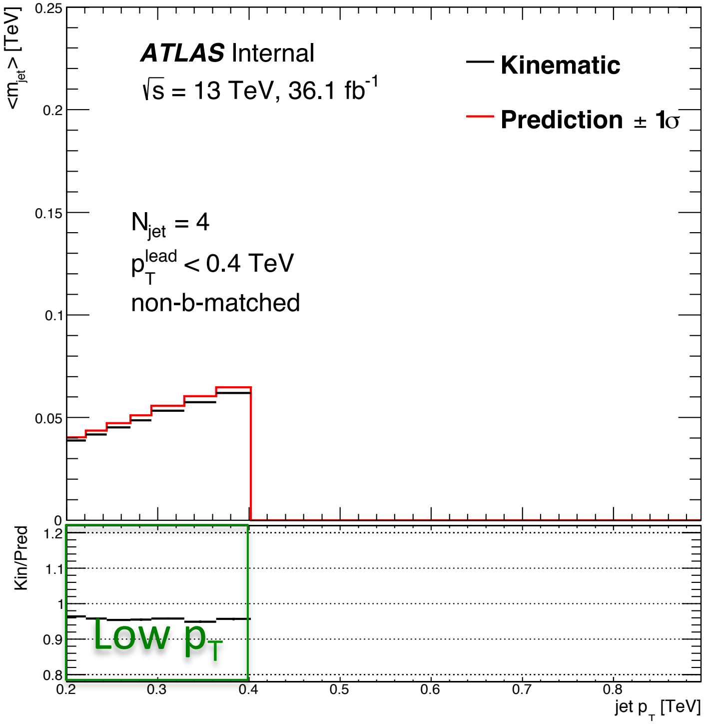
Uncertainty determination regions (UDRs)

- *UDR1*
  - **2 large-R jets, p_T leading > 400 GeV**
  - Harder jets more closely associated with partons in hard scattering
  - Softer jets more likely to be radiated from partons in hard scattering; events imbalanced (due to hard leading jet pT cut and ht trigger)
- *UDR2*
  - **4 large-R jets, p_T leading < 400 GeV**
  - Jets likely to be radiated from partons in hard scattering; more balanced events

These UDRs represent two extremes; 4j, 5j regions are in between the extremes

Uncertainty determination regions (UDRs)





$\|\eta\|$	low p_T	intermediate p_T	high p_T
$0 < \|\eta\| < .5$	10.96	10.63	2.31
$.5 < \|\eta\| < 1.0$	11.17	11.14	2.66
$1.0 < \|\eta\| < 1.5$	10.07	11.07	4.10
$1.5 < \|\eta\| < 2.0$	11.82	13.36	4.45

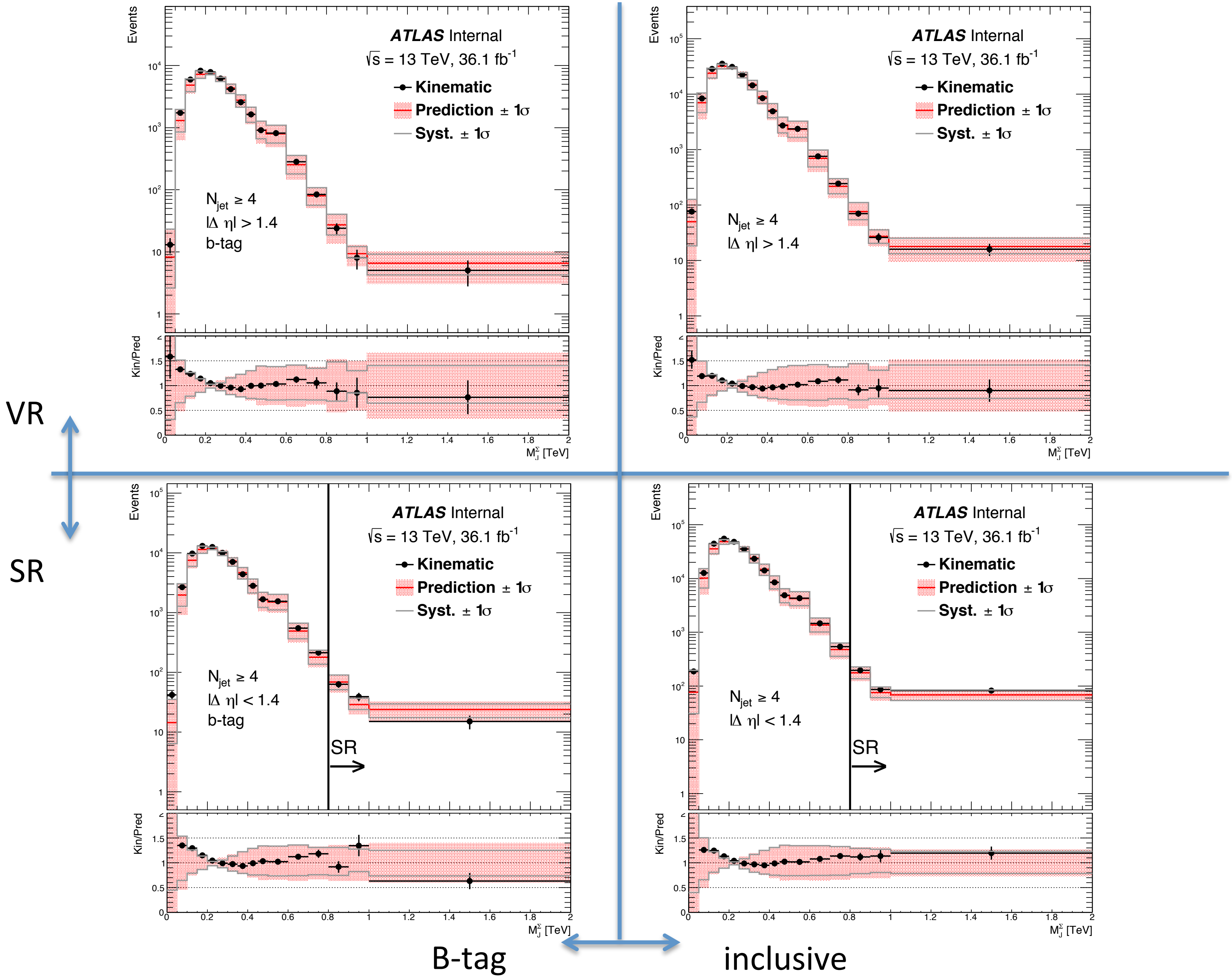
Background prediction and observed yield

Region	$\geq M_J^{\Sigma}$ [TeV]	Observed	Expected ($\pm$ (Stat.) $\pm$ (High p_T) $\pm$ (Low p_T))
5jSRb	0.6	61	44.0 ± 7.5 ± 11.2 ± 7.2
5jSRb	0.8	10	7.0 ± 2.4 ± 1.9 ± .7
5jSR	0.8	31	18.0 ± 3.7 ± 4.6 ± 1.5
4jSRb	1.0	15	23.6 ± 4.6 ± 6.1 ± 1.7
4jSR	1.0	82	68.2 ± 7.6 ± 15.8 ± 4.4

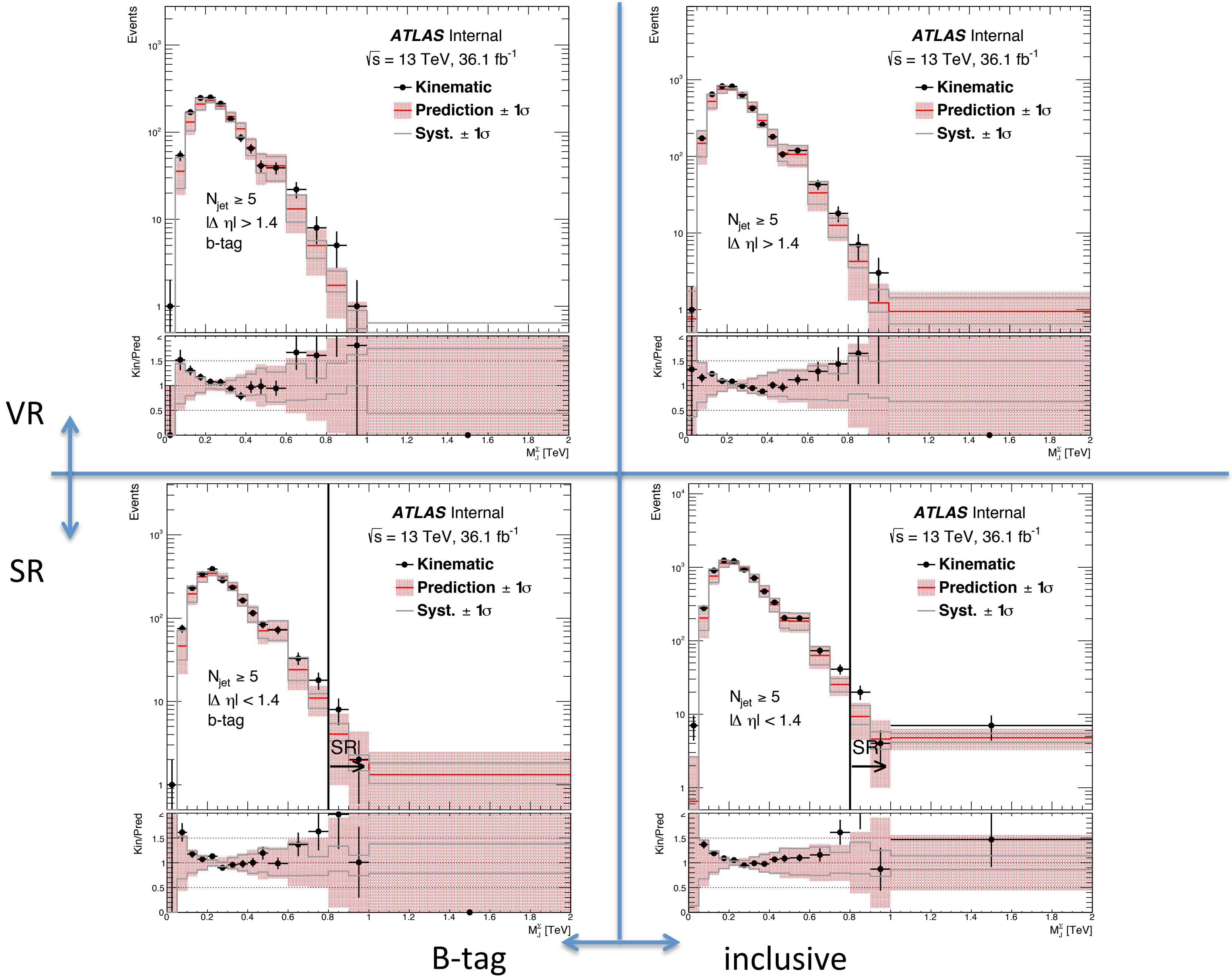
SRs chosen based on sensitivity to RPV models

High p_T includes both high p_T and intermediate p_T components

Background prediction and observed yield



Background prediction and observed yield



Statistical interpretation

Correcting signal contamination

- Subtract the signal contribution from the background prediction

$$\lambda = \mu \times s + b$$

$$\lambda = \mu \times s + b - \mu \times \Delta b$$

$$\lambda = \mu \times (s - \Delta b) + b.$$

DSID	$m_{\tilde{g}}$	$m_{\tilde{\chi}}$	Δb	f_{sig}	f_{bkg}
403550	700	450	2.58	0.05	0.36
403551	800	450	3.14	0.06	0.44
403552	900	450	3.31	0.05	0.47
403553	1000	50	4.18	0.30	0.59
403554	1000	250	2.54	0.08	0.36
403555	1000	450	3.10	0.05	0.44
403556	1000	650	3.34	0.06	0.47
403557	1000	850	3.26	0.08	0.46
403558	1200	50	3.39	0.32	0.48
403559	1200	250	3.16	0.12	0.45
403560	1200	450	2.99	0.06	0.42
403561	1200	650	3.85	0.06	0.55
403562	1200	850	2.97	0.05	0.42
403563	1200	1050	2.69	0.10	0.38
403564	1400	50	2.41	0.45	0.34
403565	1400	250	2.16	0.16	0.30
403566	1400	450	2.60	0.08	0.37
403567	1400	650	2.98	0.06	0.42
403568	1400	850	2.88	0.06	0.41
403569	1400	1050	2.53	0.07	0.36
403570	1400	1250	2.18	0.12	0.31
403571	1600	50	1.55	0.45	0.22
403572	1600	250	1.57	0.18	0.22
403573	1600	450	1.89	0.10	0.27
403574	1600	650	2.10	0.08	0.30
403575	1600	850	2.18	0.07	0.31
403576	1600	1050	2.06	0.07	0.29
403577	1600	1250	1.75	0.08	0.25
403578	1600	1450	1.50	0.15	0.21

