Electroweak Supersymmetry with Recursive Jigsaw Reconstruction

EARLY CAREER WORKSHOP

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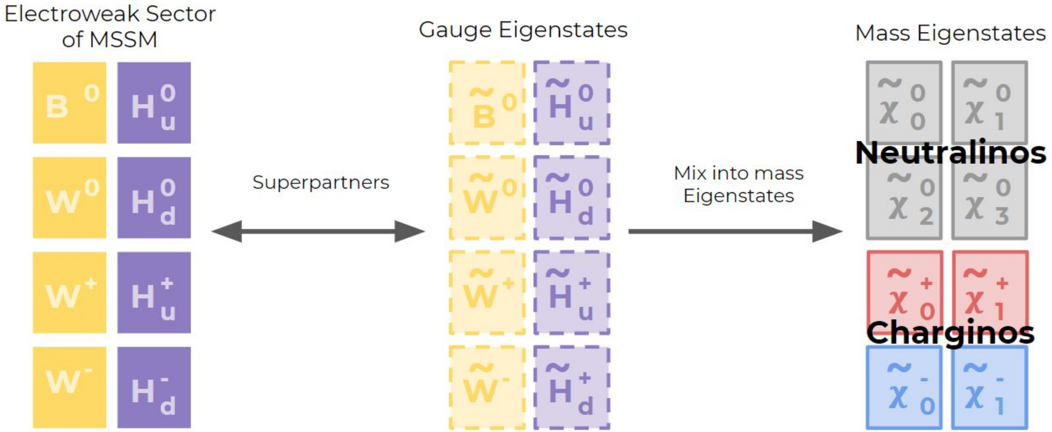
The Basics

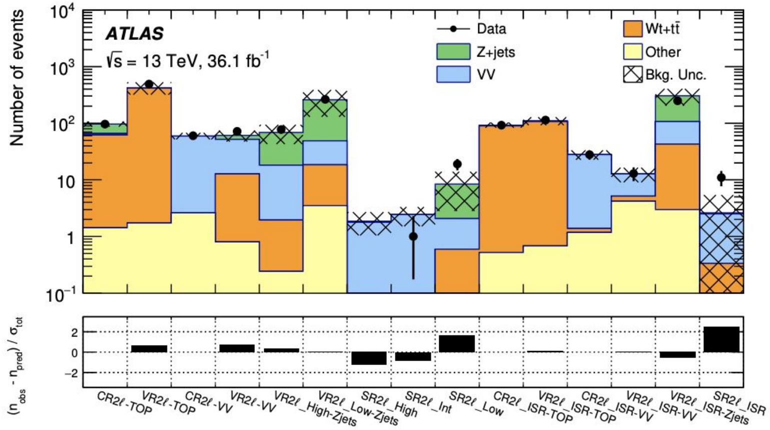
- Supersymmetry (SUSY) postulates there are (at least one) superpartner for all Standard Model particles
- Electroweak SUSY refers to the superpartners of the electroweak gauge boson (EWKinos) and sleptons
- The EWKinos mix to form mass eigenstates - **Charginos and Neutralinos**
- In some situations electroweak production has higher cross sections and cleaner signatures than strong production - we should look there too!

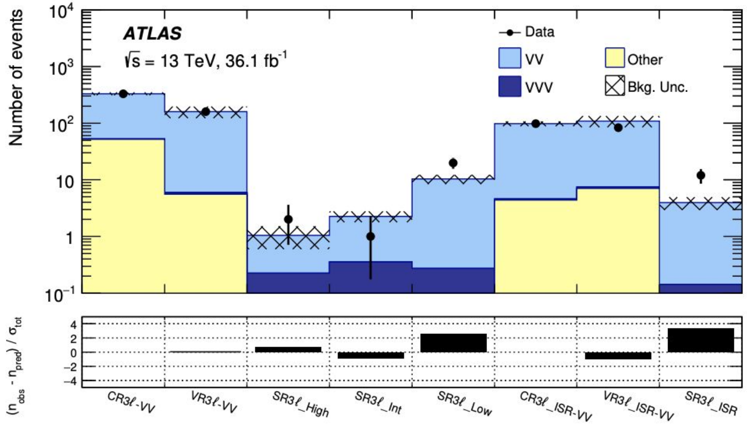


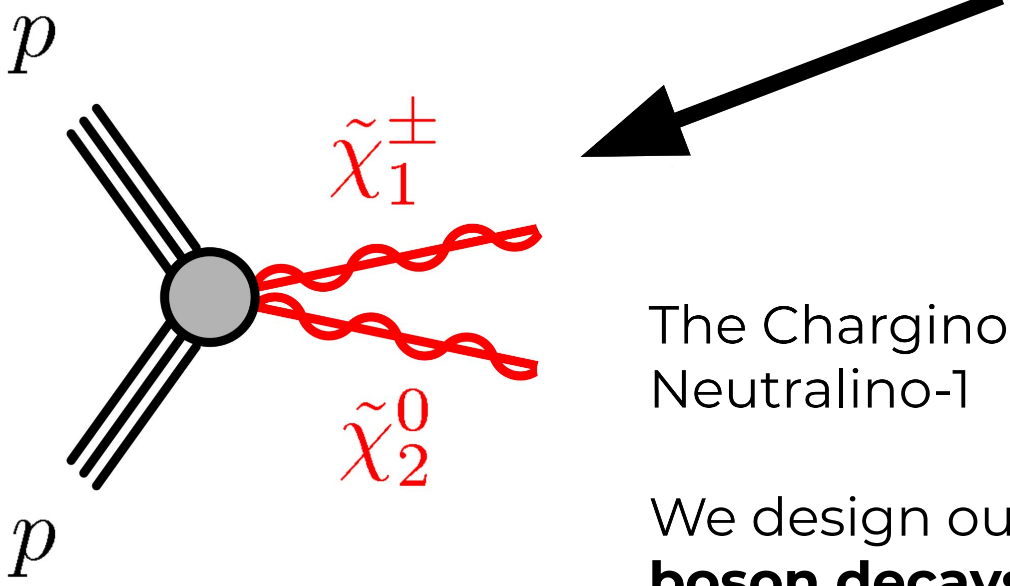
Neutralinos under certain conditions are **Dark Matter Candidates!**

Motivation

- In 2015-2016 an analysis targeting electroweak SUSY in 2 and 3 lepton final states found excesses in 4 orthogonal regions
  - **SR2L_LOW**
  - **SR2L_ISR**
  - **SR3L_LOW**
  - **SR3L_ISR**
- The analysis was frozen and a follow-up was issued



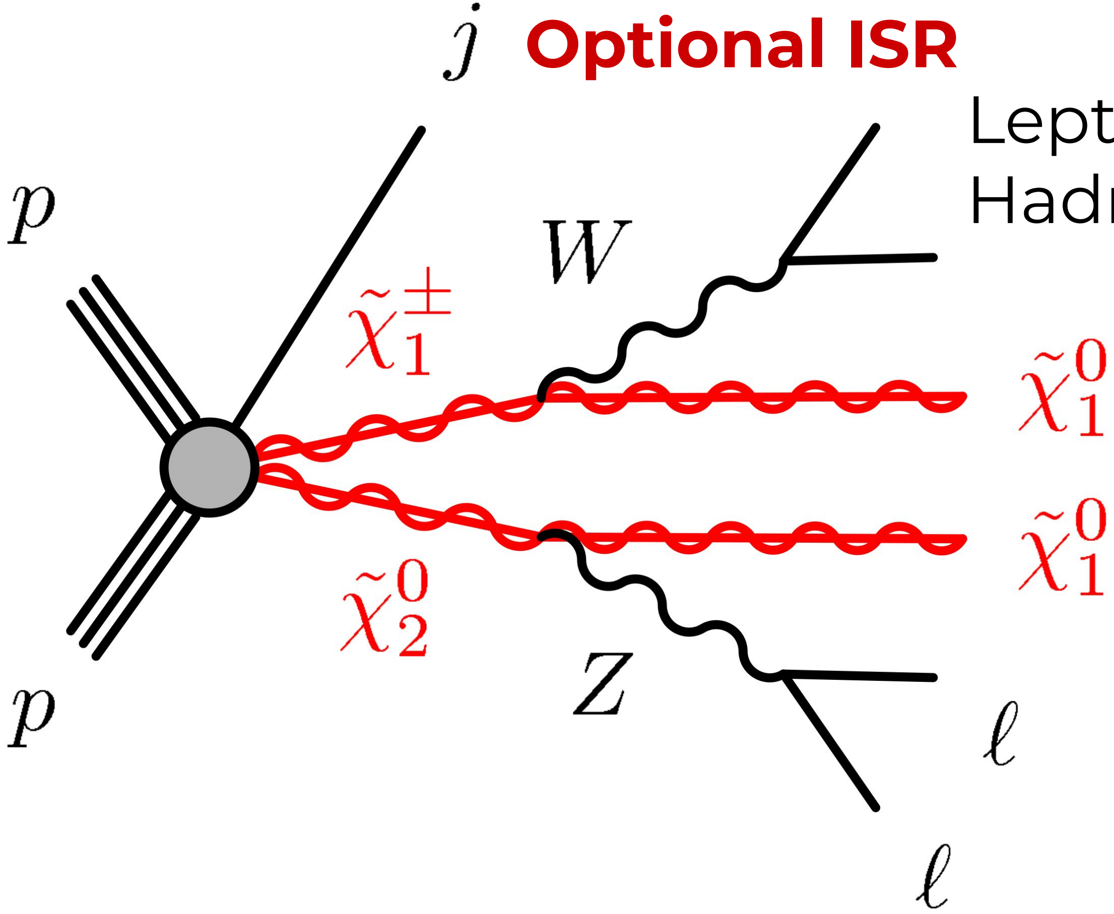




Targeting a mass degenerate Wino-like Chargino-1 & Bino-like Neutralino-2 production

The Chargino decays to a W boson and Neutralino-1

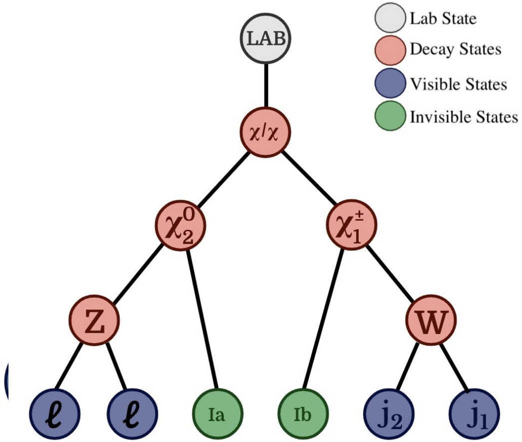
We design our analysis around the **W boson decays**



