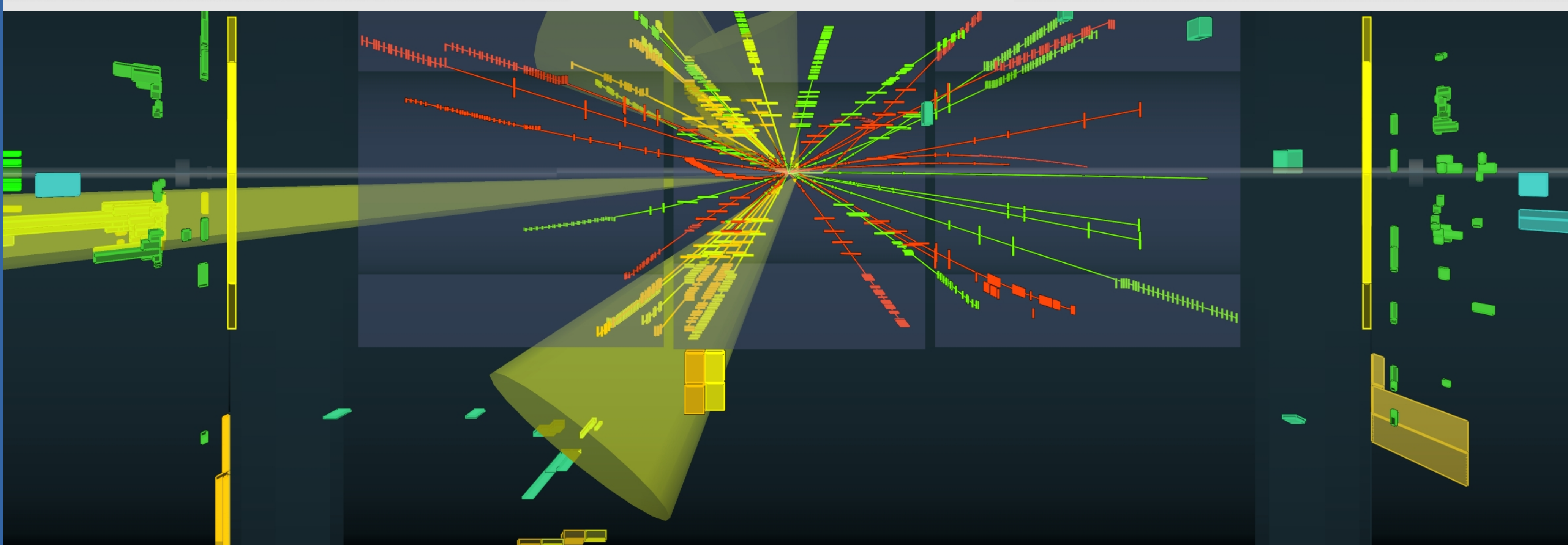


# The Recursive Jigsaw Reconstruction for SUSY, Higgs and Beyond


Marco Santoni   CoEPP 2017

*Supervisors: Paul Jackson and Martin White*

*and with Christopher Rogan*

# Outline

- What is the Recursive Jigsaw Reconstruction (RJR) technique?
- Example of study: squark and gluino pair production at LHC
  "Sparticles in motion: Analyzing compressed SUSY scenarios with a new method of event reconstruction"
  (arXiv:1607.08307 [hep-ph] – shortly in Phys. Rev. D)
- Other SUSY analyses and beyond
- Summary - Outlook