DSID	$m_{\tilde{g}}$	$m_{\tilde{\chi}}$	Δb	f_{sig}	f_{bkg}
403579	1700	50	1.28	0.49	0.18
403580	1700	250	1.26	0.21	0.18
403581	1700	450	1.39	0.11	0.19
403582	1700	650	1.65	0.09	0.23
403583	1700	850	1.76	0.08	0.25
403584	1700	1050	1.68	0.07	0.24
403585	1700	1250	1.59	0.08	0.22
403586	1700	1450	1.29	0.11	0.18
403587	1800	50	.98	0.48	0.14
403588	1800	250	1.01	0.21	0.14
403589	1800	450	1.18	0.13	0.16
403590	1800	650	1.36	0.10	0.19
403591	1800	850	1.42	0.09	0.20
403592	1800	1050	1.39	0.08	0.19
403593	1800	1250	1.36	0.09	0.19
403594	1800	1450	1.19	0.11	0.17
403595	1800	1650	.90	0.18	0.12
403597	1900	250	.74	0.23	0.10
403598	1900	450	.91	0.15	0.13
403599	1900	650	1.05	0.11	0.15
403601	1900	1050	1.14	0.09	0.16
403602	1900	1250	1.06	0.09	0.15
403603	1900	1450	.96	0.10	0.13
403615	2000	50	.53	0.56	0.07
403616	2000	250	.59	0.26	0.08
403617	2000	450	.66	0.16	0.09
403618	2000	650	.78	0.13	0.11
403619	2000	850	.85	0.11	0.12
403620	2000	1050	.86	0.10	0.12
403621	2000	1250	.85	0.10	0.12
403622	2000	1450	.79	0.11	0.11
403624	2000	1850	.52	0.20	0.07
403626	2100	250	.41	0.27	0.05
403627	2100	450	.49	0.17	0.07
403628	2100	650	.57	0.15	0.08
403629	2100	850	.64	0.13	0.09
403982	2100	1250	.66	0.11	0.09
403983	2100	1450	.61	0.11	0.08
403984	2100	1650	.55	0.13	0.07

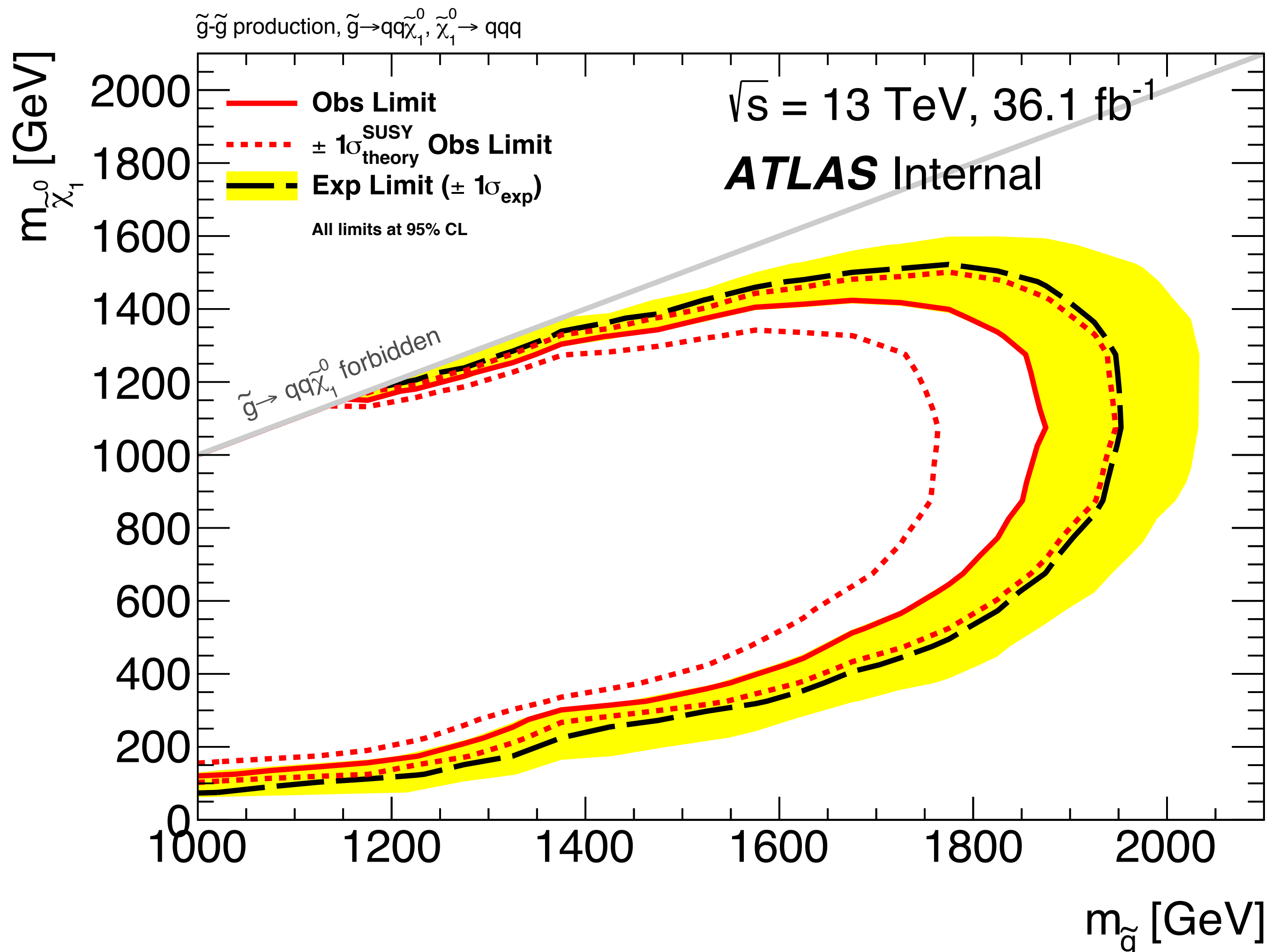
- Correction Δb, scales with μ
- A reduction of signal expectation

  Second to the last column shows the ratio of correction over expected signal yield.

Signal systematic uncertainty

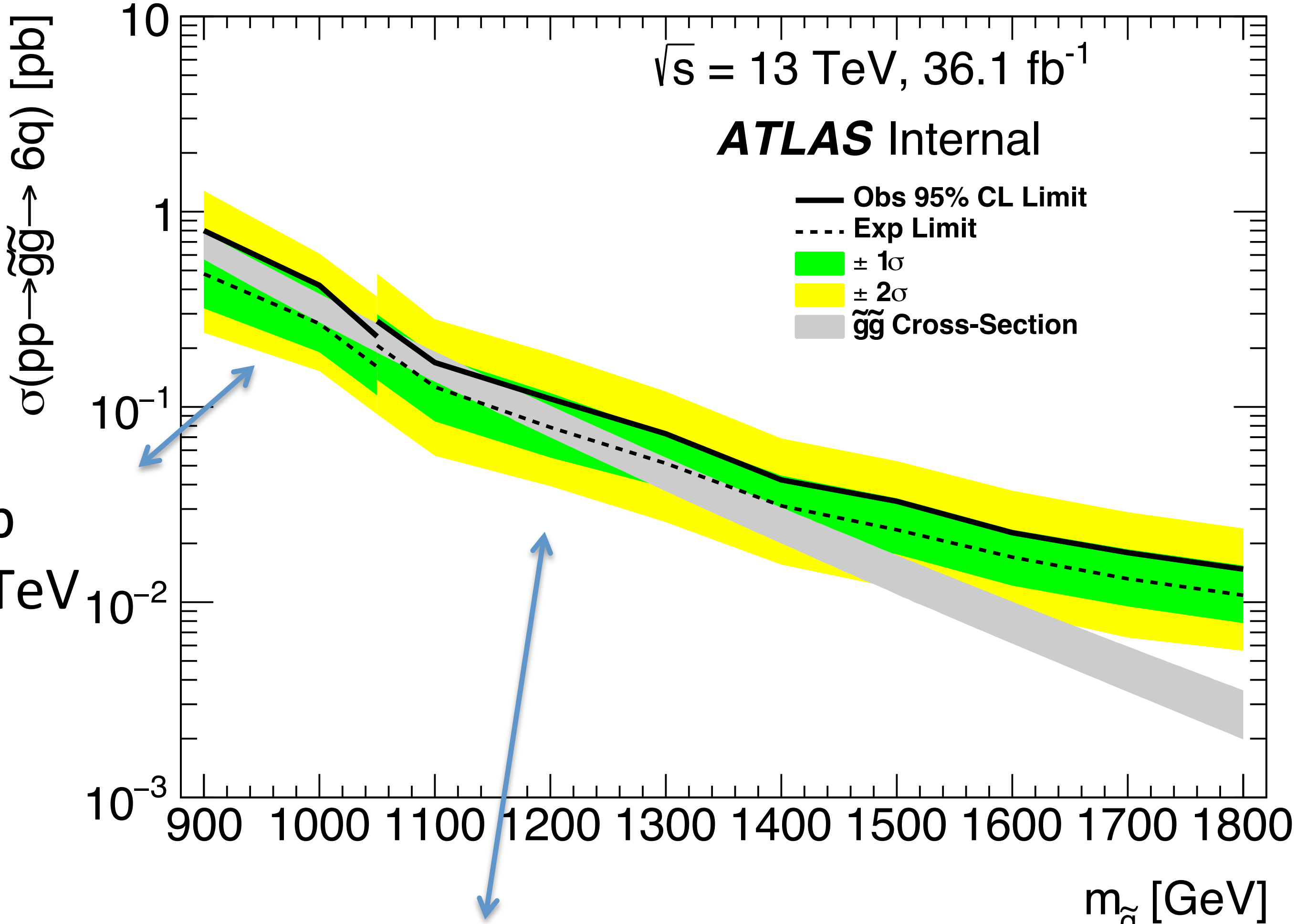
- Large-R jet uncertainty up to 25% at low gluino mass; down to ~7% at high gluino mass
- B-tagging: up to 6%, mostly ~2%
- Luminosity: 2.2%
- PDF and QCD scale: up to 20% at low gluino mass ; down to ~ 5- 6 % at high gluino mass

10 quark model



5jSRb $M_J^{\Sigma} > 0.8$ TeV

6-quark model



5jSRb
$M_J^{\Sigma} > 0.6$ TeV

5jSRb, $M_J^{\Sigma} > 0.8$ TeV

Model independent limit and p-values

Signal Region	M_J^Σ cut	Expected limit (fb)	Observed Limit (fb)	p_0-value
4jSRb	> 1.0 TeV	$0.53^{+0.20}_{-0.12}$	0.37	0.86
4jSR		$1.12^{+0.50}_{-0.32}$	1.50	0.24
5jSRb	> 0.8 TeV	$0.24^{+0.10}_{-0.06}$	0.34	0.26
5jSR		$0.43^{+0.08}_{-0.06}$	0.84	0.062

- P-value
- “model-independent” limit in four signal regions
    - No correction of signal contamination and theory uncertainties

Summary

A search for RPV SUSY signals in the multijet events is performed

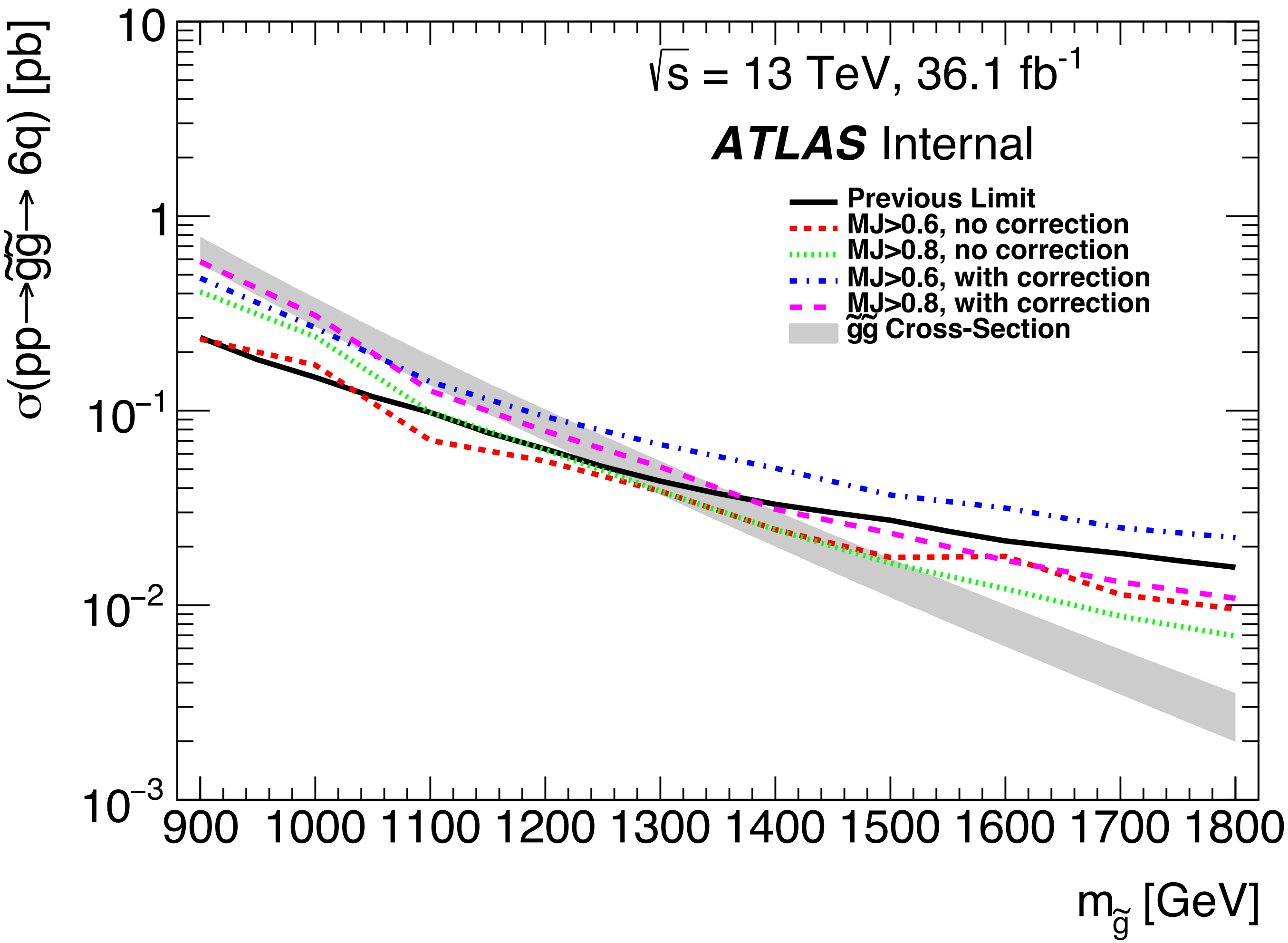
No significant excess is observed

Limits are set on the 6-quark model and 10-quark model

Model independent limits in four signal regions are also reported

Back up

Sensitivity of 6-quark model



Signal contribution to the background prediction

DSID	$m_{\tilde{g}}$	$m_{\tilde{\chi}}$	Δb	f_{sig}	f_{bkg}
403550	700	450	2.58	0.05	0.36
403551	800	450	3.14	0.06	0.44
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403554	1000	250	2.54	0.08	0.36
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403556	1000	650	3.34	0.06	0.47
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403558	1200	50	3.39	0.32	0.48
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403576	1600	1050	2.06	0.07	0.29
403577	1600	1250	1.75	0.08	0.25
403578	1600	1450	1.50	0.15	0.21