Leptonically - 3 lepton
Hadronically - 2 lepton

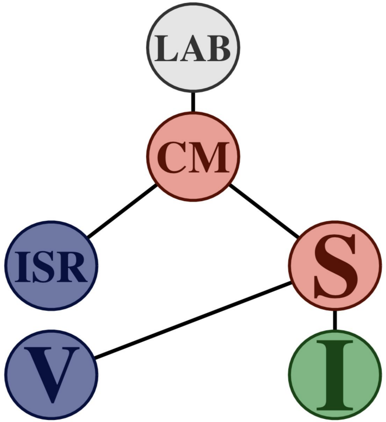
The two approaches we take

Standard decay tree

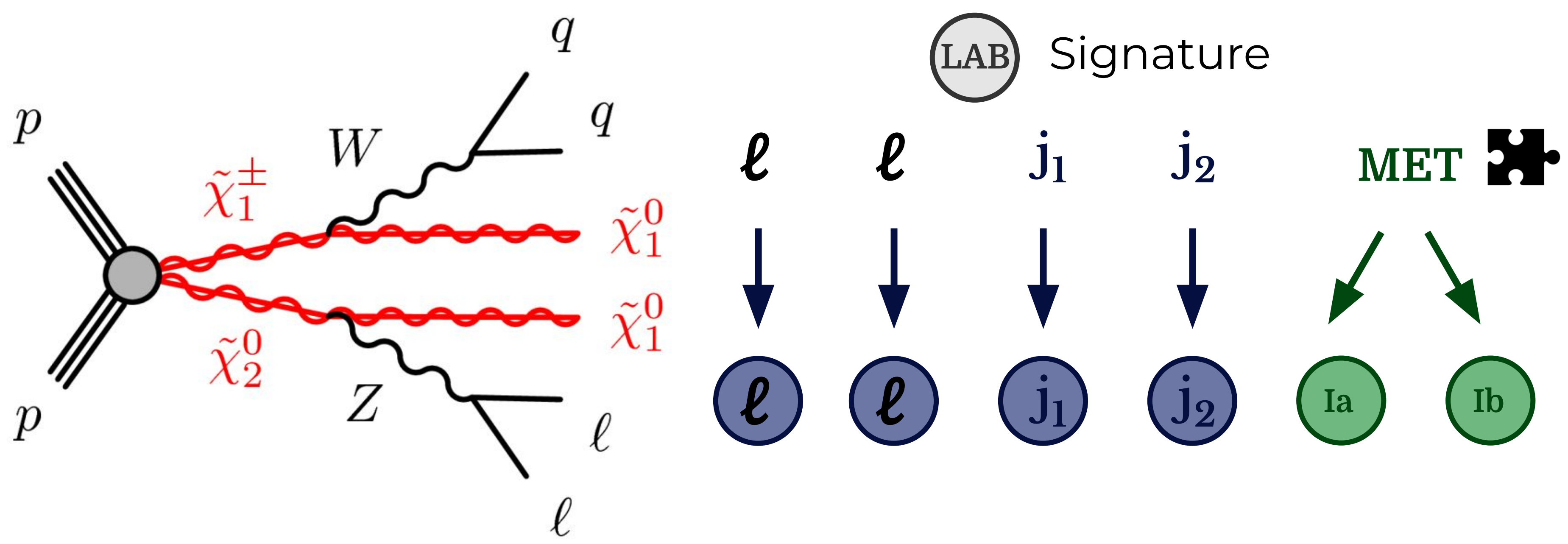


SR2L_LOW & SR3L_LOW

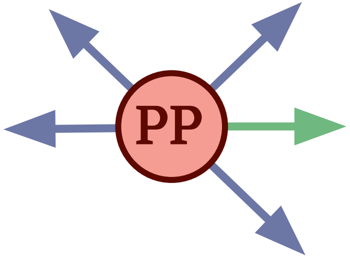
ISR decay tree



SR2L_ISR & SR3L_ISR

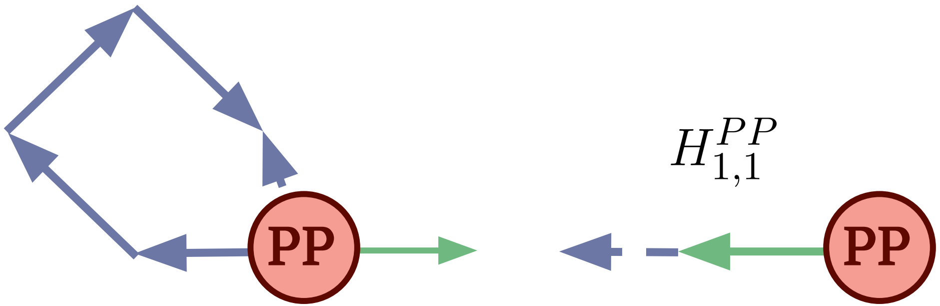

p
p
$\tilde{\chi}_1^{\pm}$
$\tilde{\chi}_2^0$
W
Z
q
q
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
ℓ
ℓ
LAB
Signature
ℓ
ℓ
j1
j2
MET
ℓ
ℓ
j1
j2
Ia
Ib

An **event** defined in the PP **frame**

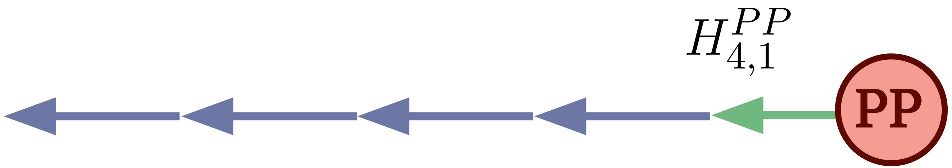


Arrows are object's four vectors in the PP frame

Vector Sum of Visibles + Invisibles



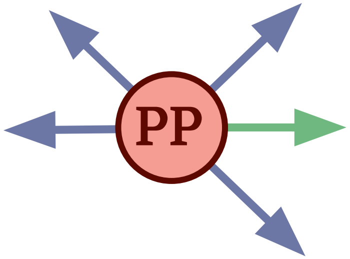
Scalar Sum of Visibles + Invisibles



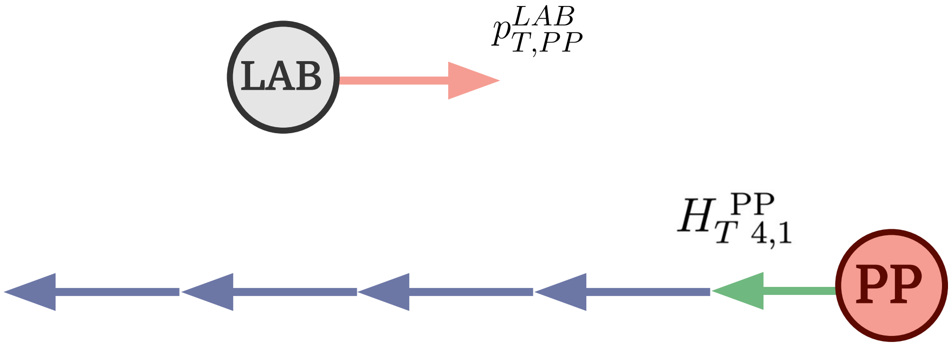
We take **ratios** of these quantities

PP frame drift - R_{PT}

An **event** defined in the PP **frame**



Arrows are object's four vectors in the PP frame

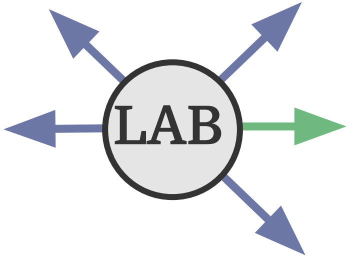


Momentum proportion of PP frame

$$R_{P_T} = \frac{p_{T,\mathrm{PP}}^{\mathrm{LAB}}}{p_{T,\mathrm{PP}}^{\mathrm{LAB}} + H_{T\ 4,1}^{\mathrm{PP}}}$$

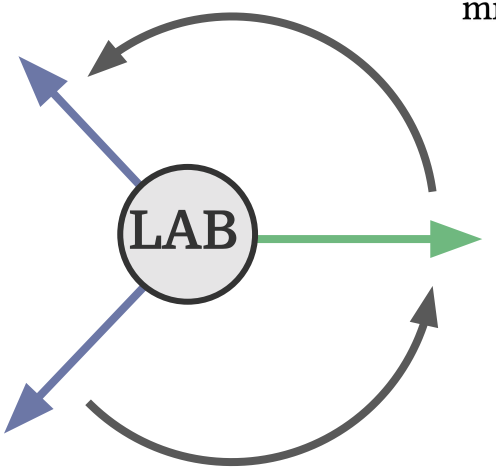
Smaller = better reconstruction

An **event** defined in the LAB **frame**



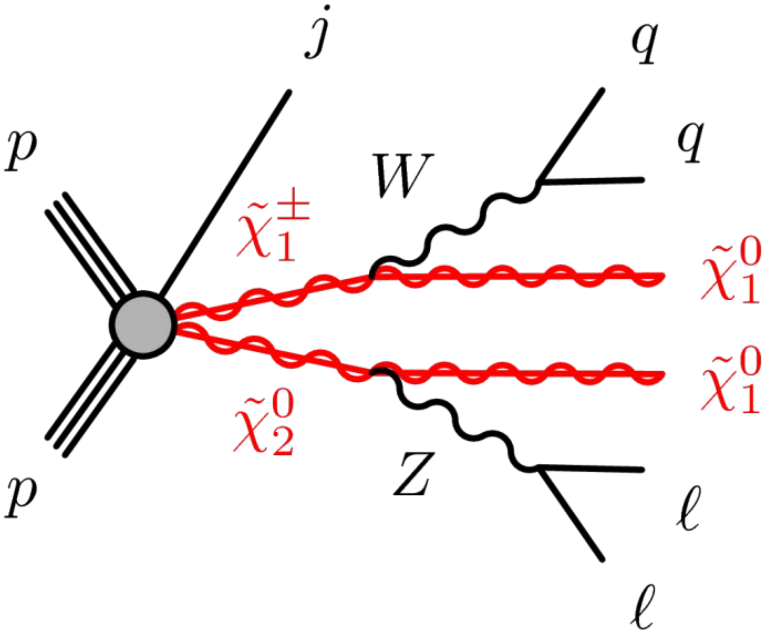
Arrows are object's four vectors in the LAB frame

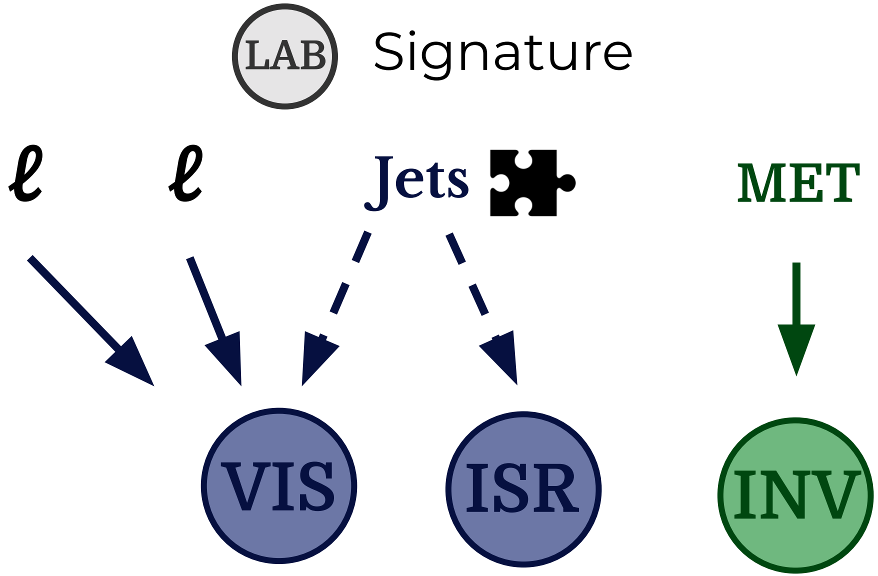
We do not want **jets** to be in the direction of **MET**