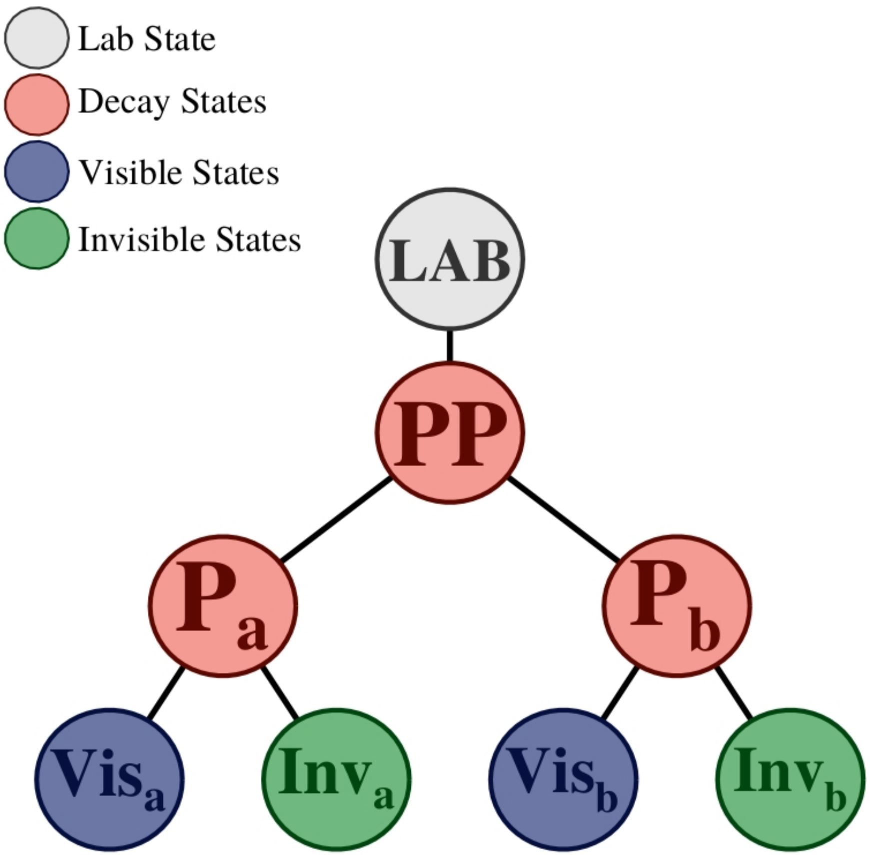
# What is the Recursive Jigsaw Reconstruction technique?

- Original method to **reconstructing** final states with weakly interacting particles

- Transform observable momenta reference-frame to reference-frame

- **Jigsaw rules**: specify the unknown d.o.f. relevant to the transformation (customizable-interchangeable like jigsaw puzzle pieces)

- The procedure is repeated **recursively**, travelling through each of the reference frames relevant to the topology




- Rather than obtaining one observable, get a complete basis of useful variables: angles, energies, masses ...

Developed by Paul Jackson and Christopher Rogan: http://RestFrames.com

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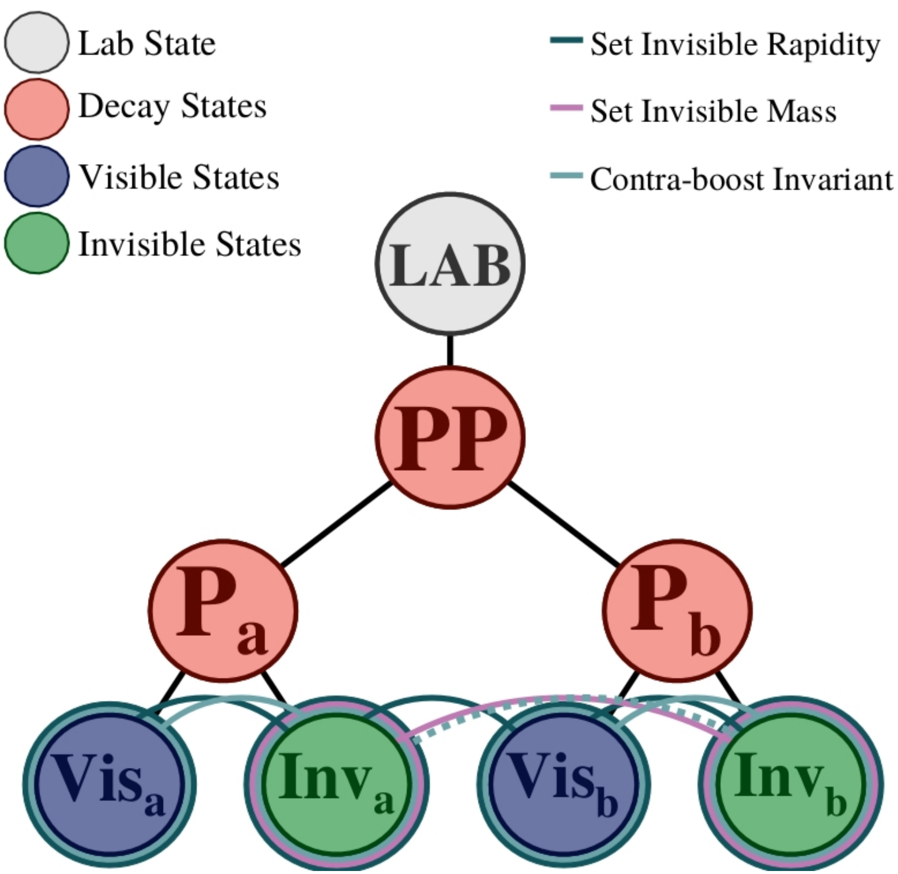