DSID	$m_{\tilde{g}}$	$m_{\tilde{\chi}}$	Δb	f_{sig}	f_{bkg}
403579	1700	50	1.28	0.49	0.18
403580	1700	250	1.26	0.21	0.18
403581	1700	450	1.39	0.11	0.19
403582	1700	650	1.65	0.09	0.23
403583	1700	850	1.76	0.08	0.25
403584	1700	1050	1.68	0.07	0.24
403585	1700	1250	1.59	0.08	0.22
403586	1700	1450	1.29	0.11	0.18
403587	1800	50	.98	0.48	0.14
403588	1800	250	1.01	0.21	0.14
403589	1800	450	1.18	0.13	0.16
403590	1800	650	1.36	0.10	0.19
403591	1800	850	1.42	0.09	0.20
403592	1800	1050	1.39	0.08	0.19
403593	1800	1250	1.36	0.09	0.19
403594	1800	1450	1.19	0.11	0.17
403595	1800	1650	.90	0.18	0.12
403597	1900	250	.74	0.23	0.10
403598	1900	450	.91	0.15	0.13
403599	1900	650	1.05	0.11	0.15
403601	1900	1050	1.14	0.09	0.16
403602	1900	1250	1.06	0.09	0.15
403603	1900	1450	.96	0.10	0.13
403615	2000	50	.53	0.56	0.07
403616	2000	250	.59	0.26	0.08
403617	2000	450	.66	0.16	0.09
403618	2000	650	.78	0.13	0.11
403619	2000	850	.85	0.11	0.12
403620	2000	1050	.86	0.10	0.12
403621	2000	1250	.85	0.10	0.12
403622	2000	1450	.79	0.11	0.11
403624	2000	1850	.52	0.20	0.07
403626	2100	250	.41	0.27	0.05
403627	2100	450	.49	0.17	0.07
403628	2100	650	.57	0.15	0.08
403629	2100	850	.64	0.13	0.09
403982	2100	1250	.66	0.11	0.09
403983	2100	1450	.61	0.11	0.08
403984	2100	1650	.55	0.13	0.07

Highlighted column

If the signal model is real, the predicted background yield that comes from signal events

Highlighted column

Signal contamination over the predicted signal yield

10% for intermediate m_{χ}

~40% for low m_{χ}

Up to 20% for high m_{χ}

Correcting signal contamination

$$\lambda = \mu \times s + b$$

$$\lambda = \mu \times s + b - \mu \times \Delta b$$

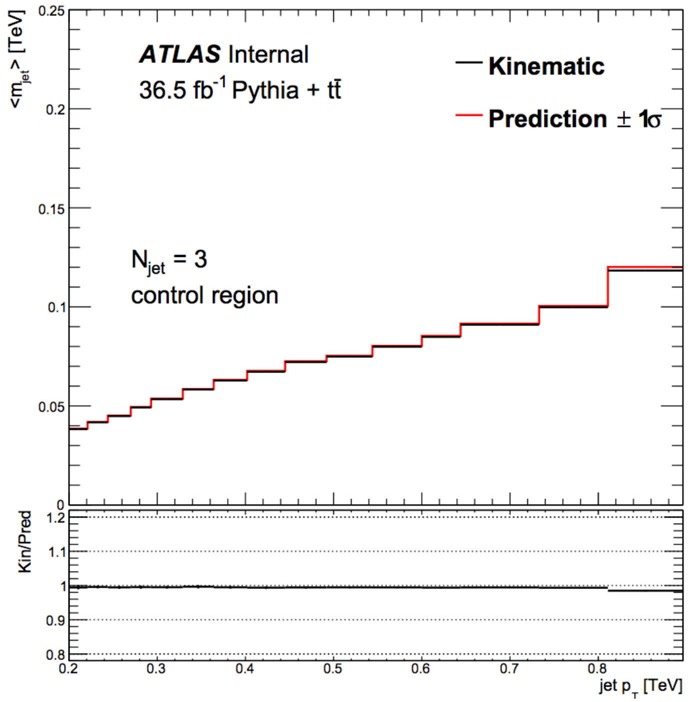
$$\lambda = \mu \times (s - \Delta b) + b.$$

$$q_\mu = -2\ln \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\theta})}$$

- Subtract the signal contribution from the background prediction
- Correction Δb, scales with μ
- a reduction of signal expectation

- Likelihood function is now model-dependent (via Δb)
  - Model independent limit not possible
  - Model independent p-value (since Δb is removed by μ = 0)

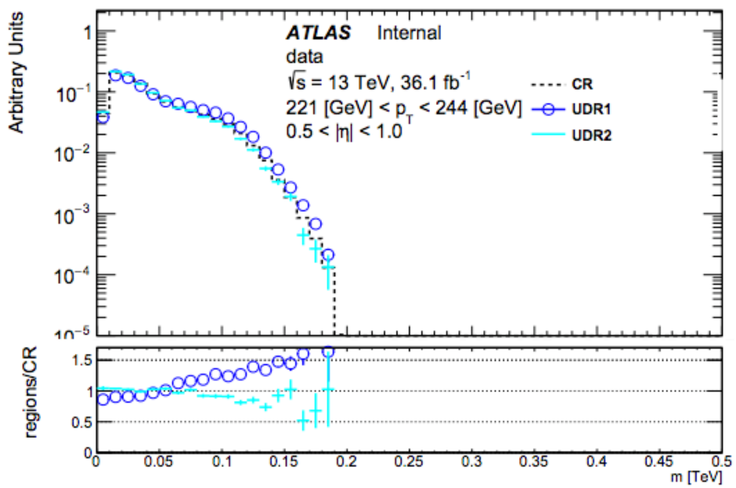
Jet mass response

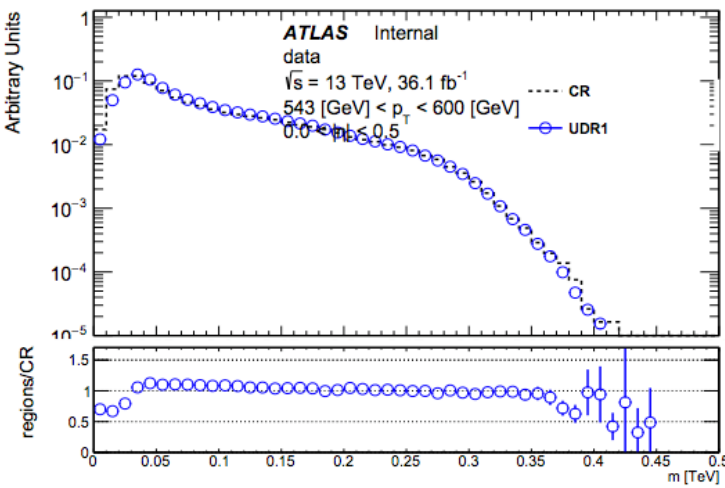


Mean jet mass in a given pT-eta bin

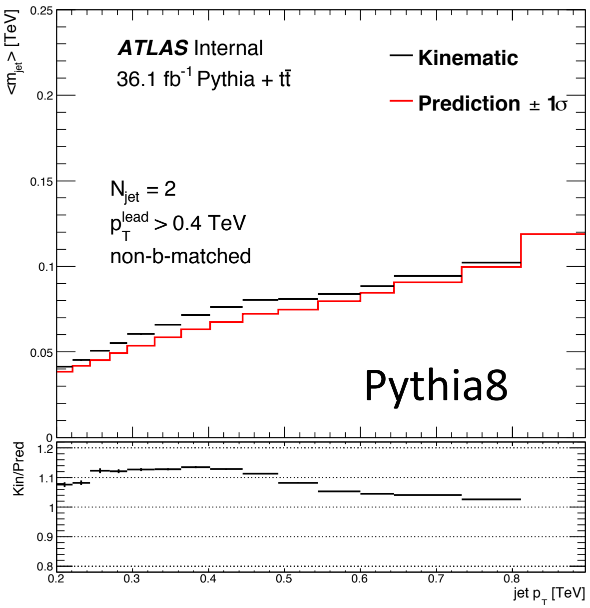
Metric used to understand the jet mass estimation performance

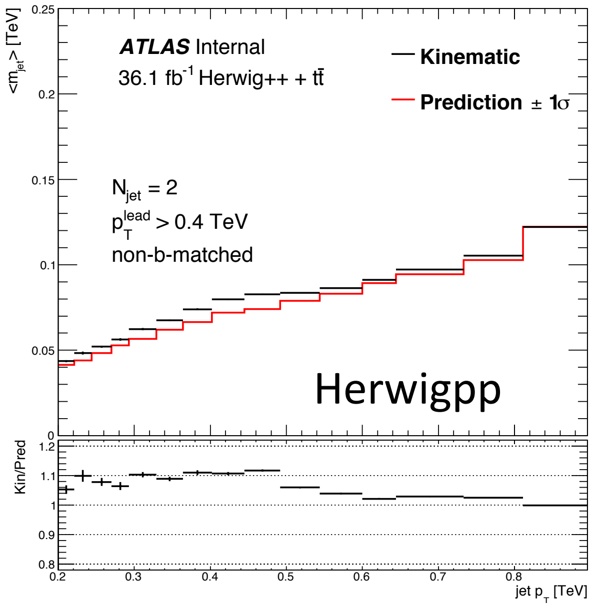
Shift in mean believed to capture the discrepancy