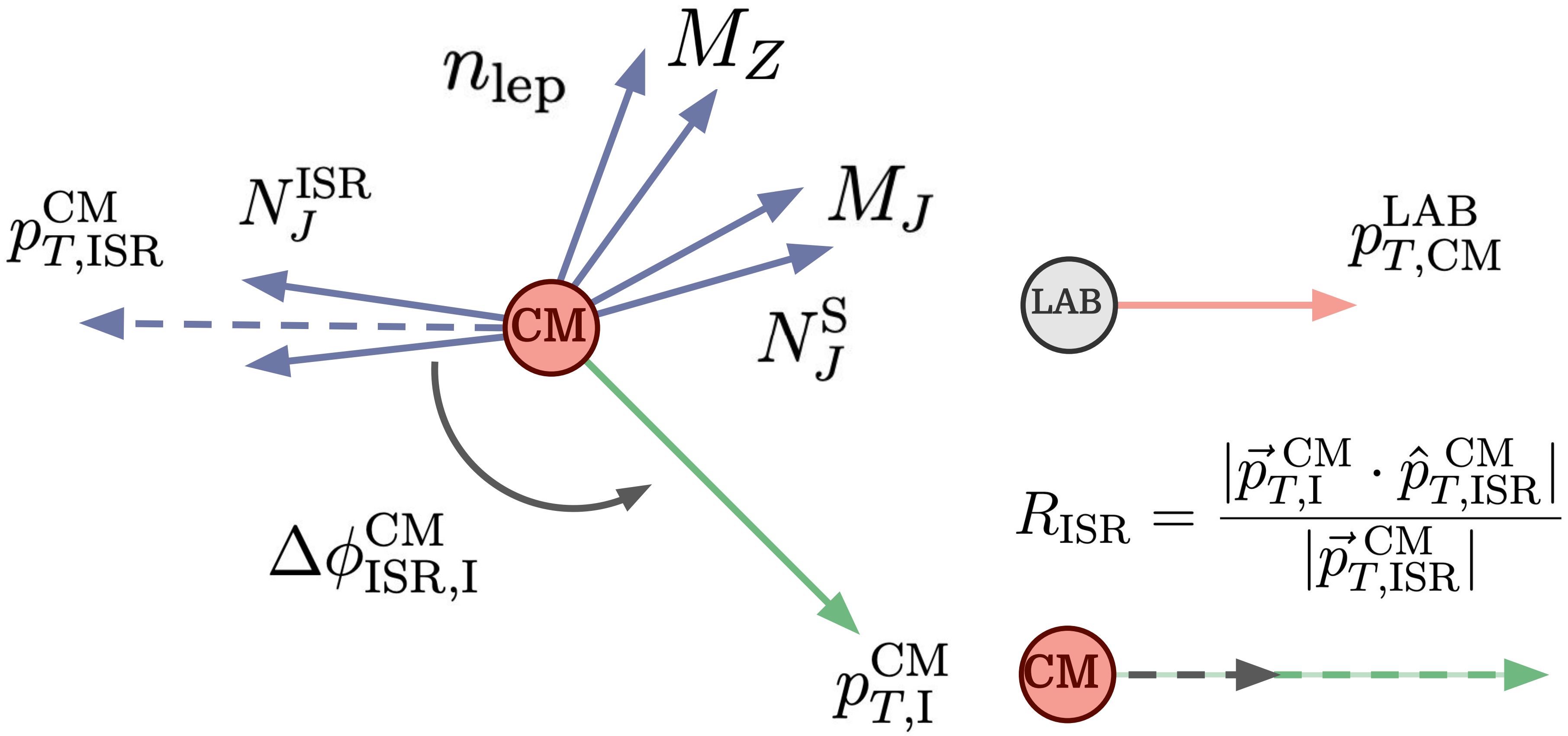
$$\min\Delta\phi(j_1/j_2, \vec{P}_{\mathrm{T}}^{\mathrm{miss}}) > 2.4$$

(Not RJ, but we use it)





Transverse Components Only


n_{lep}
M_Z
N_J^{ISR}
$p_{T,\mathrm{ISR}}^{\mathrm{CM}}$
M_J
N_J^{S}
CM
$p_{T,\mathrm{CM}}^{\mathrm{LAB}}$
LAB
$\Delta\phi_{\mathrm{ISR,I}}^{\mathrm{CM}}$
$R_{\mathrm{ISR}} = \frac{|\vec{p}_{T,\mathrm{I}}^{\,\mathrm{CM}} \cdot \hat{p}_{T,\mathrm{ISR}}^{\mathrm{CM}}|}{|\vec{p}_{T,\mathrm{ISR}}^{\,\mathrm{CM}}|}$
$p_{T,\mathrm{I}}^{\mathrm{CM}}$
CM

Our Analysis Approach

The goal for signal region design is **Signal/Background**

2L

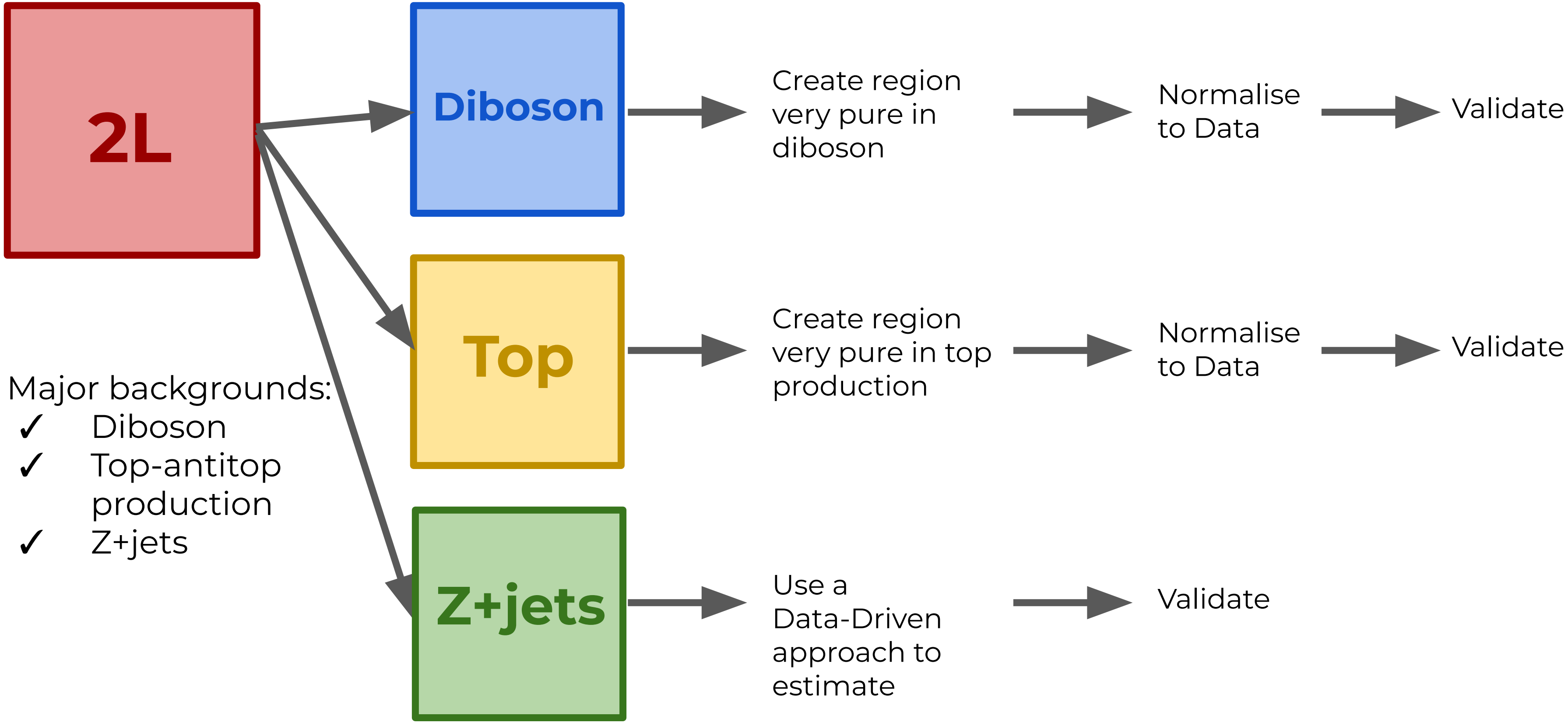
Major backgrounds:
- ✓ Diboson
- ✓ Top-antitop production
- ✓ Z+jets

3L

Major backgrounds:
- ✓ Diboson

For both **Standard** and **ISR** regions

Our 2L background estimation strategy



Major backgrounds:

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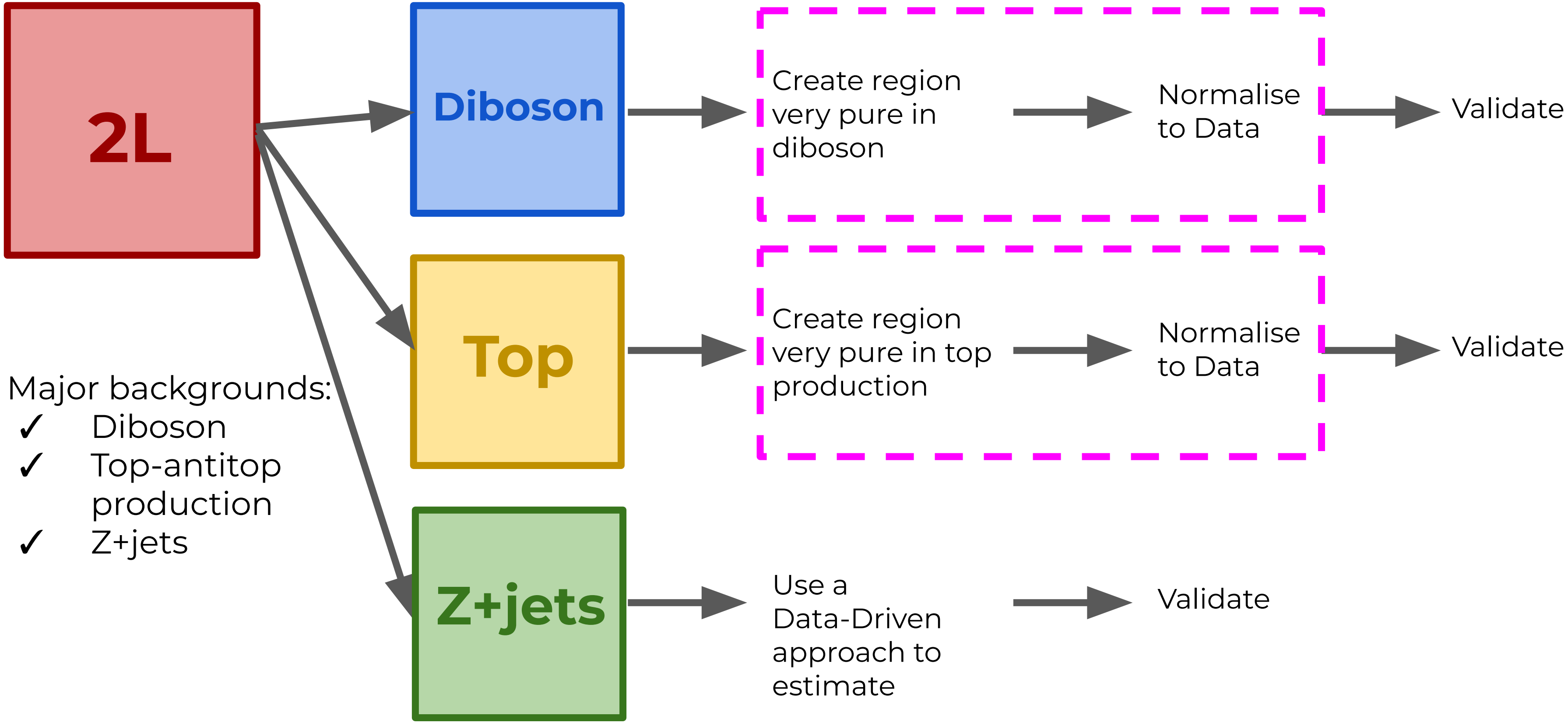
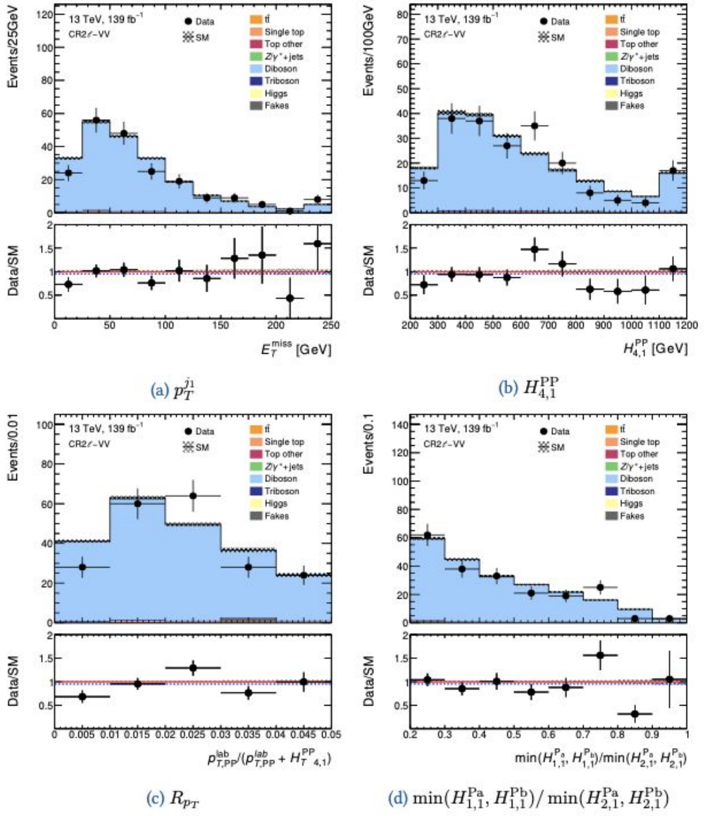
- ✓ Z+jets