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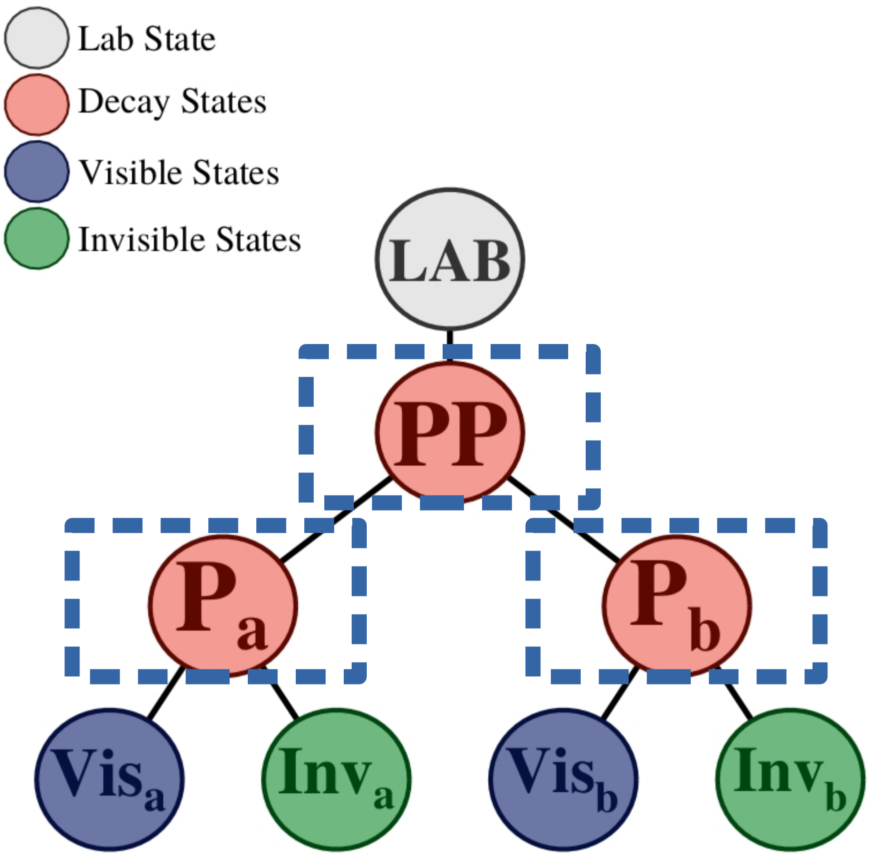


- Rather than obtaining one observable, get a complete basis of useful variables: angles, energies, masses ...

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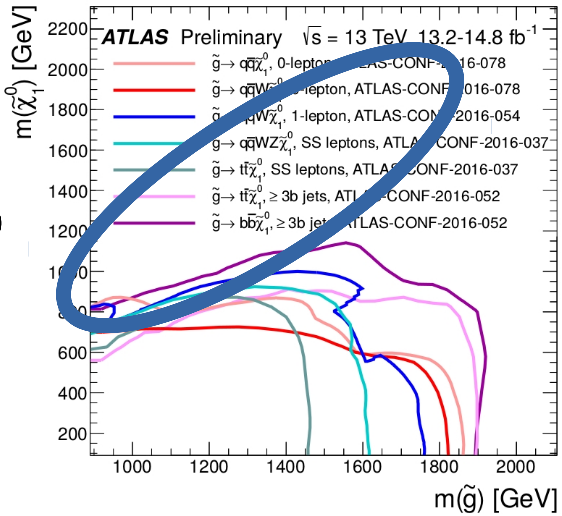
# Introduction to compressed kinematics