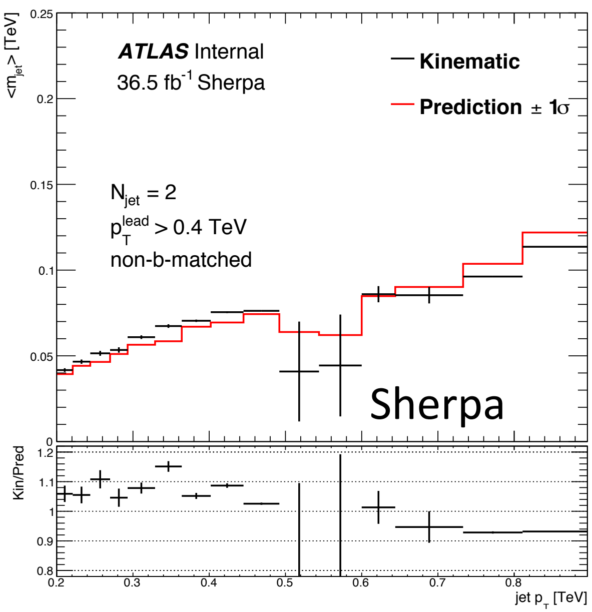


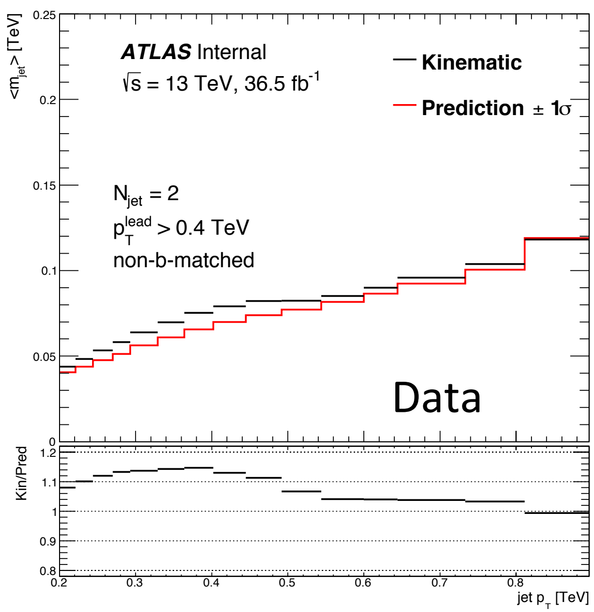


Jet mass response in the UDR1

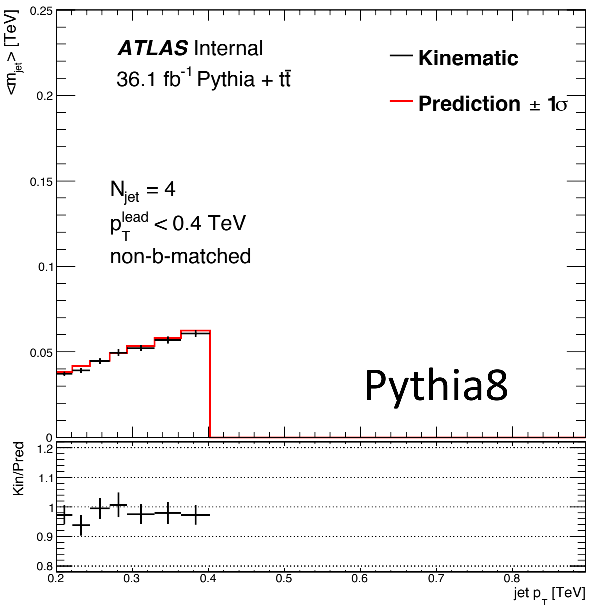


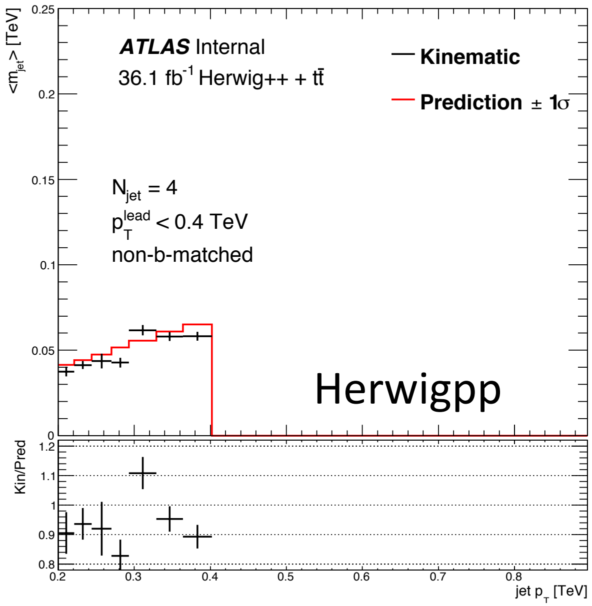


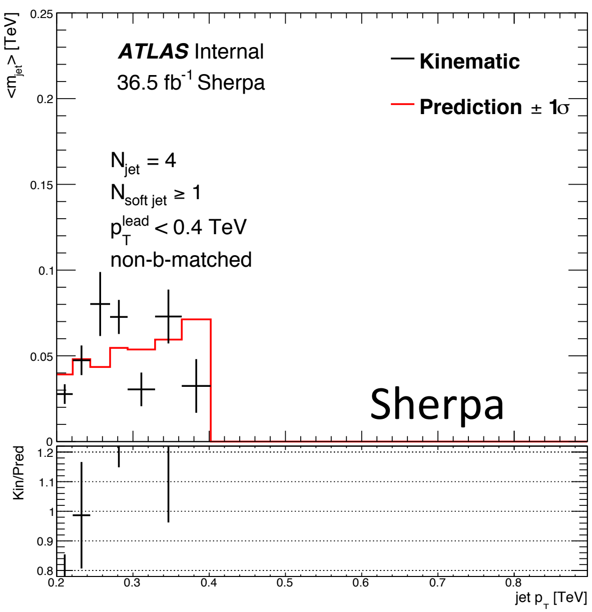


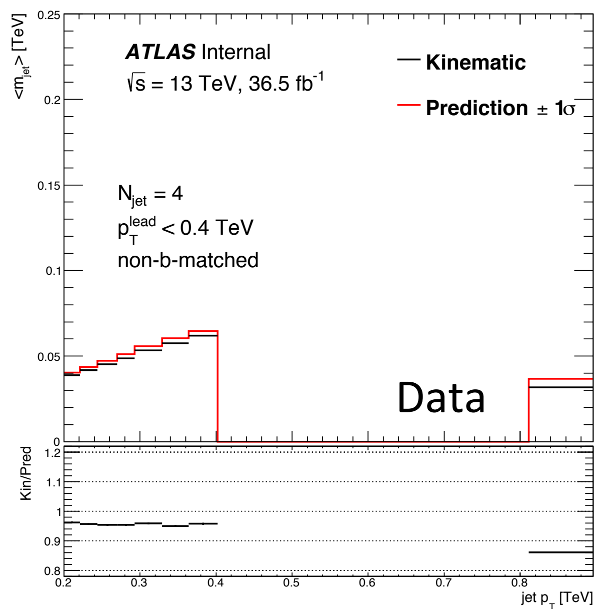


Jet mass response in the UDR2

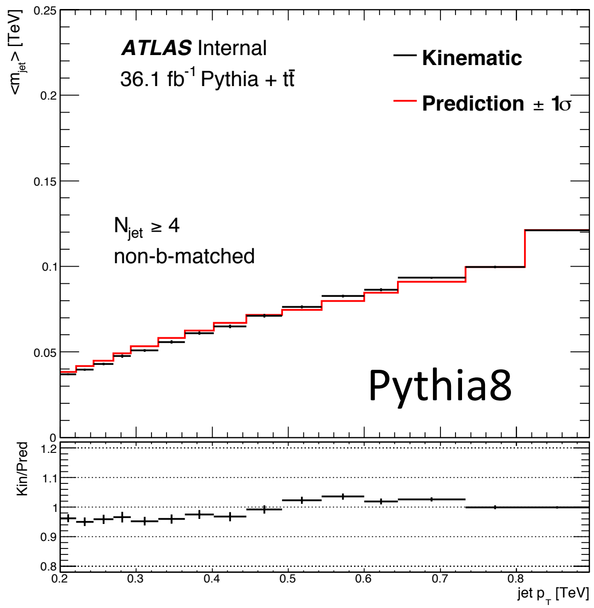


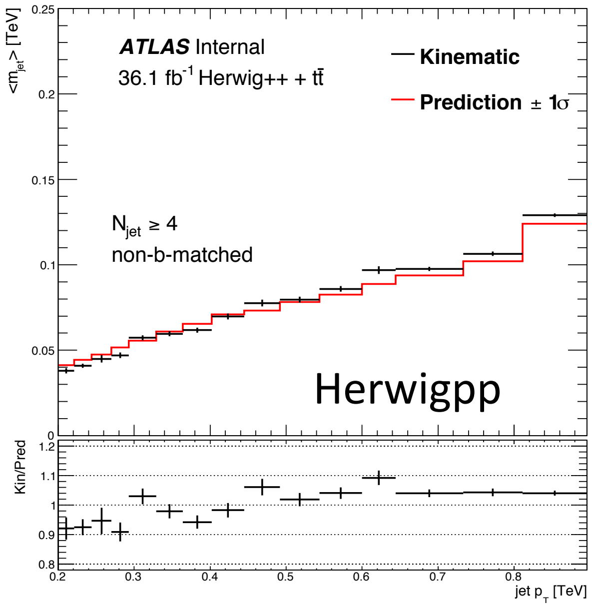


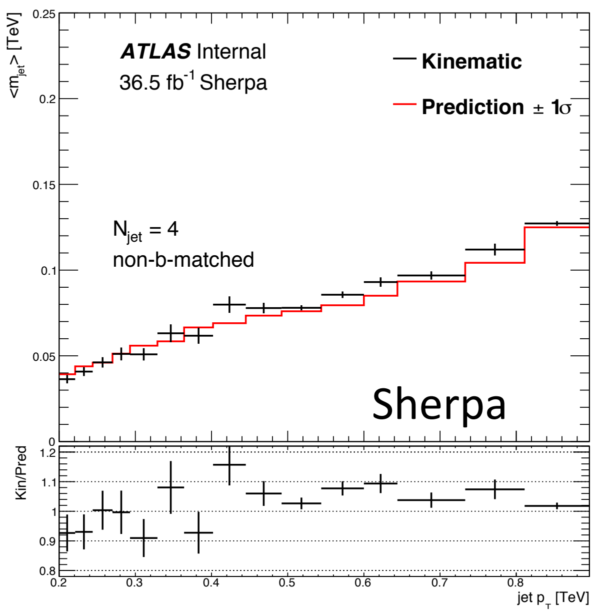




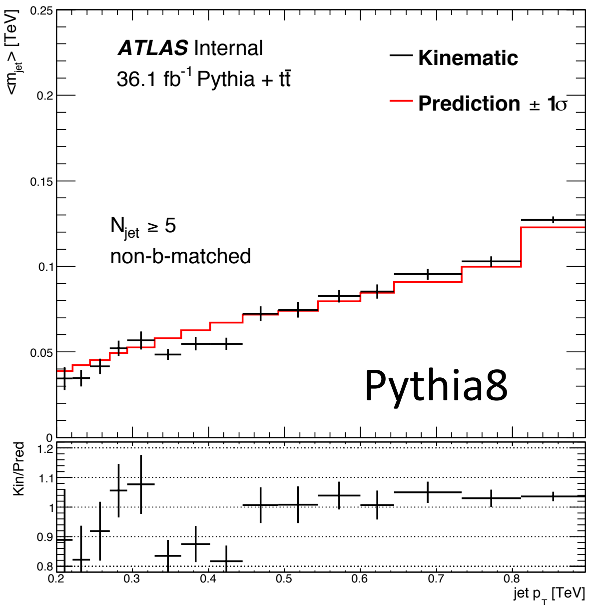
Jet mass response in >= 4jet

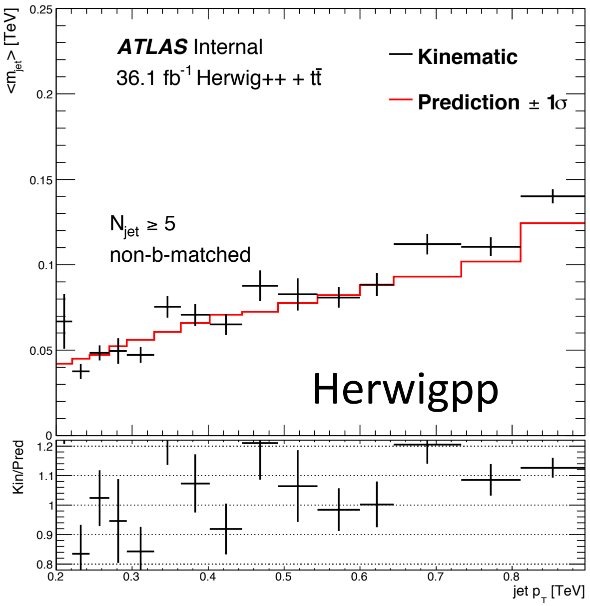


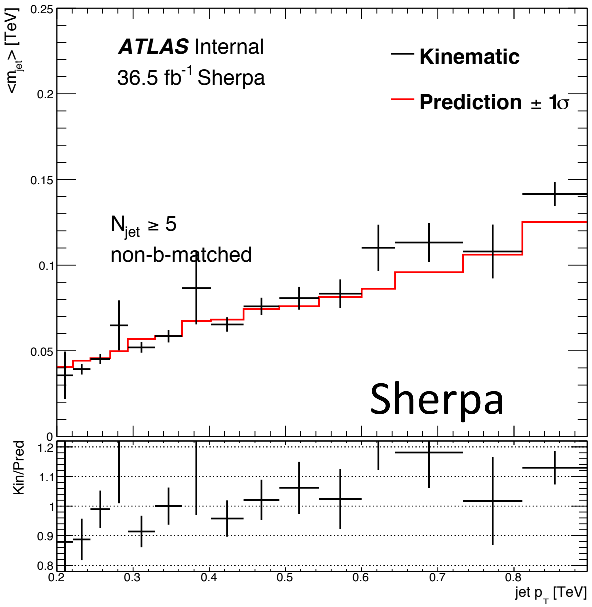




Jet mass response in >= 5jet







Observations in the UDR

	Low p_T (< 400 GeV)				Intermediate p_T (400, 600) GeV/			High p_T (> 600 GeV)		
	UDR1	UDR2	4j	5j	UDR1	4j	5j	UDR1	4j	5j
Data	Under	Over	n/a	n/a	Under	n/a	n/a	Under	n/a	n/a
Pythia8	Under	Over	Over	Over	Under	Under	Low stat	Under	Under	Under
Herwig pp	Under	Over	Over	Over	Under	Under	Low stat	Under	Under	Under
Sherpa	Under	Low stat.	Low stat.	Low stat.	Low stat	Under	Low stat	Over	Under	Under

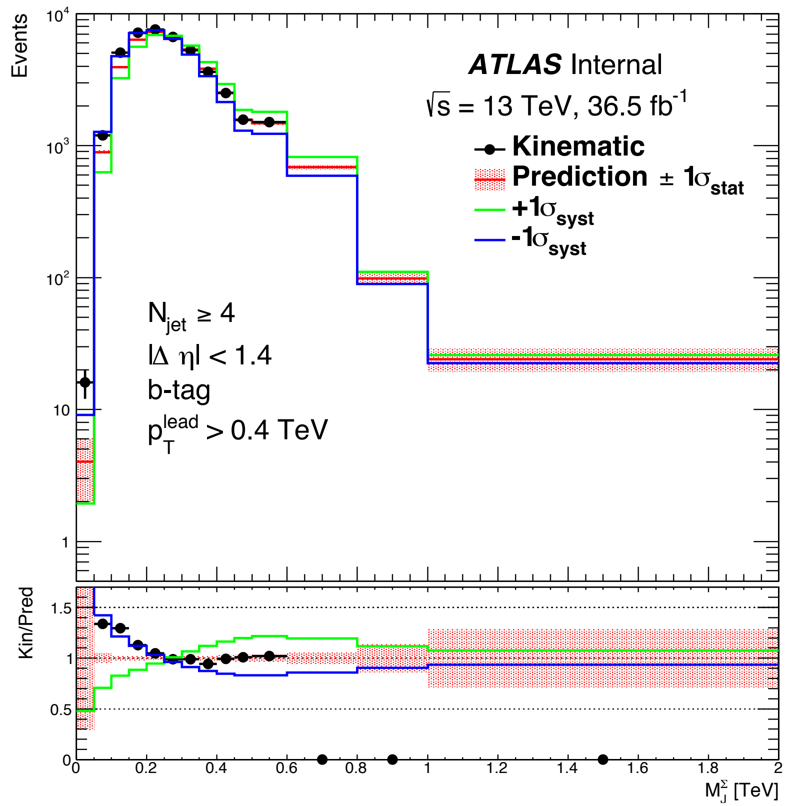
- Behaviors qualitatively consistent between data and three generators, with few exceptions
- Consistent behaviors between UDRs and 4j/5j regions
  - Except for low p_T, UDRs show opposite behavior