Our 2L background estimation strategy



Major backgrounds:

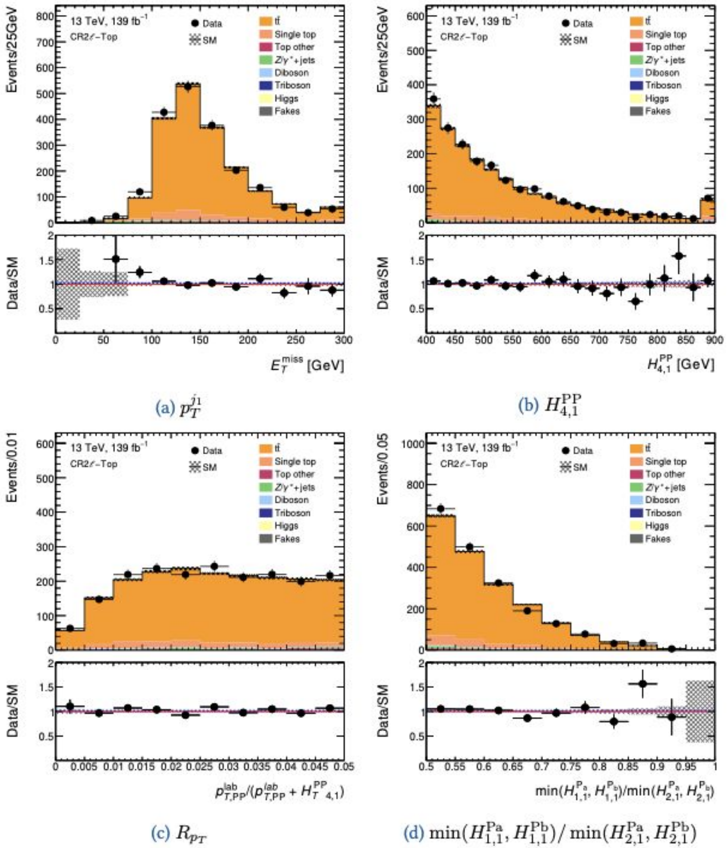
✓ Diboson
✓ Top-antitop production
✓ Z+jets



(a) $p_T^{j_1}$ (b) $H_{4,1}^{\mathrm{PP}}$ (c) R_{p_T} (d) $\min(H_{1,1}^{\mathrm{Pa}}, H_{1,1}^{\mathrm{Pb}})/\min(H_{2,1}^{\mathrm{Pa}}, H_{2,1}^{\mathrm{Pb}})$

Figure 4.36: CR2ℓ-VV: General modelling for $p_T^{j_1}$ in (a). We show $H_{4,1}^{\mathrm{PP}}$ in (b). In (c) we show R_{p_T}. In (d) we show $\min(H_{1,1}^{\mathrm{Pa}}, H_{1,1}^{\mathrm{Pb}})/\min(H_{2,1}^{\mathrm{Pa}}, H_{2,1}^{\mathrm{Pb}})$.

Great modelling in control regions



(a) $p_T^{j_1}$ (b) $H_{4,1}^{\mathrm{PP}}$ (c) R_{p_T} (d) $\min(H_{1,1}^{\mathrm{Pa}}, H_{1,1}^{\mathrm{Pb}})/\min(H_{2,1}^{\mathrm{Pa}}, H_{2,1}^{\mathrm{Pb}})$

Figure 4.37: CR2ℓ-Top: General modelling for $p_T^{j_1}$ in (a). We show $H_{4,1}^{\mathrm{PP}}$ in (b). In (c) we show R_{p_T}. In (d) we show $\min(H_{1,1}^{\mathrm{Pa}}, H_{1,1}^{\mathrm{Pb}})/\min(H_{2,1}^{\mathrm{Pa}}, H_{2,1}^{\mathrm{Pb}})$.

Additional Region Modelling

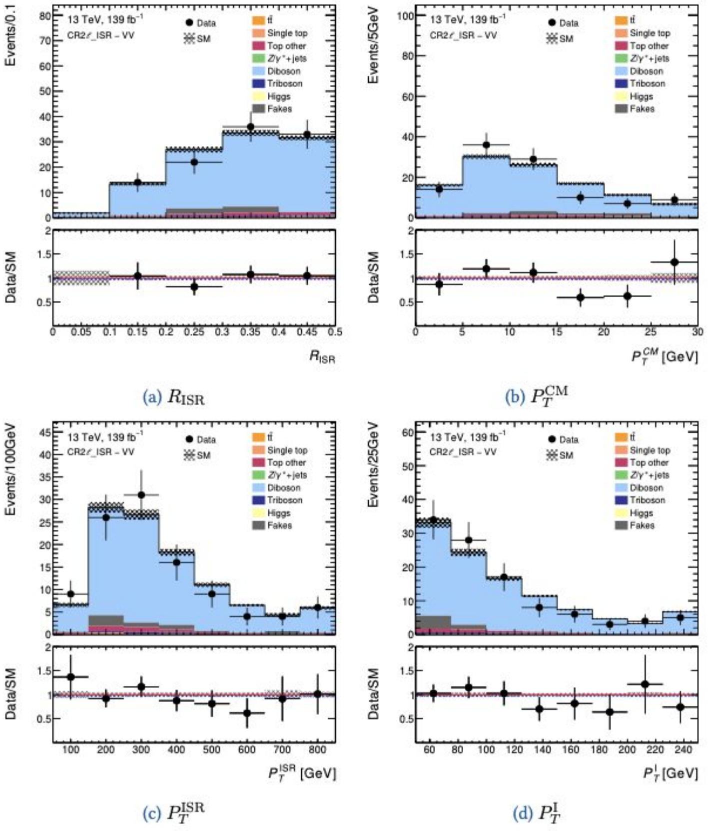


Figure 4.38: CR2ℓ_ISR-VV: General modelling for $R_{\rm ISR}$ in (a). We show $P_T^{\rm CM}$ in (b). In (c) we show $P_T^{\rm ISR}$. In (d) we show $P_T^{\rm I}$.

Great modelling in control regions

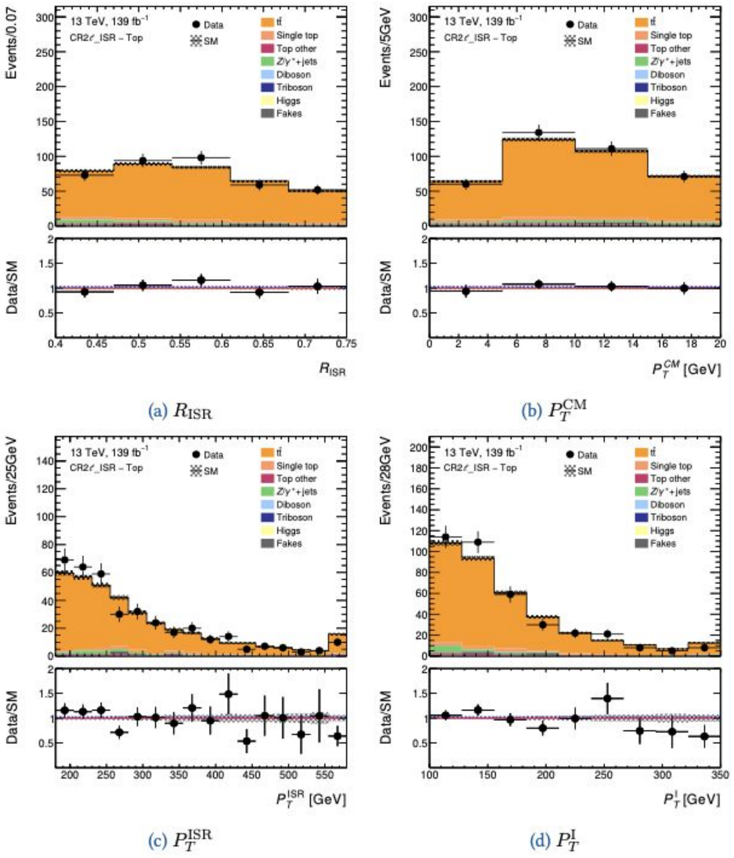
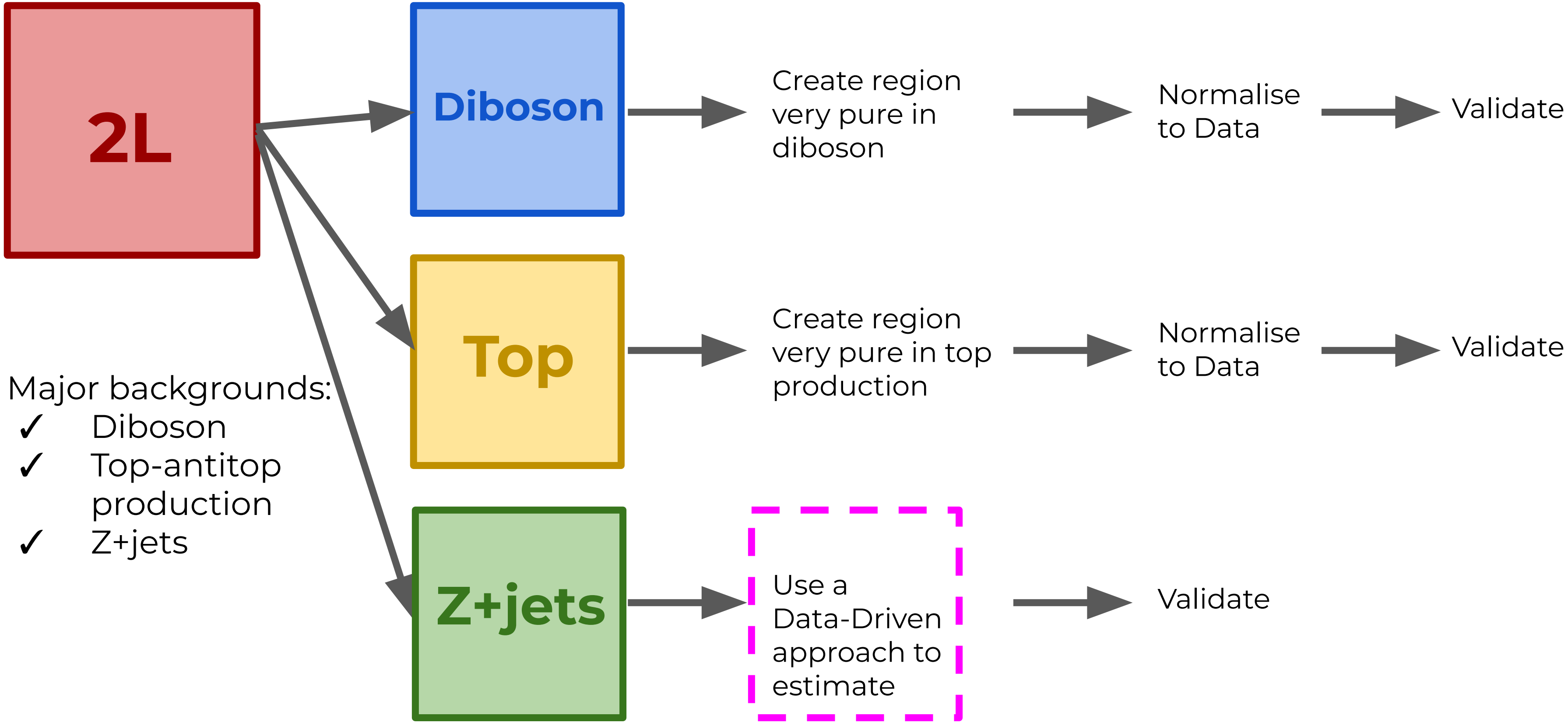


Figure 4.39: CR2ℓ_ISR-Top: General modelling for $R_{\rm ISR}$ in (a). We show $P_T^{\rm CM}$ in (b). In (c) we show $P_T^{\rm ISR}$. In (d) we show $P_T^{\rm I}$.