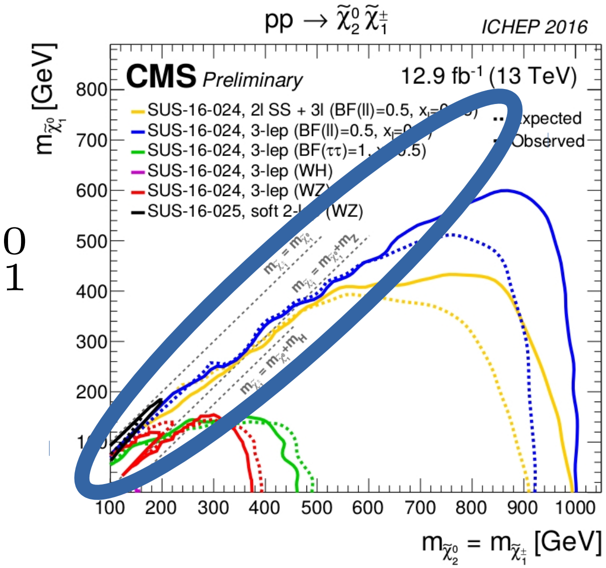
- **Compressed** scenarios refer to **small mass-splittings** $M_{\tilde{P}} - M_{\tilde{\chi}_1^0}$ between the parent superparticle $\tilde{P}$ and the lightest supersymmetric particle (LSP) $\tilde{\chi}_1^0$

$M_{\tilde{\chi}_1^0}$




$M_{\tilde{P}}$

$M_{\tilde{\chi}_1^0}$

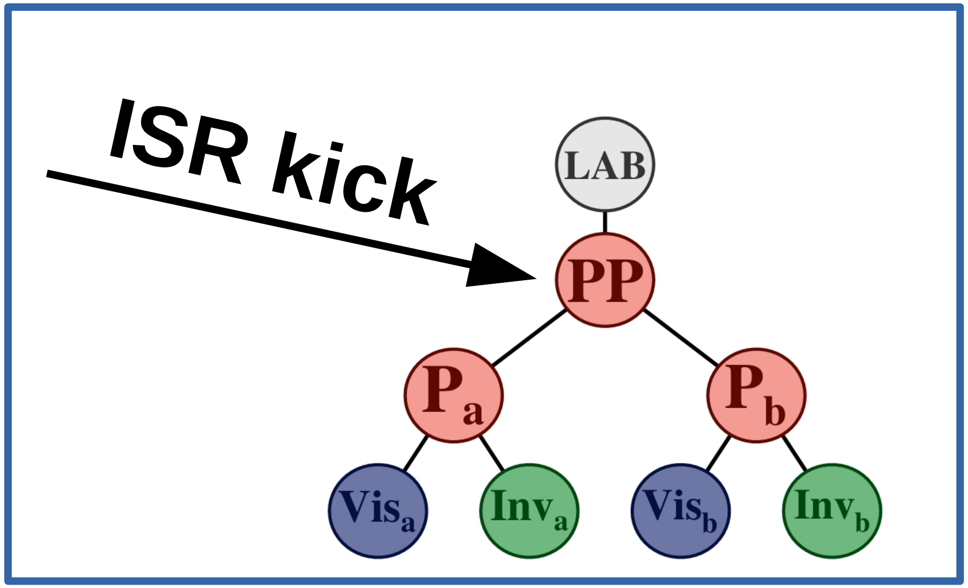



$M_{\tilde{P}}$

- **Challenge**
  - Low momentum decay products are hard to detect
  - The LSPs result in a low value of the transverse missing momentum $\vec{\not{E}}_T$
- To separate signal from BGs, consider only events with a high **momentum** of the **initial state radiation (ISR) system**
- In the limit where the LSPs receive no momentum from their parents' decays:

$$\vec{\not{E}}_T \sim -\vec{p}_T^{\,\mathrm{ISR}} \times \frac{M_{\tilde{\chi}_1^0}}{M_{\tilde{P}}}$$