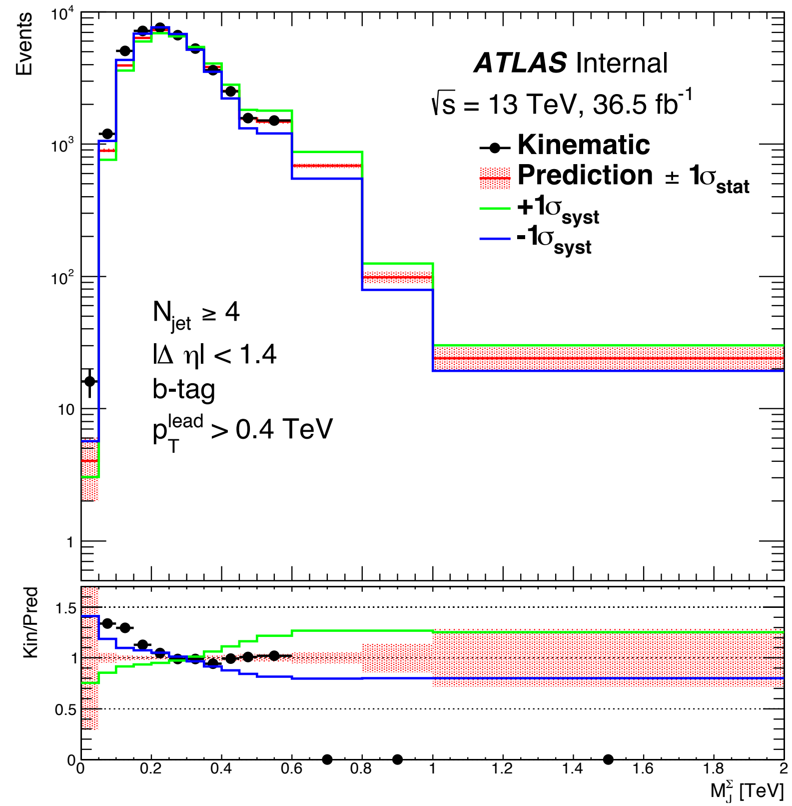
Observations in the UDR

	Low p_T (< 400 GeV)				Intermediate p_T (400, 600) GeV/			High p_T (> 600 GeV)		
	UDR1	UDR2	4j	5j	UDR1	4j	5j	UDR1	4j	5j
Data	Under	Over	n/a	n/a	Under	n/a	n/a	Under	n/a	n/a
Pythia8	Under	Over	Over	Over	Under	Under	Low stat	Under	Under	Under
Herwig pp	Under	Over	Over	Over	Under	Under	Low stat	Under	Under	Under
Sherpa	Under	Low stat.	Low stat.	Low stat.	Low stat	Under	Low stat	Over	Under	Under

- Low and high p_T: RMS of discrepancies taken as uncertainty
- Low p_T: the larger one from the UDRs is used;
- Intermediate p_T: the largest taken as the uncertainty
- Intermediate p_T and high p_T correlated, referred to as high p_T
- Low p_T not correlated with the other two

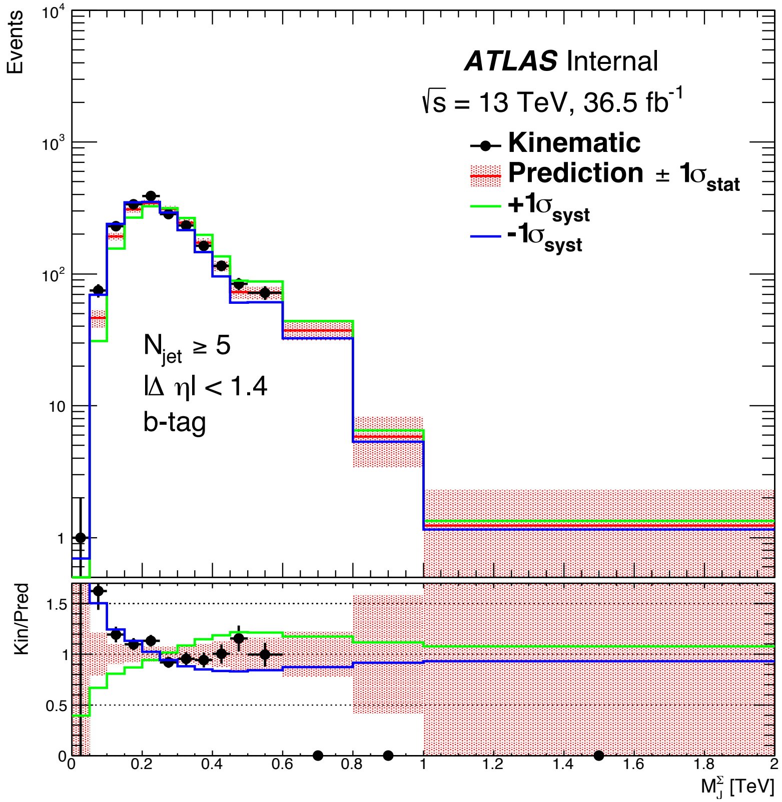
Prediction of M_J^Σ (4jSRb)

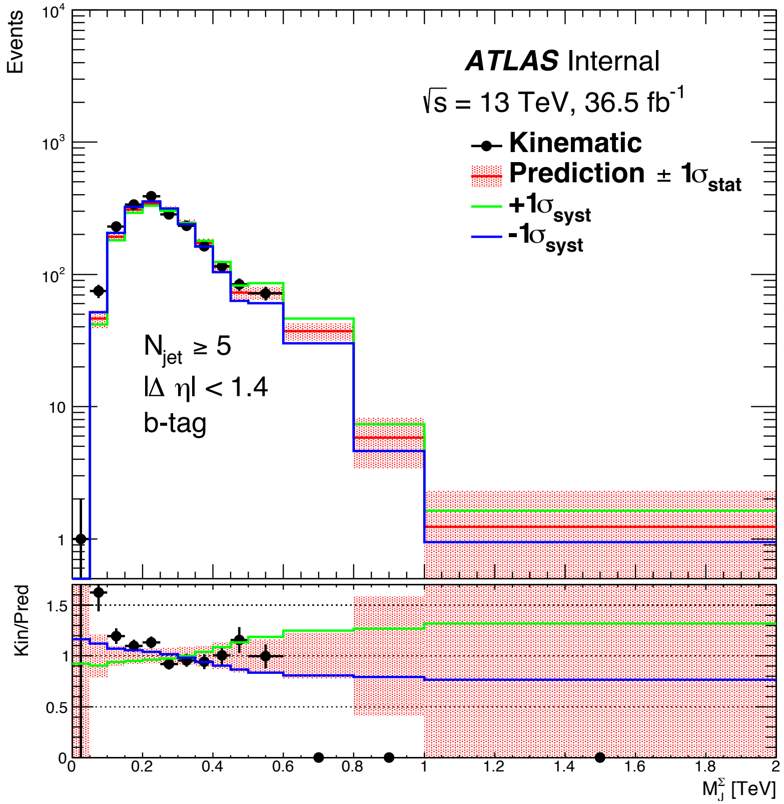




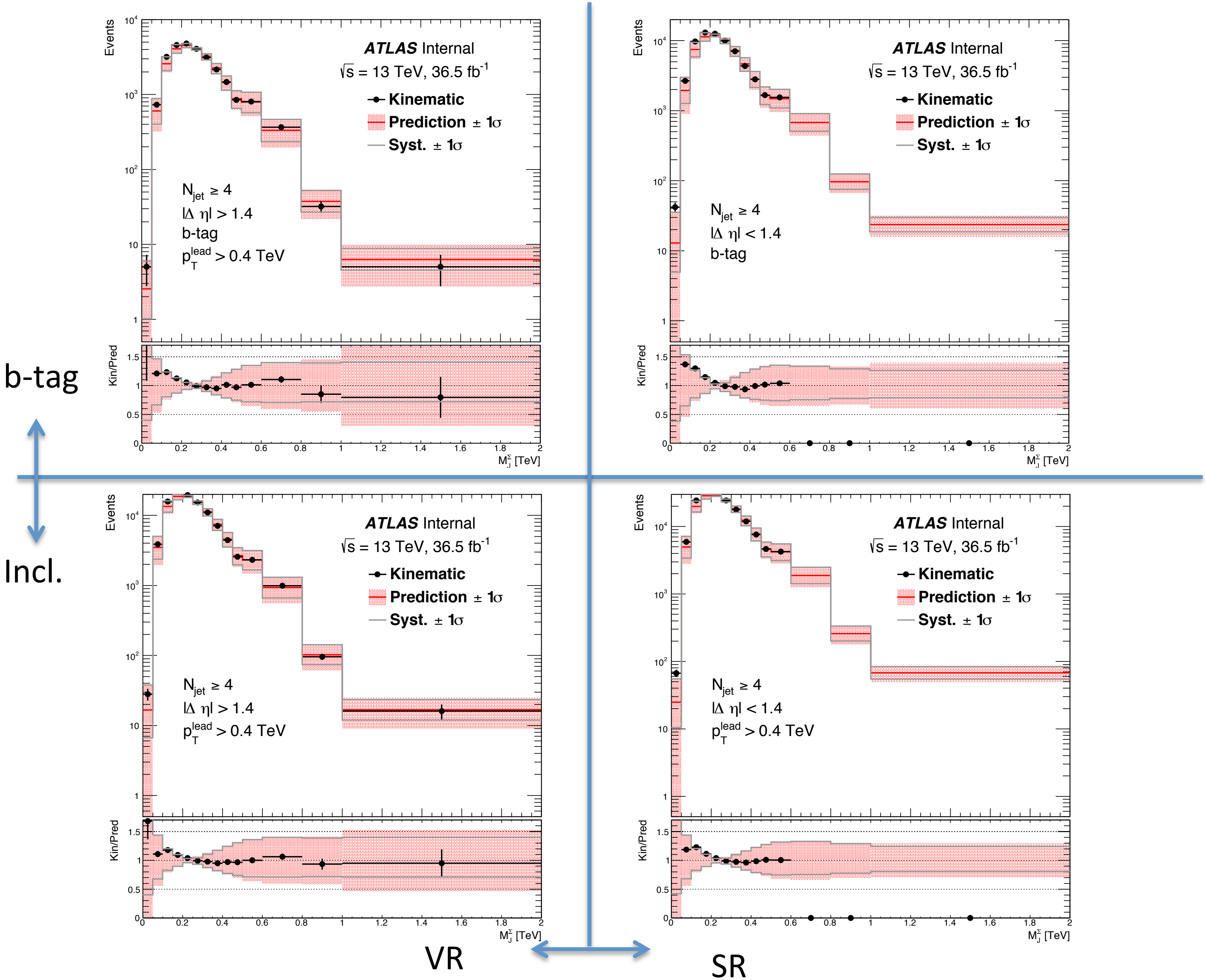
- $M_J^\Sigma > 0.6$ TeV blinded
- Left: +/- 1 sigma variation of low p_T uncertainty
- Right: +/- 1 sigma variation of correlated intermediate and high p_T uncertainty

Prediction of M_J^{Σ} (5jSRb)

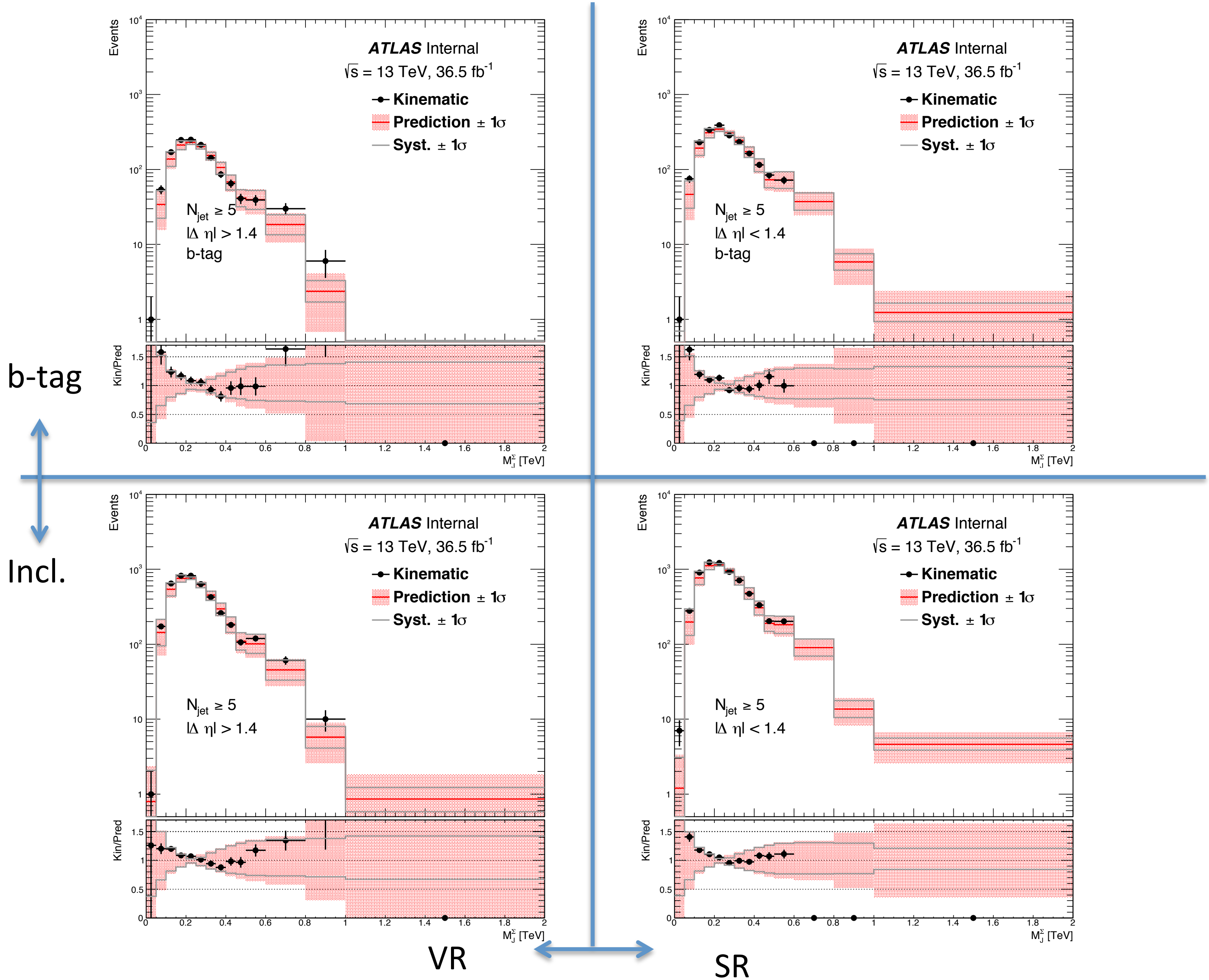




Prediction of M_J^{Σ} (4j regions)