Our 2L background estimation strategy



Major backgrounds:

✓ Diboson

✓ Top-antitop production

✓ Z+jets

- Our Z+jets estimation problem

MC

- ❌ Models data poorly in SR
- ❌ Large uncertainties
- ❌ Generator weights Incredibly large

Common problem: "We can't simulate this well, what do we do?"

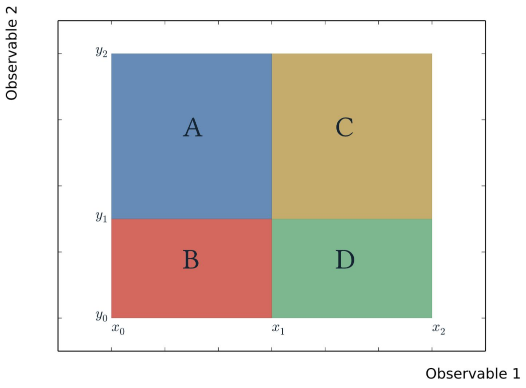
Answer: Let the data tell you whats happening!

ABCD Data Driven Estimate

Overview of the Method

1. Define your SR
2. Define regions A, B, C, and D
3. Calculate a data-driven estimate by subtracting non-Z+jets from data
4. Calculate an estimate in your SR (C)
5. Account for systematic uncertainties by varying boundaries and non-dominant cross sections

2D ABCD plane



Data driven estimate

$$N_i = D_i - MC_i^{\text{non } Z+\text{jets}}$$

Relate the different regions via:

$$\frac{N_A}{N_B} = \frac{N_C}{N_D} \longrightarrow N_C = N_D \times \frac{N_A}{N_B}$$

- Our Z+jets estimation problem

MC

- ❌ Models data poorly in SR
- ❌ Large uncertainties
- ❌ Generator weights Incredibly large

ABCD

- ✓ Independent on Z+jets MC
- ✓ Smaller uncertainties
- ❌ Only estimate, no modelling

COMPARISON

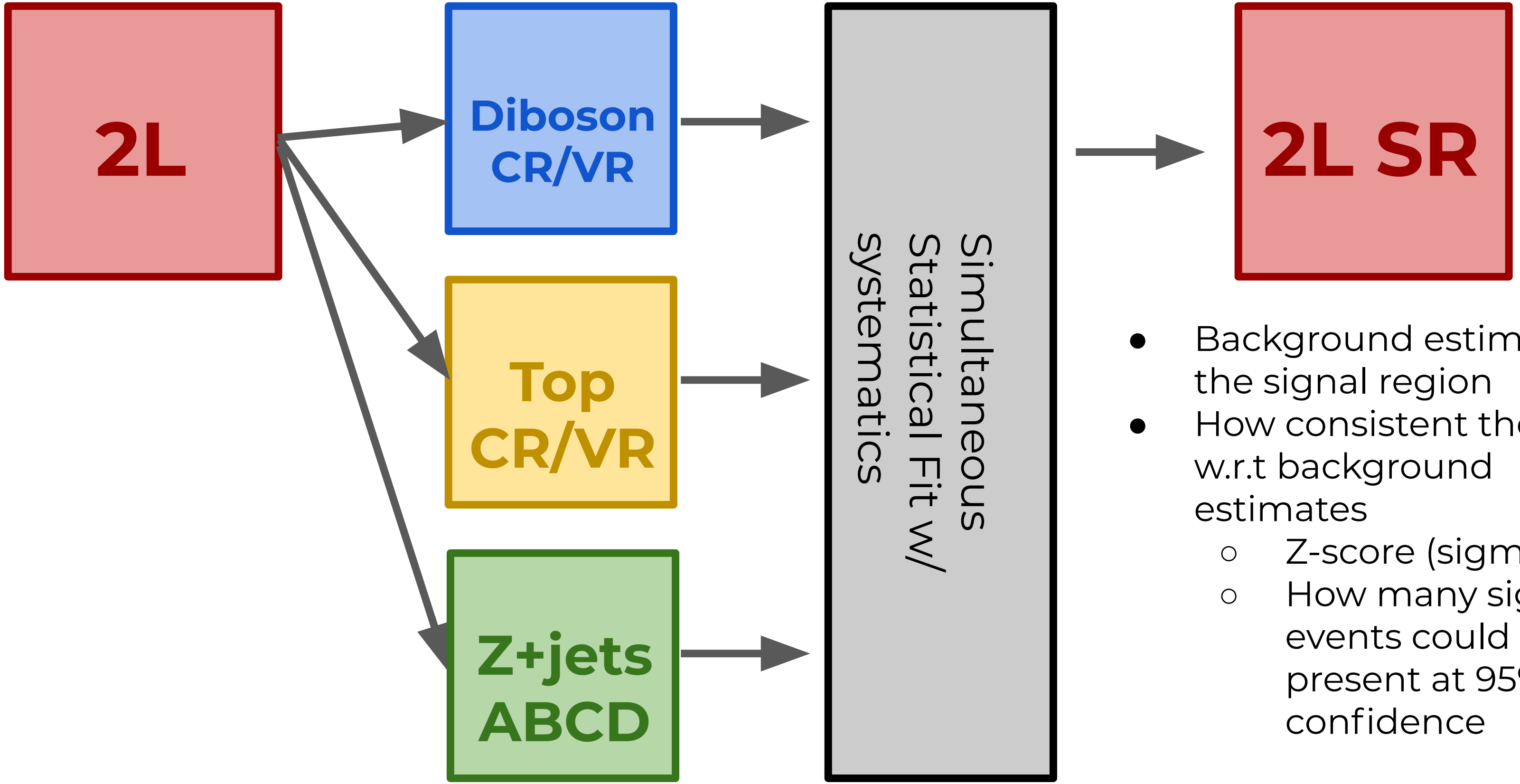
Standard region estimate

Region	STAT+SYS
$N_{\mathrm{ABCD}}^{\mathrm{Z+jets}}$	29.24 ± 7.64
$N_{\mathrm{mjj}}^{\mathrm{Z+jets}}$	28.14 ± 17.3
$N_{\mathrm{MC}}^{\mathrm{Z+jets}}$ (STAT)	42.20 ± 17.23

ISR region estimate

Region	STAT+SYS
$N_{\mathrm{ABCD}}^{\mathrm{Z+jets}}$	12.86 ± 7.48
$N_{\mathrm{mjj}}^{\mathrm{Z+jets}}$	13.37 ± 18.27
$N_{\mathrm{MC}}^{\mathrm{Z+jets}}$ (STAT)	17.57 ± 1.82

Our 2L background estimation strategy



- Background estimate in the signal region
- How consistent the data is w.r.t background estimates
  - Z-score (sigma)
  - How many signal events could be present at 95% confidence

Our 3L background estimation strategy

3L → **Diboson CR/VR** → Simultaneous Statistical Fit w/ systematics → **3L SR**

This is a **considerably** simpler analysis

- Background estimate in the signal region
- How consistent the data is w.r.t background estimates
    - Z-score (sigma)
    - How many signal events could be present at 95% confidence

Concluding Remarks

- Electroweak supersymmetry is and remains an interesting benchmark scenario
- We are following up on these two EWK regions from the 2015-2016 dataset
- By using Data-driven techniques we've improved upon passed results
- There is still plenty to learn : -)
- The next decade of the LHC is primed to be an interesting one!

Thanks for the Opportunity to Speak!

Additional Material

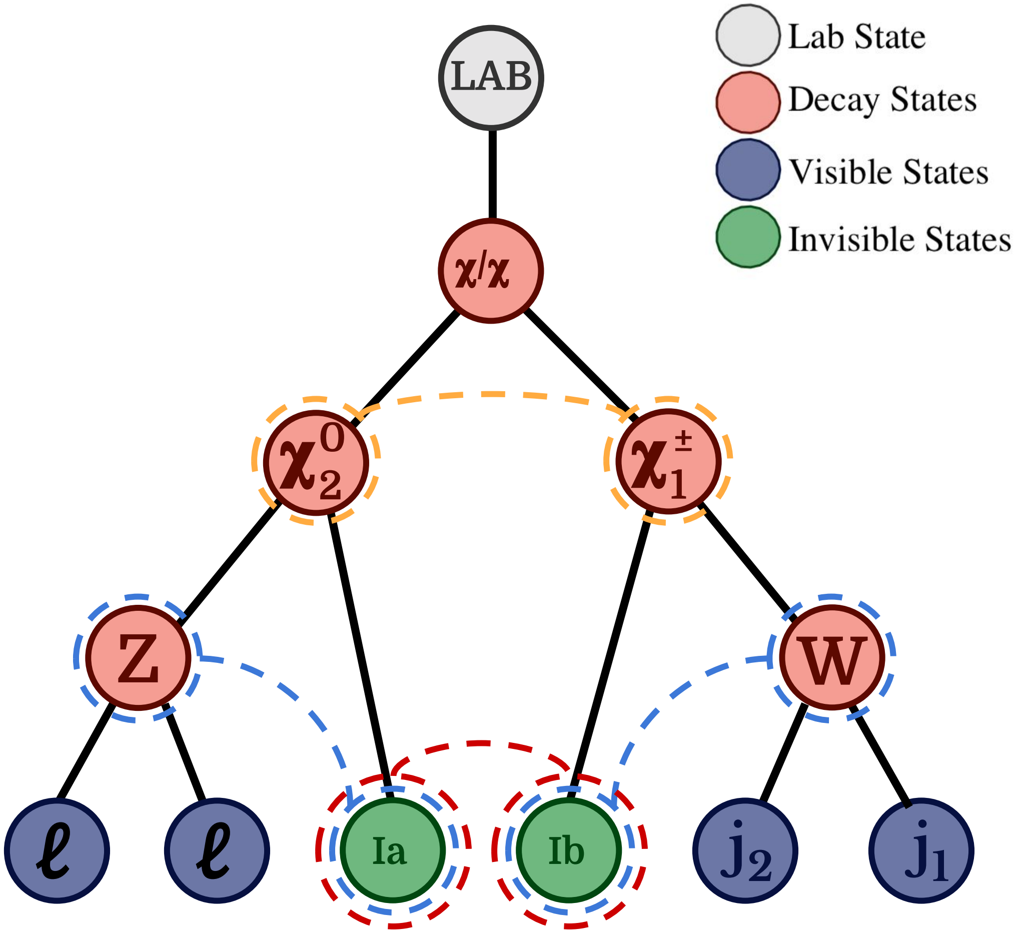
How do we split the **MET** ?