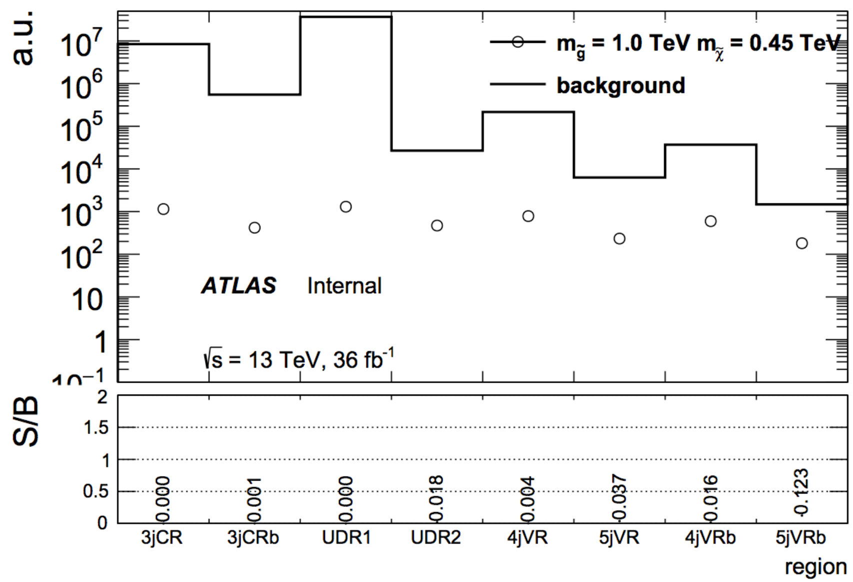
Prediction of M_J^Σ (5j regions)

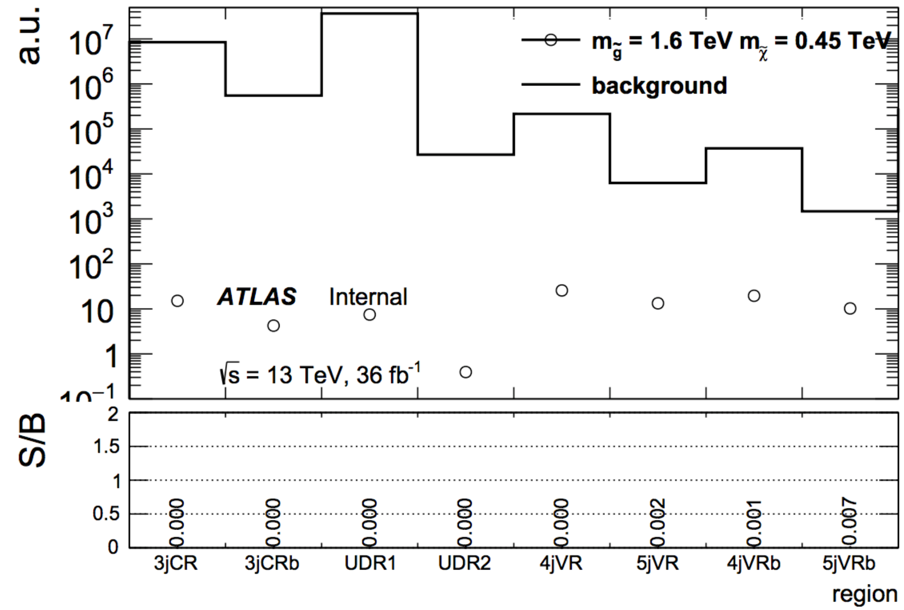


Signal contamination

Impact on systematic uncertainty?
Impact on predicted background yield?

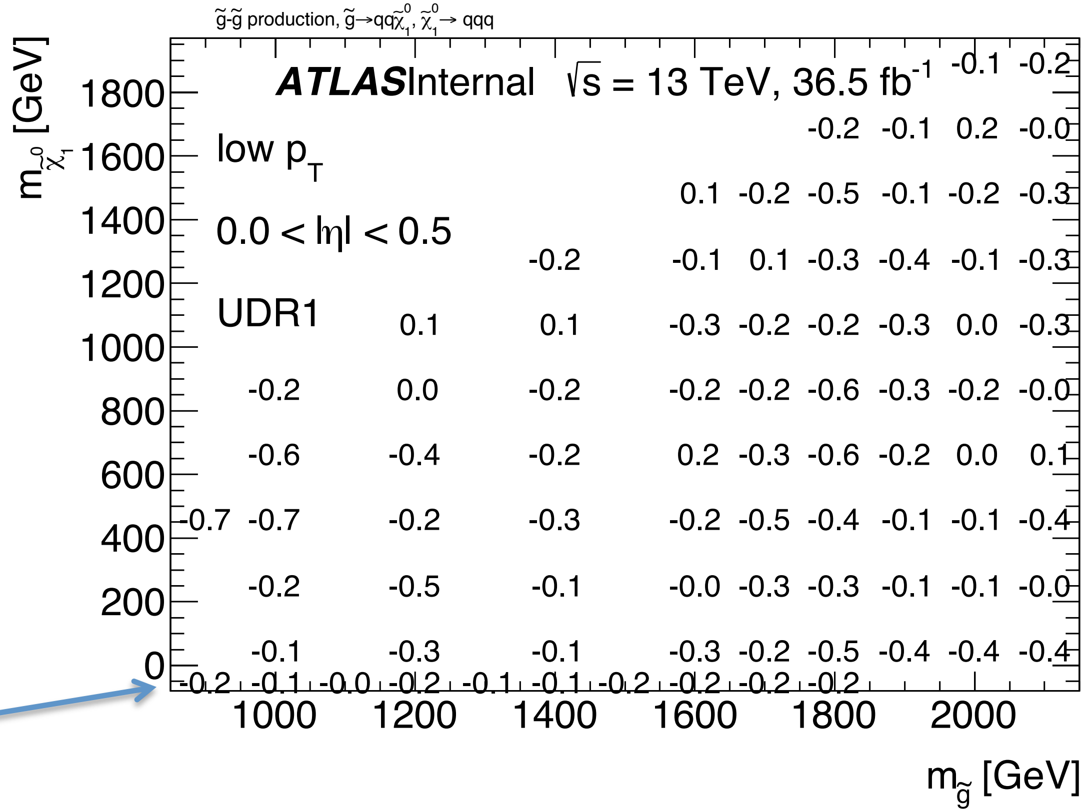
Signal contamination





Signal over background ratios in various regions
Left: signal point right below Run-1 exclusion
Right: signal point right beyond 2016 CONF NOTE exclusion

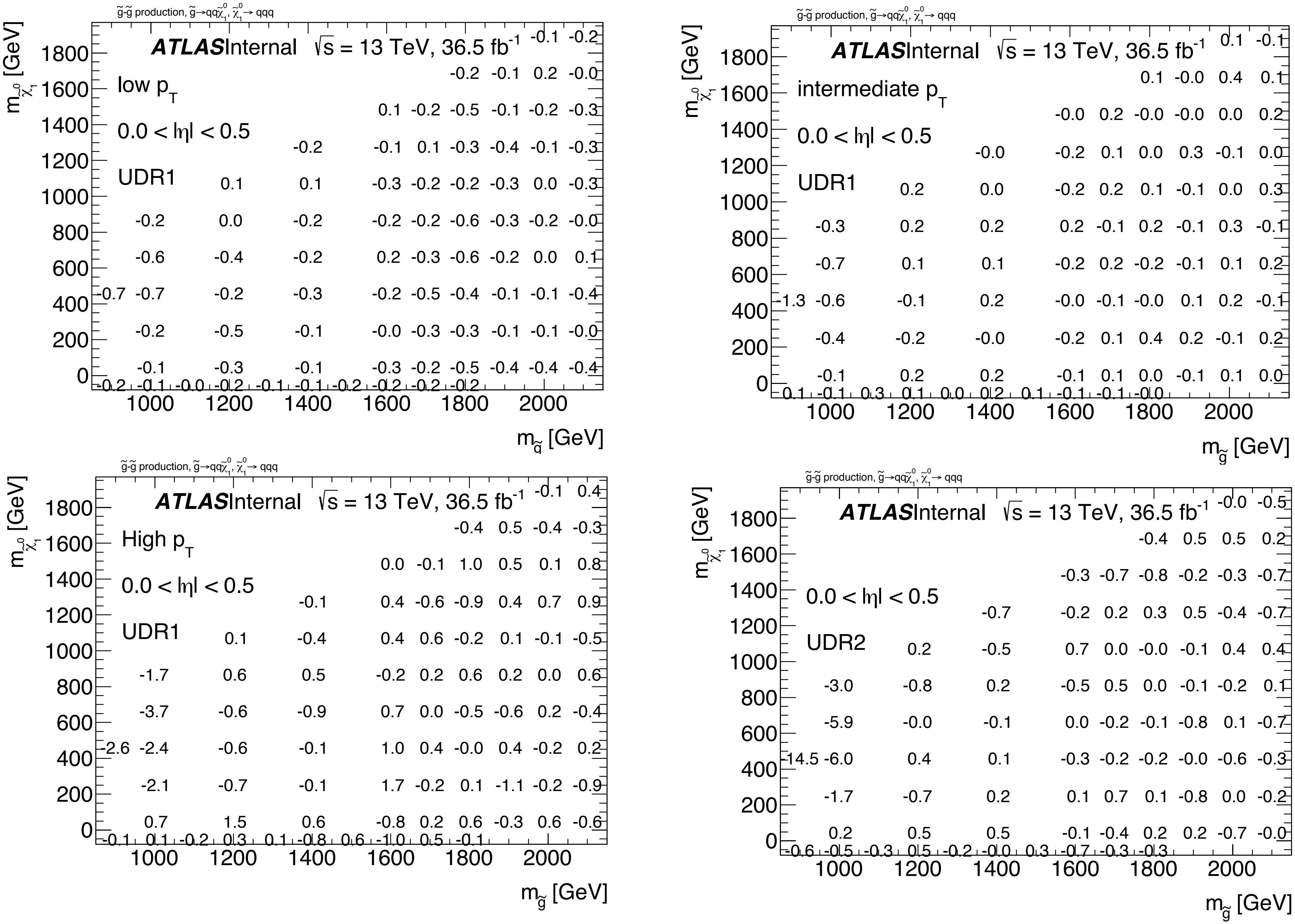
Impact on the jet mass prediction uncertainty



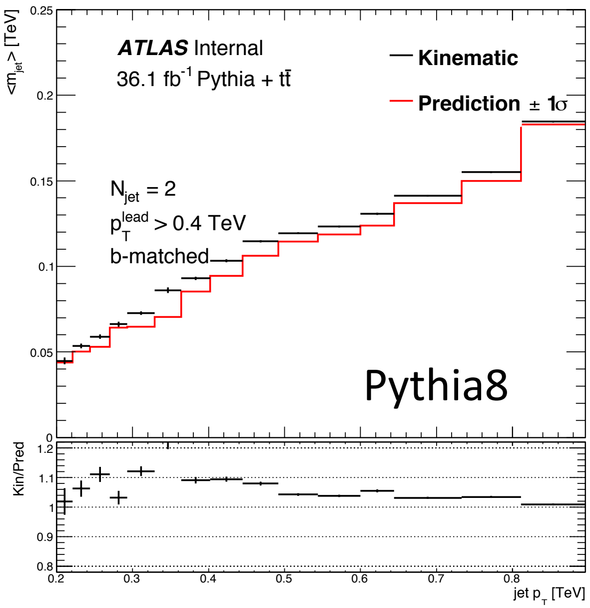
RPV 6

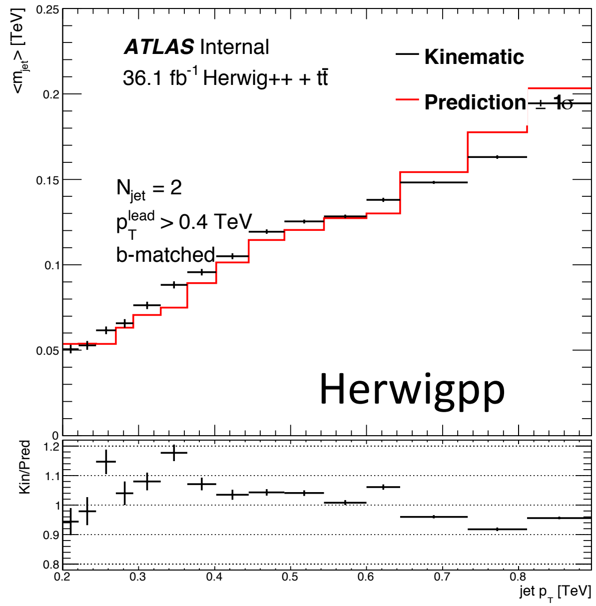
- Signal injected to data sample and uncertainties reevaluated
- Percentage change shown for low p_T in UDR1
  - ~ 0.3% change of a ~10% level uncertainty -> 0.03% change in the absolute value. Negligible!

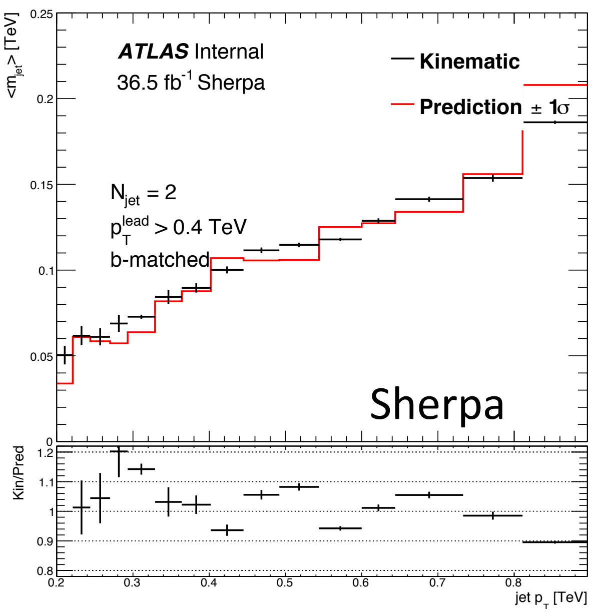
Impact on the jet mass prediction uncertainty

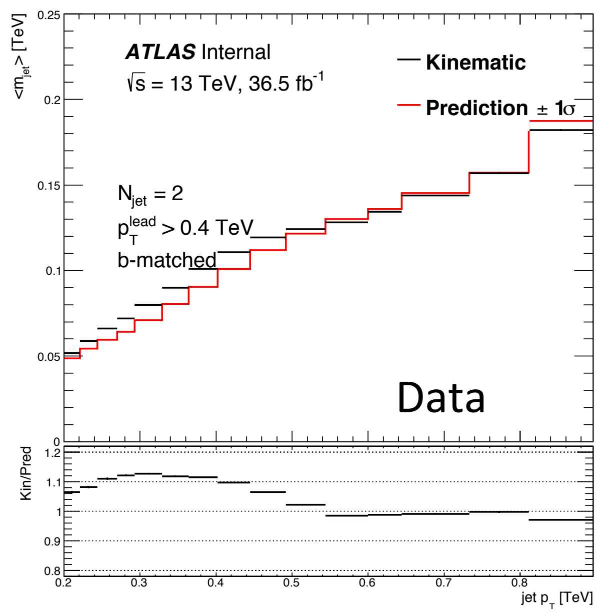


Jet mass response in the UDR1

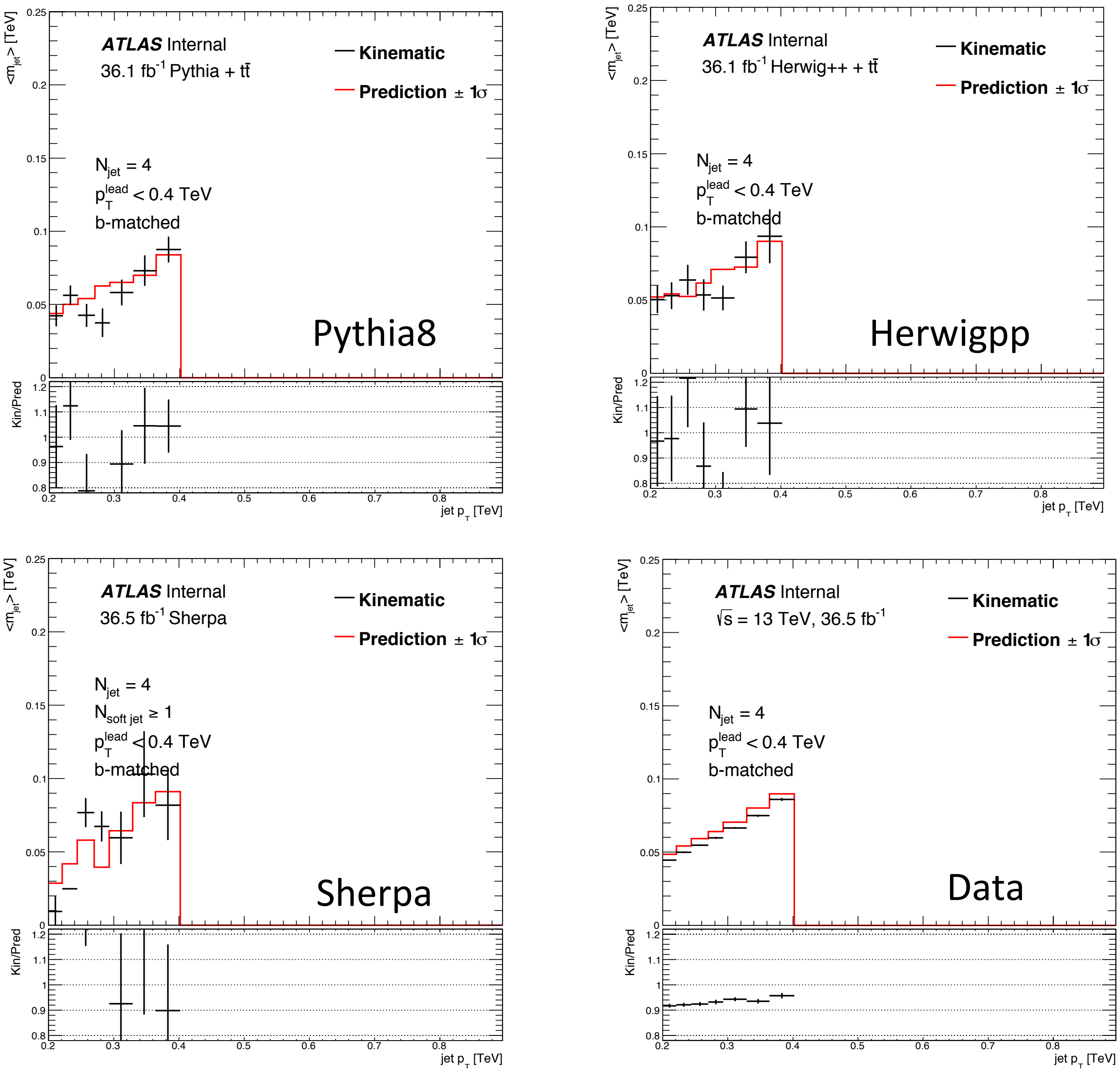






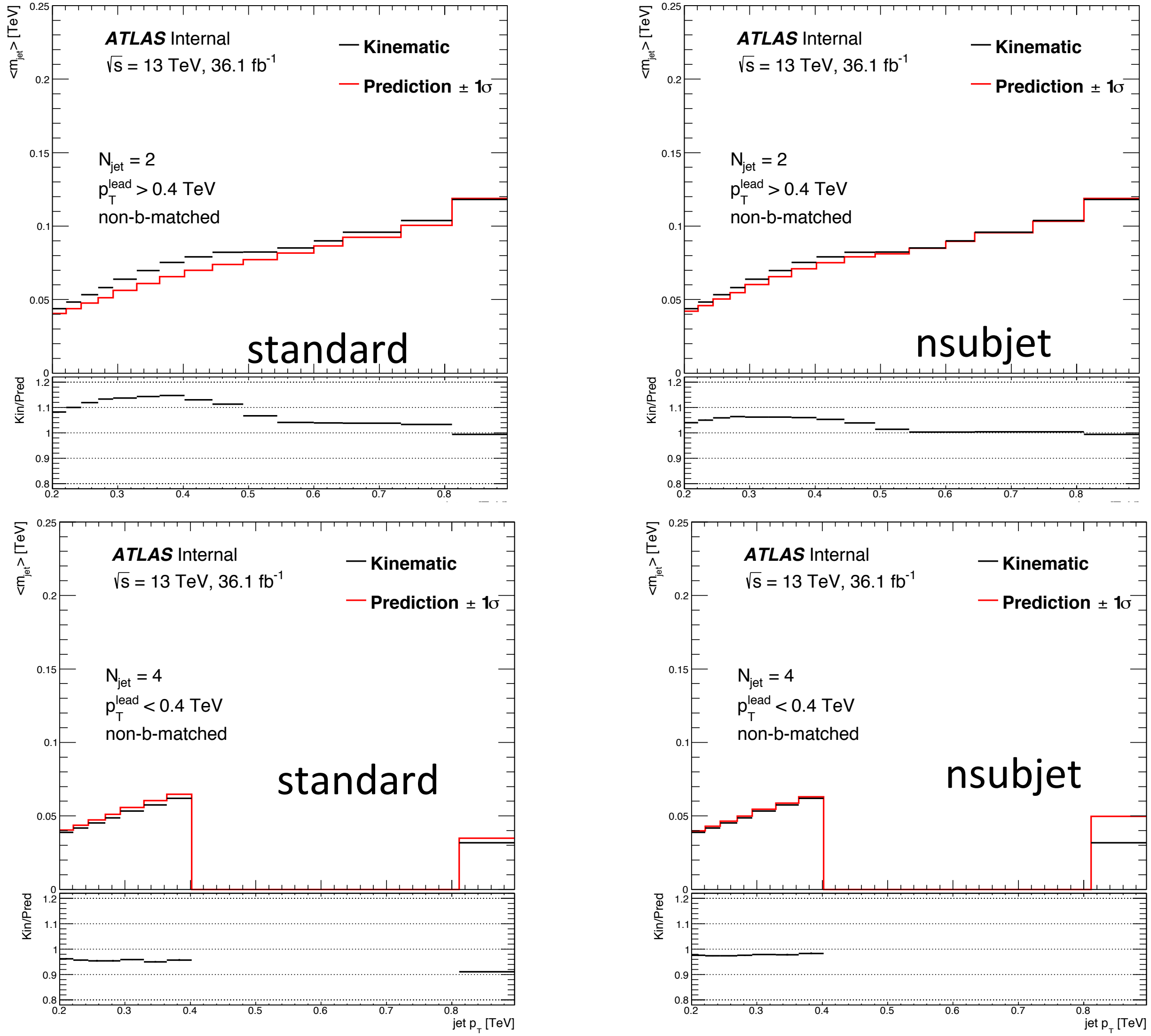


Jet mass response in the UDR2



Check

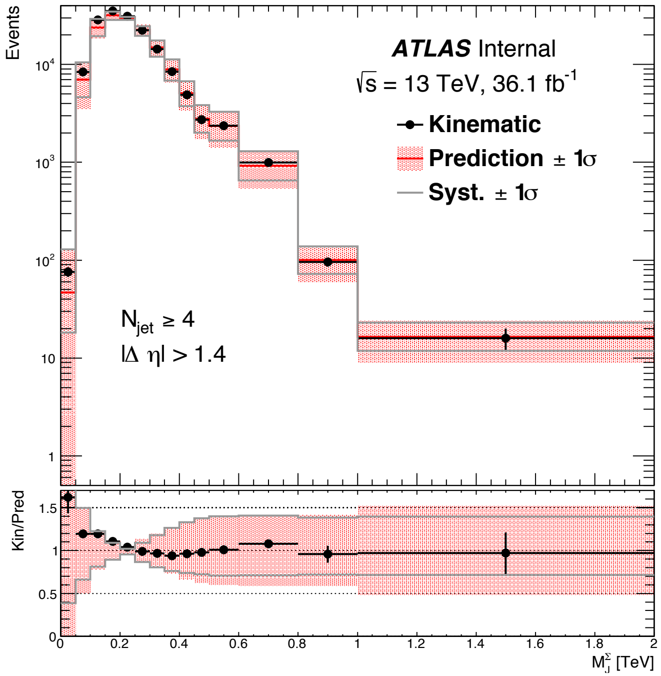
- Bin jets using number of subjets, known to give better prediction, but subject to significant signal contamination

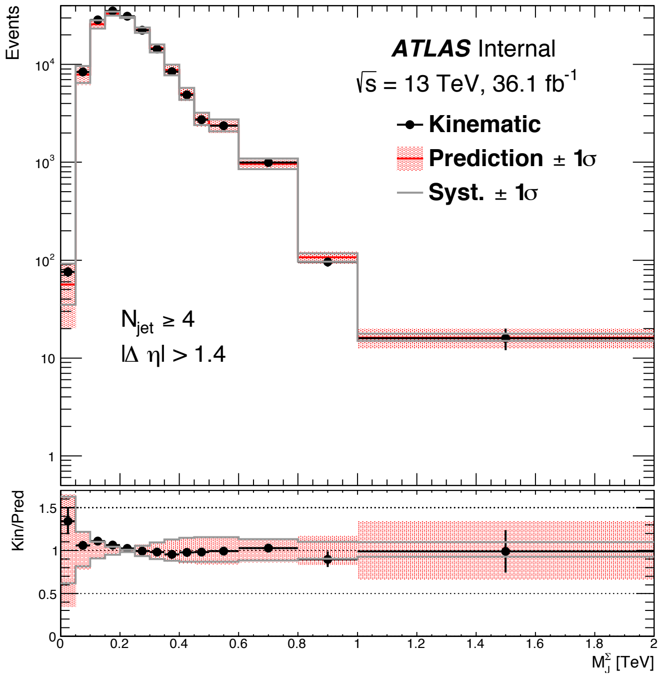


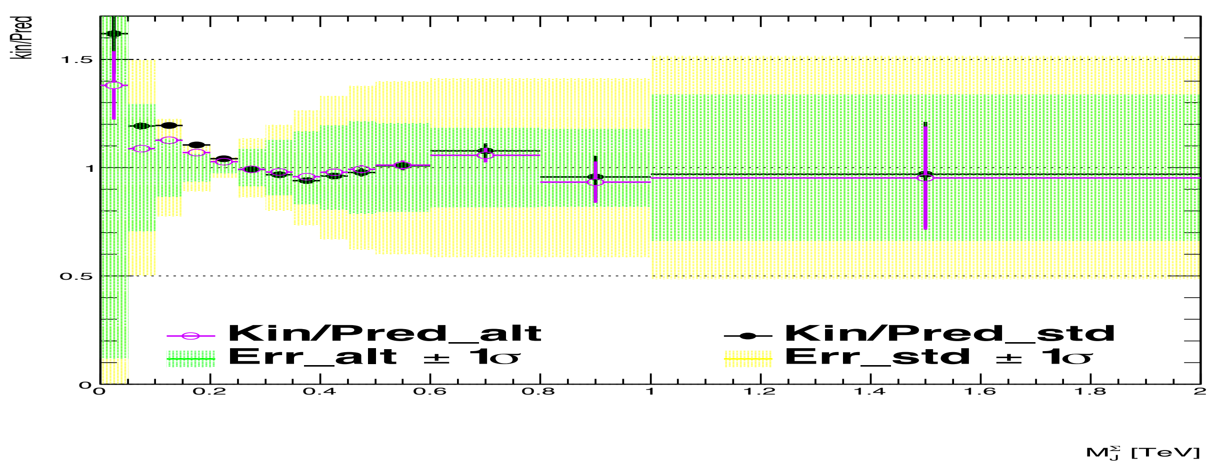
Goal: Show discrepancies in UDRs predicative of discrepancies in the 4j/5j regions