We apply **"Jigsaw Rules"**

We set the pseudrapidity of **invisibles (Ia+Ib)** to the **visibles** **($\ell\ell$+ℓ)** for each branch

Minimise the mass of **(Ia+Ib)**

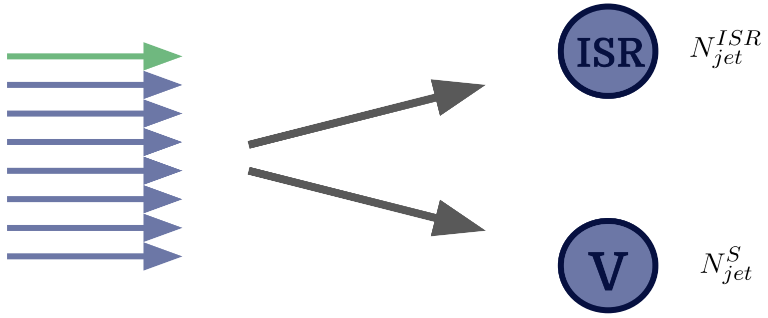
Require Chargino-1 and Neutralino-2 to be the same mass

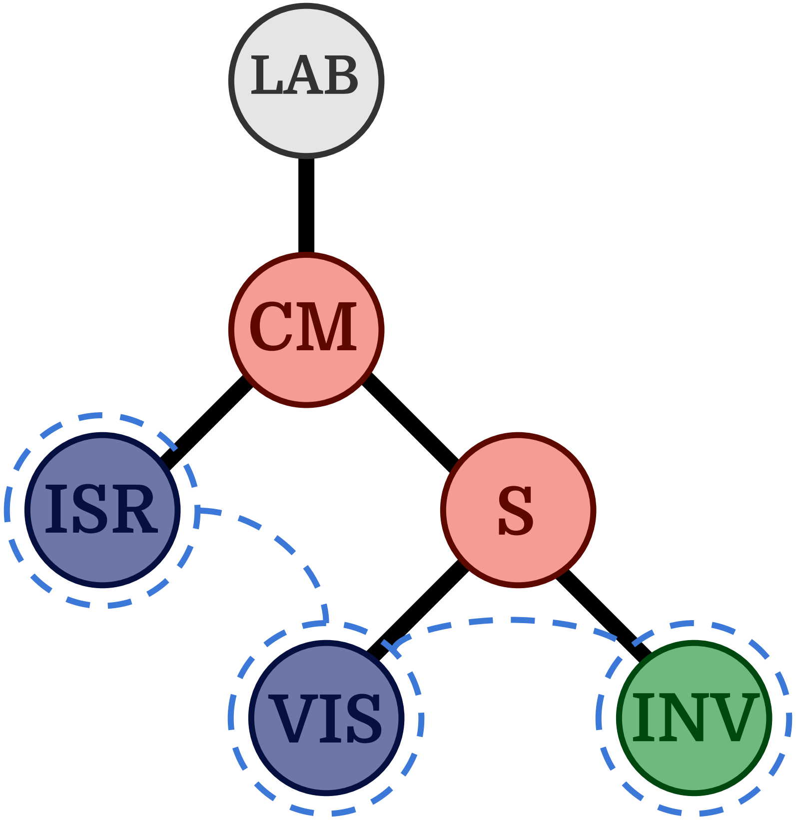


How do we determine **ISR** ?

We apply a **Jigsaw Rule**

We add take all combinations of jets into **ISR** and **VIS** and assign based on the minimum mass combination





Muon definitions

- We use eta 2.4 not 2.7 as recommended (frozen object)
- Moved to FCTight from GradientLoose (not supported)

Table 4.2: Summary of the muon selection criteria. The signal selection requirements are applied in addition to the baseline selection criteria, and take place after overlap removal.

Category	Acceptance	PID Quality	Isolation	Impact Parameter
Baseline Muon	$p_T > 10$ GeV $\|\eta^{\text{clust}}\| < 2.40$	`Medium`	-	$\|z_0 \sin\theta\| < 0.5$ mm
Signal Muon	$p_T > 10$ GeV $\|\eta^{\text{clust}}\| < 2.40$	`Medium`	`FixedCutTight`	$\|z_0 \sin\theta\| < 0.5$ mm $\|d_0/\sigma_{d_0}\| < 3$

Electron definitions

- We moved to FCTight from GradientLoose (not supported)

Table 4.3: Summary of the electron selection criteria. The signal selection requirements are applied in addition to the baseline selection criteria, and take place after overlap removal.

Category	Acceptance	PID Quality	Isolation	Impact Parameter
Baseline Electron	$p_T > 10$ GeV $\|\eta^{\text{clust}}\| < 2.47$	`LooseAndBLayerLLH`	- -	$\|z_0 \sin\theta\| < 0.5$ mm
Signal Electron	$p_T > 10$ GeV $\|\eta^{\text{clust}}\| < 2.47$	`LLHMedium`	`FixedCutTight`	$\|z_0 \sin\theta\| < 0.5$ mm $\|d_0/\sigma_{d_0}\| < 5$

Jet definitions

- We use eta 2.4 not 2.7 as recommended (frozen object)

Table 4.4: Summary of the jet and b-jet selection criteria. The signal selection requirements are applied in addition to basline requirements. Signal b-jet selection is in addition to the signal requirements. These requirements take place after overlap removal. * JVT is only applied for jets with $p_T < 60$ GeV and $|\eta| < 2.4$.

Category	Collection	Acceptance	JVT	b-tagger Algorithm	Efficiency
Baseline jet	`AntiKt4EMTopo`	$p_T > 20$ GeV, $\|\eta\| < 4.5$	-	-	-
Signal jet	`AntiKt4EMTopo`	$p_T > 20$ GeV, $\|\eta\| < 2.4$	$\|\text{JVT}\| > 0.59^*$	-	-
Signal b-jet	`AntiKt4EMTopo`	$p_T > 20$ GeV, $\|\eta\| < 2.4$	$\|\text{JVT}\| > 0.59^*$	`MV2c10`	77%

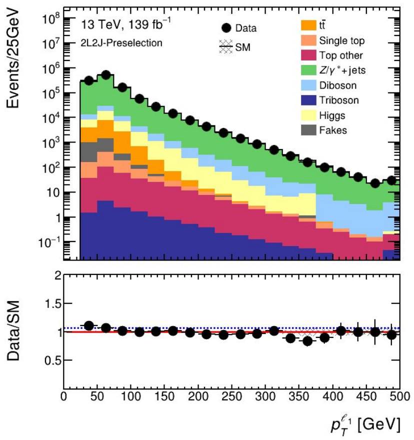
Table 4.7: The two lepton preselection regions defined to validate our MC modelling of the run-II ATLAS dataset.

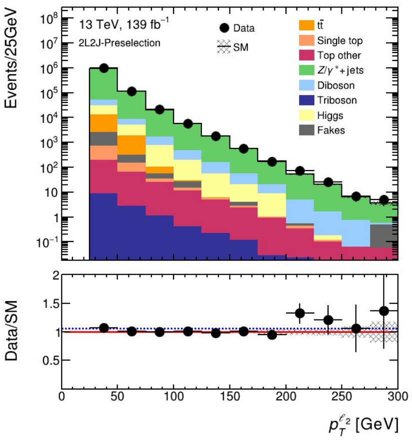
Region	Selection	N_{Jets}	$p_T^{\ell_1}$ [GeV]	$p_T^{\ell_2}$ [GeV]	$p_T^{j_1}$ [GeV]	$p_T^{j_2}$ [GeV]	$m_{\ell\ell}/M_Z$ [GeV]	m_{jj}/M_J [GeV]
RJ2ℓA	$l^{\pm}l^{\mp}$	$= 2$	> 25	> 25	> 30	> 30	$\in [80, 100]$	$\in [60, 100]$
RJ2ℓB	$l^{\pm}l^{\mp}$	$>= 2$	> 25	> 25	> 30	> 30	$\in [80, 100]$	$\in [60, 100]$

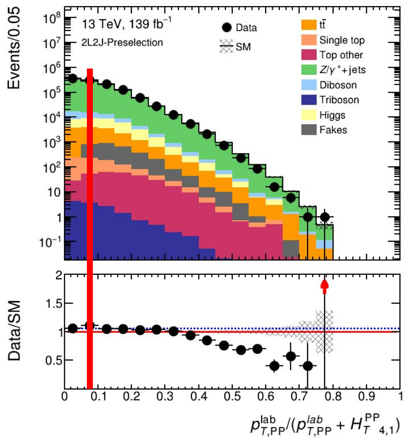
Table 4.8: The three lepton preselection regions defined to validate our MC modelling of the run-II ATLAS dataset.

Region	Selection	N_{Jets}	$p_T^{\ell_1}$ [GeV]	$p_T^{\ell_2}$ [GeV]	$p_T^{\ell_3}$ [GeV]	$m_{\ell\ell}$ [GeV]	m_T^W [GeV]
RJ3ℓA	$\ell^{\pm}\ell^{\mp}\ell$	$>= 0$	> 25	> 25	> 20	$\in [75, 105]$	> 50
RJ3ℓB	$\ell^{\pm}\ell^{\mp}\ell$	> 0	> 25	> 25	> 20	$\in [75, 105]$	> 50

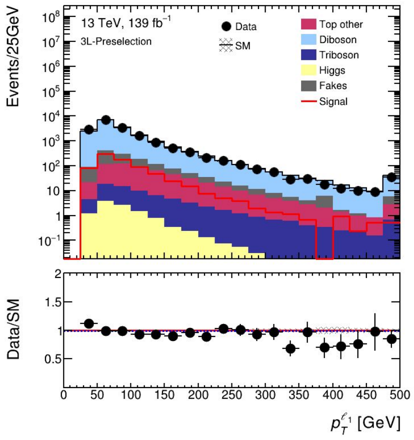
Preselection validation (2L above / 3L below)

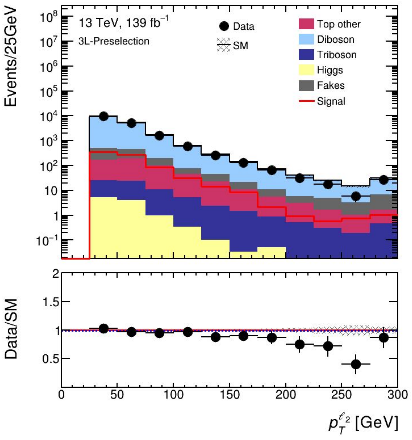


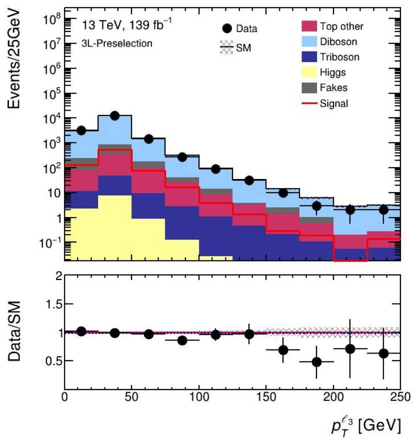


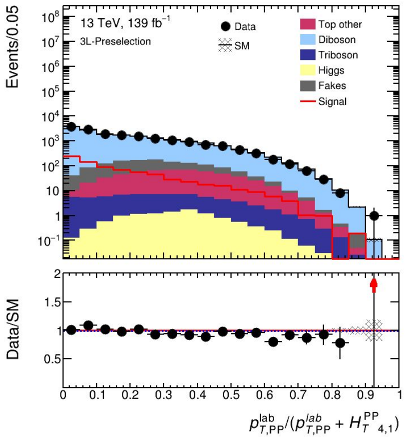


Preselection modelling looks good









Triggers and Monte Carlo

Triggers and MC

We use standard dilepton triggers

- ee triggers
- e mu triggers
- mu mu triggers

Summary of triggers

Year	ee trigger	$\mu\mu$ trigger	$e\mu$ trigger
2015	2e12_lhloose_L12EM10VH	2mu10	e17_lhloose_mu14
2016	2e17_lhvloose_nod0	mu22_mu8noL1 or 2mu14	e17_lhloose_nod0_mu14 or e7_lhmedium_nod0_mu24
2017	2e17_lhvloose_nod0 or 2e24_lhvloose_nod0	mu22_mu8noL1 or 2mu14	e17_lhloose_nod0_mu14 or e7_lhmedium_nod0_mu24
2018	2e17_lhvloose_nod0 or 2e24_lhvloose_nod0	mu22_mu8noL1 or 2mu14	e17_lhloose_nod0_mu14 or e7_lhmedium_no0_mu24

Summary of Monte Carlo Generators

Table 4.1: The SUSY signals and the Standard Model background MC samples used in this search. The generators, the order in α_s of cross-section calculations used for yield normalization, PDF sets, parton showers and parameter tunes used for the underlying event are shown.