Smaller discrepancies seen in the UDRs

Check

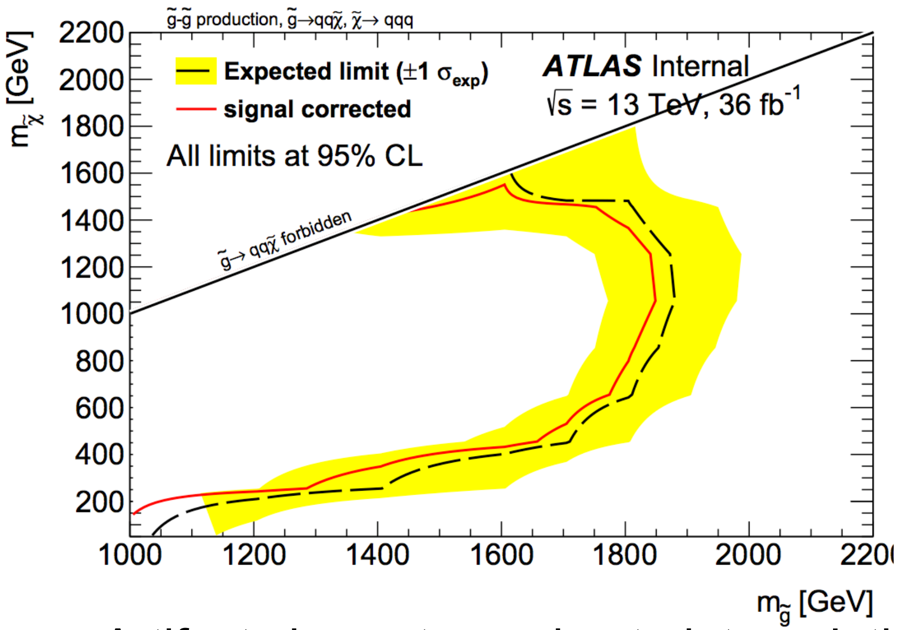


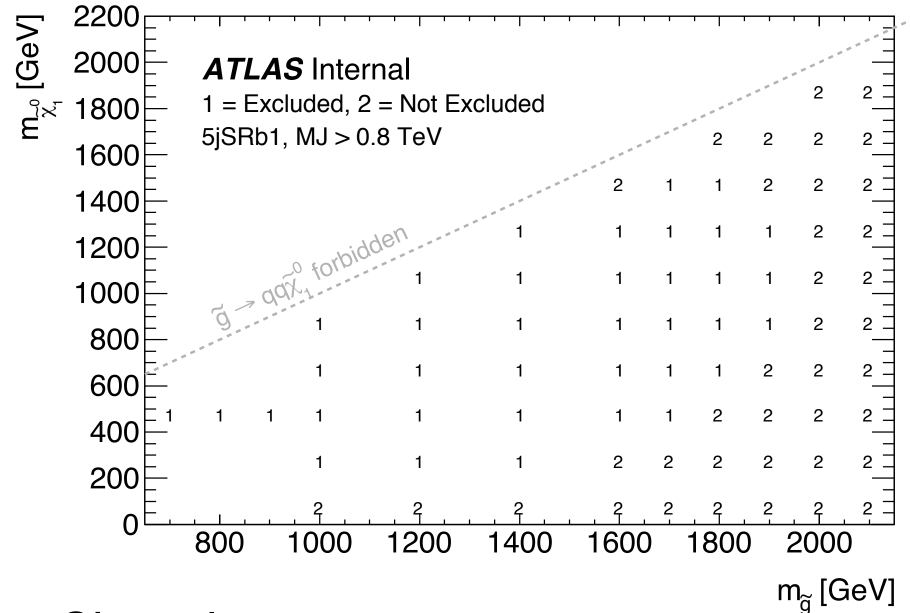




Smaller discrepancies seen in M_J^{Σ} distribution

Expected limit



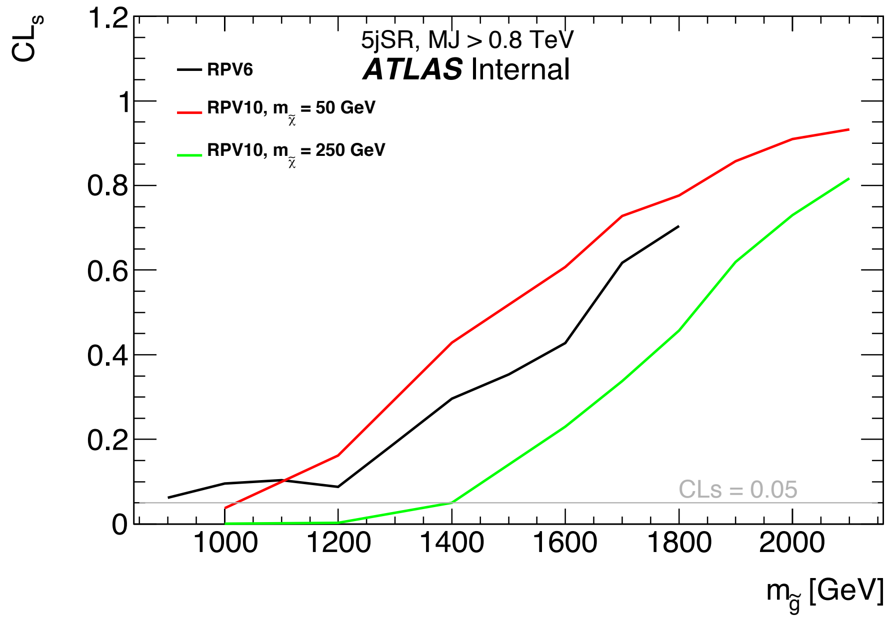


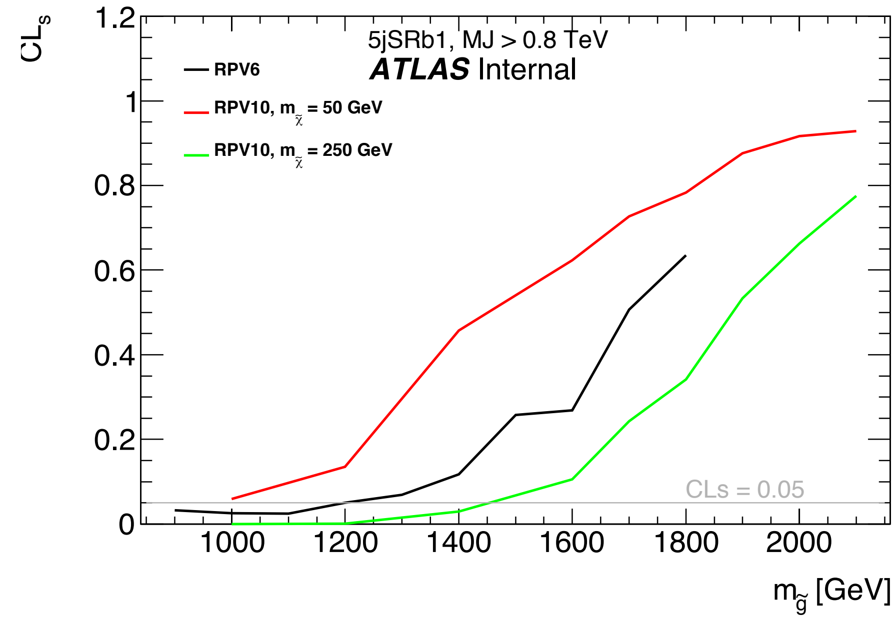
Artifacts in contours due to interpolating CLs values

Left: interpolated expected limit contours; effect of correcting signal contamination shown
Right: expected limit, not interpolated, shown for signal points where samples exist

5jSRb with M_J^{Σ} > 0.8 TeV most sensitive, except for low m_{χ} (= 50 GeV)

Expected limit m_χ (= 50 GeV) and RPV6

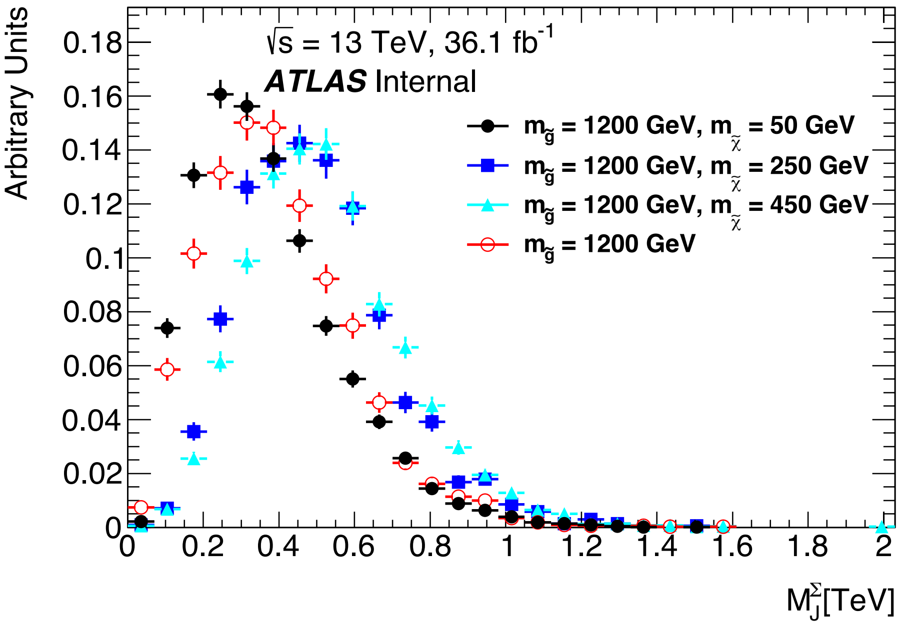


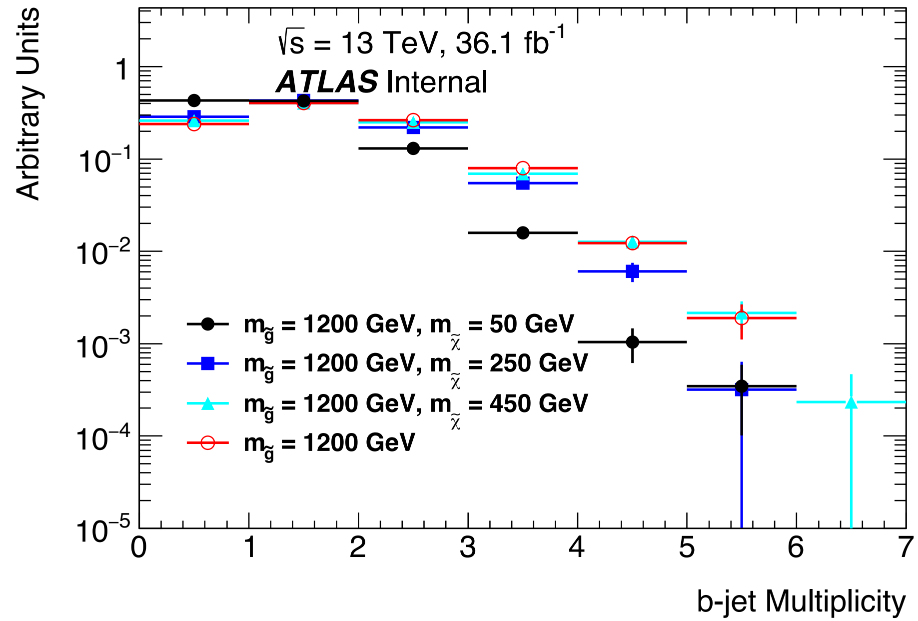


5jSRb with M_J^Σ > 0.8 TeV most sensitive for RPV 6, expected limit at m_g ~ 1200 GeV

5jSR with M_J^Σ > 0.8 TeV most sensitive for RPV 10, m_χ (= 50 GeV) expected limit slightly beyond m_g ~ 1000 GeV

Compare signal shapes at the same gluino mass





For $m_{\chi} < m_{top}$, the RPV decay final states with a top quark are turned off

- Lower M_J^{Σ} for m_{χ} = 50 GeV
- Lower b-jet multiplicity (0 b/t-quark event goes up from 4% to 11%; rate of 0 b-jet event consistent with expectation)

Expected significance (with the best M_J^{Σ} cut)