Physics process	Generator	Cross-section normalization	PDF set	Parton shower	Tune
SUSY processes	MadGraph v2.2.3	NLO+NLL	NNPDF2.3LO	Pythia 8.186	A14
$Z/\gamma^*(\rightarrow \ell\ell)$ + jets	Sherpa 2.2.1	NNLO	NNPDF3.0NNLO	Sherpa	Sherpa default
γ + jets	Sherpa 2.1.1	LO	CT10	Sherpa	Sherpa default
$H(\rightarrow \tau\tau)$, $H(\rightarrow WW)$	Powheg-Box v2	NLO	CTEQ6L1	Pythia 8.186	A14
HW, HZ	MG5_aMC@NLO 2.2.2	NLO	NNPDF2.3LO	Pythia 8.186	A14
$t\bar{t} + H$	MG5_aMC@NLO 2.2.2	NLO	CTEQ6L1	Herwig 2.7.1	A14
$t\bar{t}$	Powheg-Box v2	NNLO+NNLL	CT10	Pythia 6.428	Perugia2012
Single top (Wt-channel)	Powheg-Box v2	NNLO+NNLL	CT10	Pythia 6.428	Perugia2012
Single top (s-channel)	Powheg-Box v2	NLO	CT10	Pythia 6.428	Perugia2012
Single top (t-channel)	Powheg-Box v1	NLO	CT10f4	Pythia 6.428	Perugia2012
Single top (Zt-channel)	MG5_aMC@NLO 2.2.1	LO	CTEQ6L1	Pythia 6.428	Perugia2012
$t\bar{t} + W/WW$	MG5_aMC@NLO 2.2.2	NLO	NNPDF2.3LO	Pythia 8.186	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.3	NLO	NNPDF2.3LO	Pythia 8.186	A14
WW, WZ, ZZ	Sherpa 2.2.1	NLO	NNPDF30NNLO	Sherpa	Sherpa default
$V\gamma$	Sherpa 2.1.1	LO	CT10	Sherpa	Sherpa default
Triboson	Sherpa 2.2.1	NLO	NNPDF30NNLO	Sherpa	Sherpa default

R20 Region Breakdowns

R20 Yields summary

Signal region	SR2ℓ_High	SR2ℓ_Int	SR2ℓ_Low	SR2ℓ_ISR
Total observed events	0	1	19	11
Total background events	1.9 ± 0.8	2.4 ± 0.9	8.4 ± 5.8	$2.7^{+2.8}_{-2.7}$
Other	0.02 ± 0.01	$0.05^{+0.12}_{-0.05}$	$0.02^{+1.07}_{-0.02}$	$0.06^{+0.33}_{-0.06}$
Fit output, $Wt + t\bar{t}$	0.00 ± 0.00	0.00 ± 0.00	0.57 ± 0.20	$0.28^{+0.34}_{-0.28}$
Fit output, VV	1.8 ± 0.7	2.4 ± 0.8	1.5 ± 0.9	2.3 ± 1.1
Z+jets	$0.07^{+0.78}_{-0.07}$	$0.00^{+0.74}_{-0.00}$	6.3 ± 5.8	$0.10^{+2.58}_{-0.10}$
Fit input, $Wt + t\bar{t}$	0.00	0.00	0.63	0.28
Fit input, VV	1.9	2.6	1.6	2.4

Signal region	SR3ℓ_High	SR3ℓ_Int	SR3ℓ_Low	SR3ℓ_ISR
Total observed events	2	1	20	12
Total background events	1.1 ± 0.5	2.3 ± 0.5	10 ± 2	3.9 ± 1.0
Other	$0.03^{+0.07}_{-0.03}$	0.04 ± 0.02	$0.02^{+0.34}_{-0.02}$	$0.06^{+0.19}_{-0.06}$
Triboson	0.19 ± 0.07	0.32 ± 0.06	0.25 ± 0.03	0.08 ± 0.04
Fit output, VV	0.83 ± 0.39	1.9 ± 0.5	10 ± 2	3.8 ± 1.0
Fit input, VV	0.76	1.8	9.2	3.4

Region Definitions

Table 2: Preselection criteria for the three standard-decay-tree 2ℓ SRs and the associated CRs and VRs. The variables are defined in the text.

Region	n_{leptons}	n_{jets}	$n_{b\text{-tag}}$	$p_T^{\ell_1,\ell_2}$ [GeV]	$p_T^{j_1,j_2}$ [GeV]	$m_{\ell\ell}$ [GeV]	m_{jj} [GeV]	m_T^W [GeV]
CR2ℓ-VV	$\in [3,4]$	≥ 2	=0	> 25	> 30	$\in (80,100)$	> 20	$\in (70,100)$ if $n_{\text{leptons}} = 3$
CR2ℓ-Top	$= 2$	≥ 2	=1	> 25	> 30	$\in (80,100)$	$\in (40,250)$	–
VR2ℓ-VV	$= 2$	≥ 2	=0	> 25	> 30	$\in (80,100)$	$\in (40,70)$	–
							or $\in (90,500)$	–
VR2ℓ-Top	$= 2$	≥ 2	=1	> 25	> 30	$\in (20,80)$	$\in (40,250)$	–
						or > 100		–
SR2ℓ_High	$= 2$	≥ 2	$= 0$	> 25	> 30	$\in (80,100)$	$\in (60,100)$	–
SR2ℓ_Int	$= 2$	≥ 2	$= 0$	> 25	> 30	$\in (80,100)$	$\in (60,100)$	–
SR2ℓ_Low	$= 2$	$= 2$	$= 0$	> 25	> 30	$\in (80,100)$	$\in (70,90)$	–

The ISR regions are further defined with a series of requirements based on the variables reconstructed from the compressed decay tree. These requirements are listed in Table 5. The ISR SR is defined by requiring a highly energetic ISR jet system which recoils against the entire signal system in the CM frame. In VR2ℓ_ISR-VV the m_Z requirement is inverted in order to be orthogonal to the CR2ℓ_ISR-VV. The top CRs (CR2ℓ_ISR-Top) and VR (VR2ℓ_ISR-Top) are defined with a b-tag jet requirement and have broader m_Z and m_J windows. The broader mass windows help to increase the numbers of data

Table 3: Selection criteria for the three standard-decay-tree 2ℓ SRs and the associated CRs and VRs. The variables are defined in the text

Region	$H_{4,1}^{\text{PP}}$ [GeV]	$H_{1,1}^{\text{PP}}$ [GeV]	$\frac{p_{\text{T PP}}^{\text{lab}}}{p_{\text{T PP}}^{\text{lab}}+H_{\text{T }4,1}^{\text{PP}}}$	$\frac{\min(H_{1,1}^{\text{Pa}},H_{1,1}^{\text{Pb}})}{\min(H_{2,1}^{\text{Pa}},H_{2,1}^{\text{Pb}})}$	$\frac{H_{1,1}^{\text{PP}}}{H_{4,1}^{\text{PP}}}$	$\Delta\phi_{\text{V}}^{\text{P}}$	$\min\Delta\phi(j_1/j_2,\vec{p}_{\text{T}}^{\text{ miss}})$
CR2ℓ-VV	> 200	–	< 0.05	> 0.2	–	$\in (0.3,2.8)$	–
CR2ℓ-Top	> 400	–	< 0.05	> 0.5	–	$\in (0.3,2.8)$	–
VR2ℓ-VV	> 400	> 250	< 0.05	$\in (0.4,0.8)$	–	$\in (0.3,2.8)$	–
VR2ℓ-Top	> 400	–	< 0.05	> 0.5	–	$\in (0.3,2.8)$	–
							-
							-
SR2ℓ_High	> 800	–	< 0.05	> 0.8	–	$\in (0.3,2.8)$	–
SR2ℓ_Int	> 600	–	< 0.05	> 0.8	–	$\in (0.6,2.6)$	–
SR2ℓ_Low	> 400	–	< 0.05	–	$\in (0.35,0.60)$	–	> 2.4

2L ISR Region Definitions

Table 4: Preselection criteria for the compressed-decay-tree 2ℓ SR and the associated CRs and VRs. The variables are defined in the text.

Region	n_{leptons}	$N_{\text{jet}}^{\text{ISR}}$	$N_{\text{jet}}^{\text{S}}$	n_{jets}	$n_{b\text{-tag}}$	$p_{\text{T}}^{\ell_1,\ell_2}$ [GeV]	$p_{\text{T}}^{j_1,j_2}$ [GeV]
CR2ℓ_ISR-VV	$\in [3,4]$	≥ 1	≥ 2	> 2	$= 0$	> 25	> 30
CR2ℓ_ISR-Top	$= 2$	≥ 1	$= 2$	$\in [3,4]$	$= 1$	> 25	> 30
VR2ℓ_ISR-VV	$\in [3,4]$	≥ 1	≥ 2	≥ 3	$= 0$	> 25	> 20
VR2ℓ_ISR-Top	$= 2$	≥ 1	$= 2$	$\in [3,4]$	$= 1$	> 25	> 30
VR2ℓ_ISR-Zjets	$= 2$	≥ 1	≥ 1	$\in [3,5]$	$= 0$	> 25	> 30
SR2ℓ_ISR	$= 2$	≥ 1	$= 2$	$\in [3,4]$	$= 0$	> 25	> 30

Table 5: Selection criteria for the compressed-decay-tree 2ℓ SR and the associated CRs and VRs. The variables are defined in the text.

Region	m_Z [GeV]	m_J [GeV]	$\Delta\phi_{\text{ISR,I}}^{\text{CM}}$	R_{ISR}	$p_{\text{T ISR}}^{\text{CM}}$ [GeV]	$p_{\text{T I}}^{\text{CM}}$ [GeV]	p_{T}^{CM} [GeV]
CR2ℓ_ISR-VV	$\in (80, 100)$	> 20	> 2.0	$\in (0.0, 0.5)$	> 50	> 50	< 30
CR2ℓ_ISR-Top	$\in (50, 200)$	$\in (50, 200)$	> 2.8	$\in (0.4, 0.75)$	> 180	> 100	< 20
VR2ℓ_ISR-VV	$\in (20, 80)$ or > 100	> 20	> 2.0	$\in (0.0, 1.0)$	> 70	> 70	< 30
VR2ℓ_ISR-Top	$\in (50, 200)$	$\in (50, 200)$	> 2.8	$\in (0.4, 0.75)$	> 180	> 100	> 20
VR2ℓ_ISR-Zjets	$\in (80, 100)$	< 50 or > 110	–	–	> 180	> 100	< 20
SR2ℓ_ISR	$\in (80, 100)$	$\in (50, 110)$	> 2.8	$\in (0.4, 0.75)$	> 180	> 100	< 20

3L Region Definitions

Table 6: Preselection criteria for the 3ℓ CR, VR and SR with the standard decay tree. The variables are defined in the text.

Region	n_{leptons}	n_{jets}	$n_{b\text{-tag}}$	$p_T^{\ell_1}$ [GeV]	$p_T^{\ell_2}$ [GeV]	$p_T^{\ell_3}$ [GeV]
CR3ℓ-VV	$= 3$	< 3	$= 0$	> 60	> 40	> 30
VR3ℓ-VV	$= 3$	< 3	$= 0$	> 60	> 40	> 30
SR3ℓ_High	$= 3$	< 3	$= 0$	> 60	> 60	> 40
SR3ℓ_Int	$= 3$	< 3	$= 0$	> 60	> 50	> 30
SR3ℓ_Low	$= 3$	$= 0$	$= 0$	> 60	> 40	> 30

Table 7: Selection criteria for the 3ℓ CR, VR and SR with the standard decay tree. The variables are defined in the text.

Region	$m_{\ell\ell}$ [GeV]	m_T^W [GeV]	$H_{3,1}^{\text{PP}}$ [GeV]	$\frac{p_{T\,\text{PP}}^{\text{lab}}}{p_{T\,\text{PP}}^{\text{lab}}+H_{T\,3,1}^{\text{PP}}}$	$\frac{H_{T\,3,1}^{\text{PP}}}{H_{3,1}^{\text{PP}}}$	$\frac{H_{1,1}^{\text{P}_b}}{H_{2,1}^{\text{P}_b}}$
CR3ℓ-VV	$\in (75, 105)$	$\in (0, 70)$	> 250	< 0.2	> 0.75	–
VR3ℓ-VV	$\in (75, 105)$	$\in (70, 100)$	> 250	< 0.2	> 0.75	–
SR3ℓ_High	$\in (75, 105)$	> 150	> 550	< 0.2	> 0.75	> 0.8
SR3ℓ_Int	$\in (75, 105)$	> 130	> 450	< 0.15	> 0.8	> 0.75
SR3ℓ_Low	$\in (75, 105)$	> 100	> 250	< 0.05	> 0.9	–

3L ISR Region Definitions

Table 8: Preselection criteria for the 3ℓ CR, VR and SR with the compressed decay tree. The variables are defined in the text.

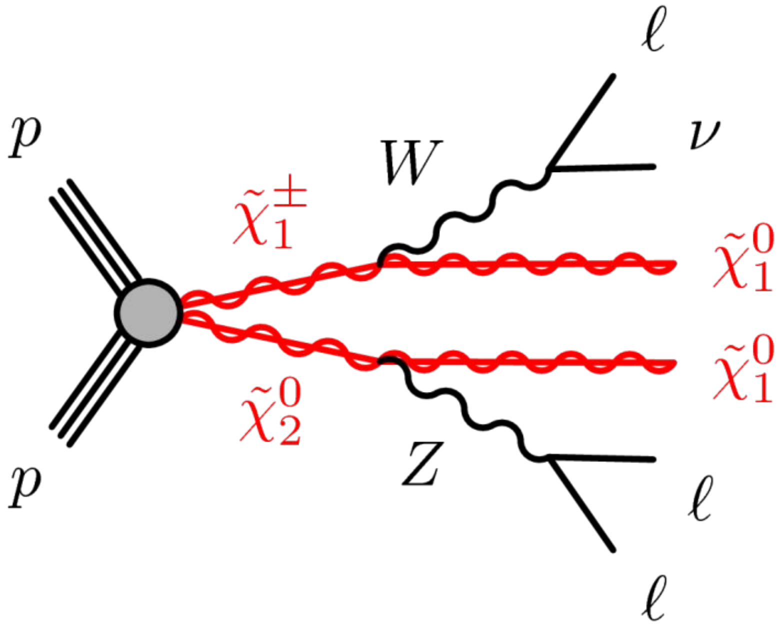
Region	n_{leptons}	n_{jets}	$n_{b\text{-tag}}$	$p_{\mathrm{T}}^{\ell_1}$ [GeV]	$p_{\mathrm{T}}^{\ell_2}$ [GeV]	$p_{\mathrm{T}}^{\ell_3}$ [GeV]
CR3ℓ_ISR-VV	$= 3$	≥ 1	$= 0$	> 25	> 25	> 20
VR3ℓ_ISR-VV	$= 3$	≥ 1	$= 0$	> 25	> 25	> 20
SR3ℓ_ISR	$= 3$	$\in [1, 3]$	$= 0$	> 25	> 25	> 20

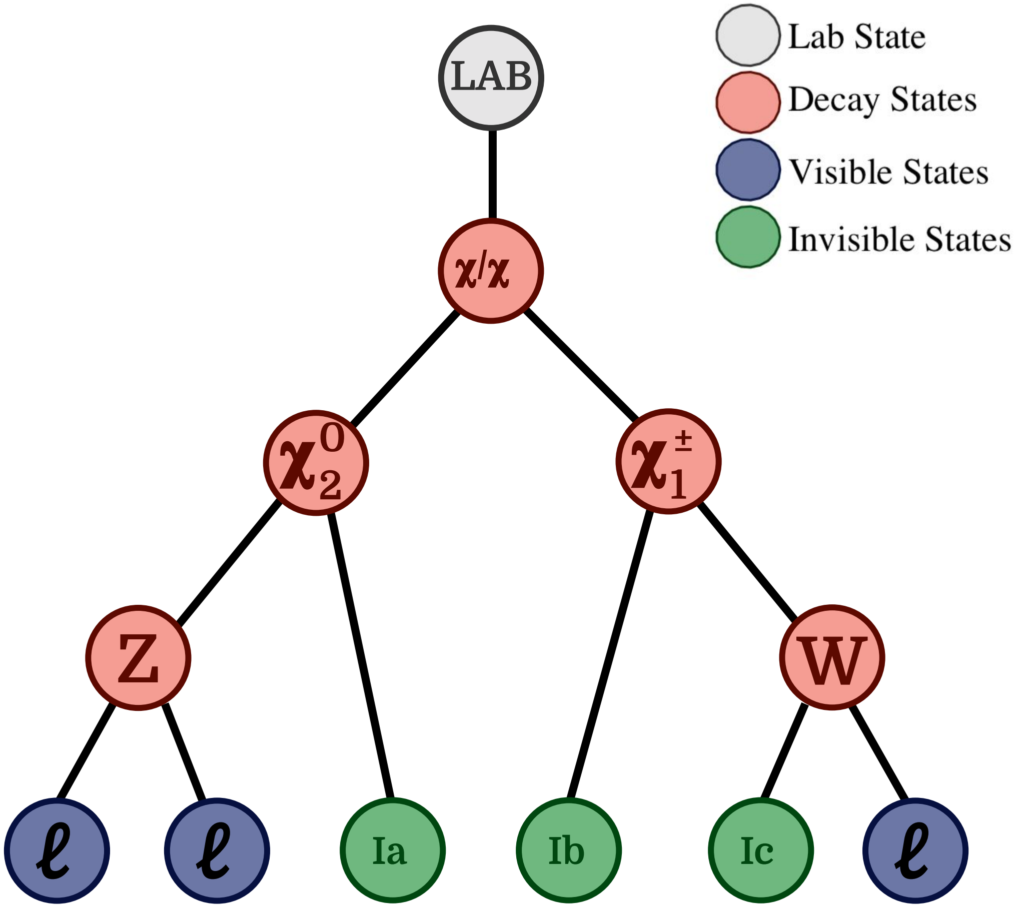
Table 9: Selection criteria for the 3ℓ CR, VR and SR with the compressed decay tree. The variables are defined in the text.

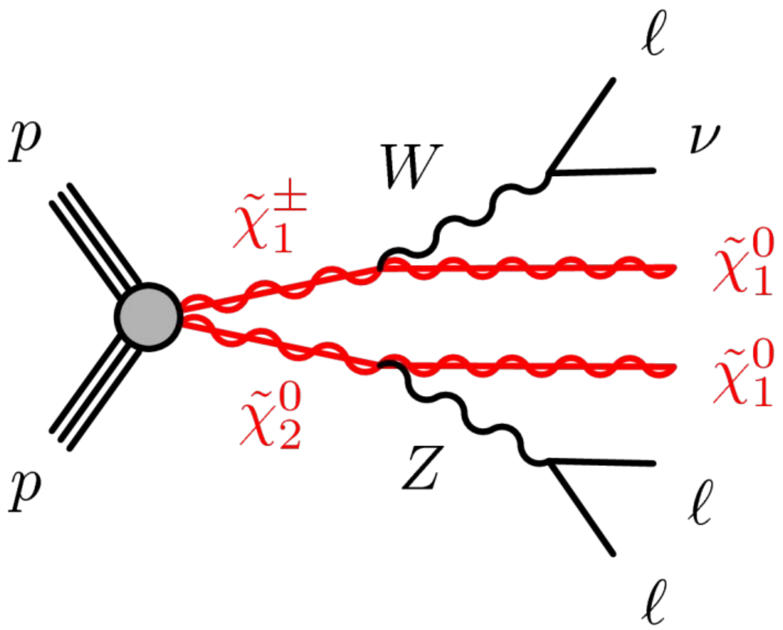
Region	$m_{\ell\ell}$ [GeV]	m_{T}^{W} [GeV]	$\Delta\phi^{\mathrm{CM}}_{\mathrm{ISR,I}}$	R_{ISR}	$p^{\mathrm{CM}}_{\mathrm{T\,ISR}}$ [GeV]	$p^{\mathrm{CM}}_{\mathrm{T\,I}}$ [GeV]	$p^{\mathrm{CM}}_{\mathrm{T}}$ [GeV]
CR3ℓ_ISR-VV	$\in (75, 105)$	< 100	> 2.0	$\in (0.55, 1.0)$	> 80	> 60	< 25
VR3ℓ_ISR-VV	$\in (75, 105)$	> 60	> 2.0	$\in (0.55, 1.0)$	> 80	> 60	> 25
SR3ℓ_ISR	$\in (75, 105)$	> 100	> 2.0	$\in (0.55, 1.0)$	> 100	> 80	< 25

3L RJ treatment

Recursive Jigsaw Reconstruction



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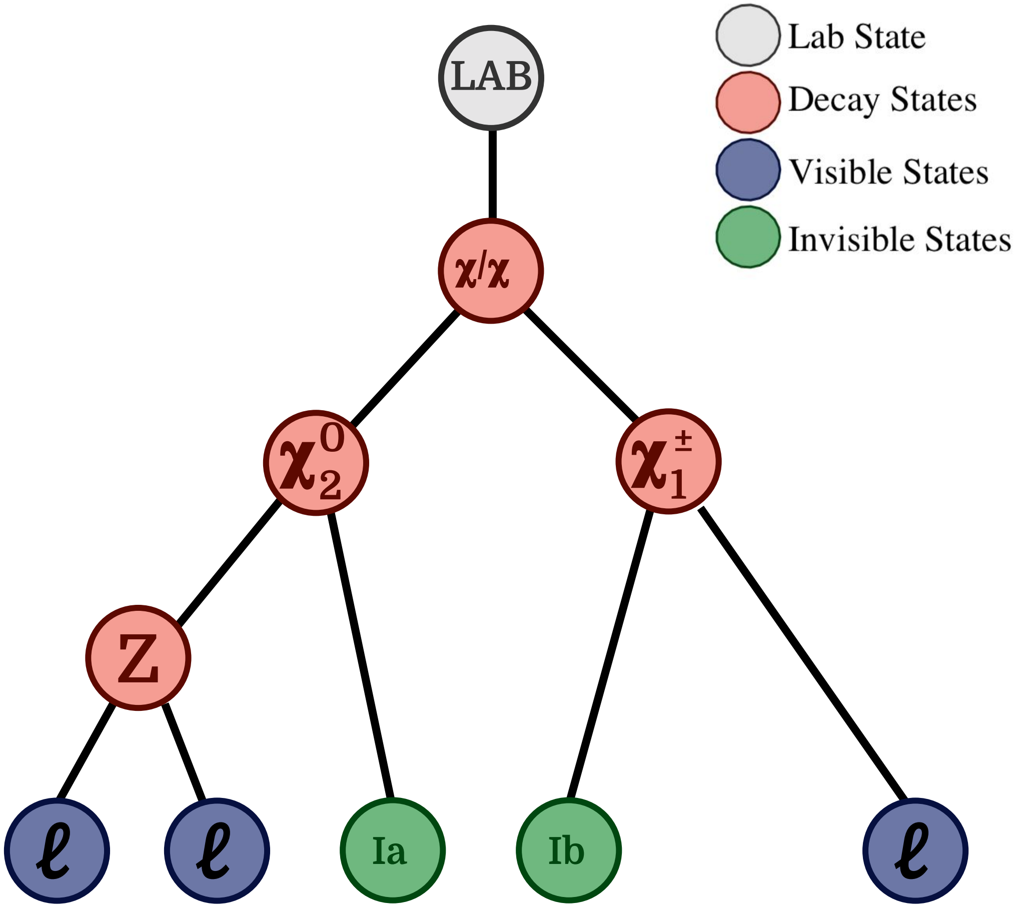
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