# Sparticles in motion

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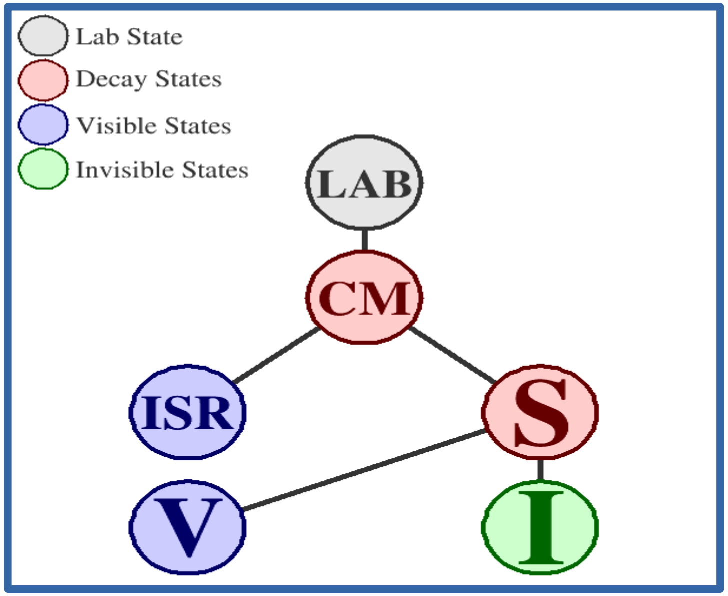



- A ***simple transverse*** decay view of the event:
  - **CM**: centre-of-mass system including all visible objects and MET
  - **ISR:** radiation not coming from sparticle decays
  - **S**: the Signal/SUSY system decaying in
  - **V**: Visible system,
  - **I**: Invisible system = missing transverse momentum
- How do we separate initial state radiation from the other decay products?

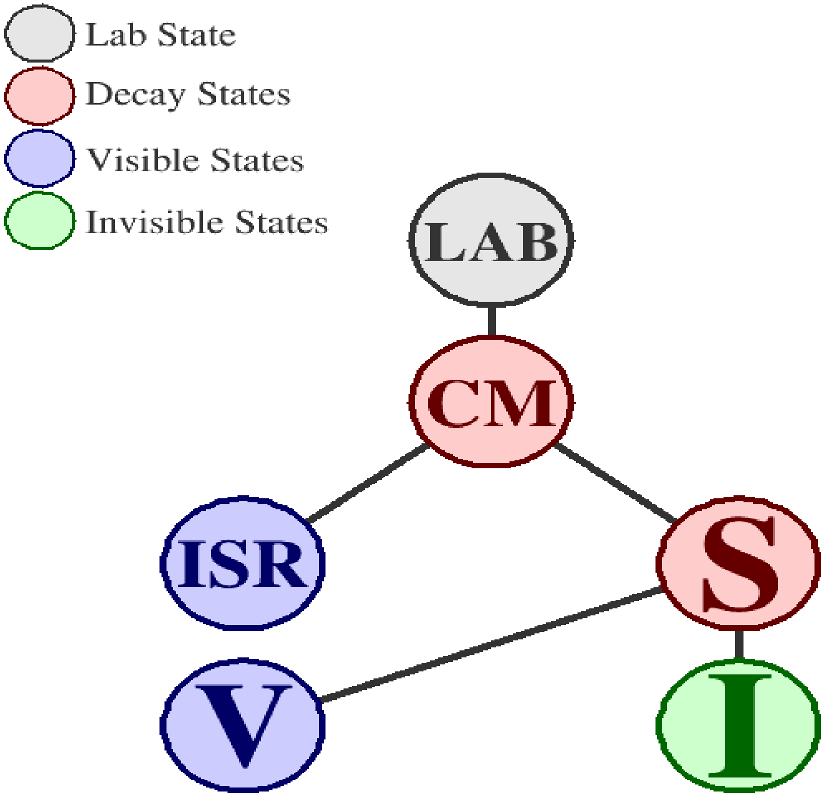
# The compressed Recursive Jigsaw Reconstruction tree

- **Consider the worst scenario: final states with only light jets and MET**
- We want to **separate** the jets between the visible system (**V**) and those recoiling against it (**ISR**)
- *Transverse* view of the event $(P_z\,(jet_i) = 0)$
- Zero mass for **I** system
- $\vec{P}_T(\mathrm{CM}) = \vec{\not{E}}_T + \sum_i \vec{P}_T\,(jet_i)$

  Boost in the *estimated* **CM** frame
- Combinatoric jigsaw rule based on the minimization of the masses

  In CM frame $E_{CM} \equiv M_{\mathrm{CM}} = \sqrt{M_{\mathrm{ISR}} + p^2} + \sqrt{M_{\mathrm{S}} + p^2}$

  Equivalent to maximize p or find the thrust axis in the CM frame



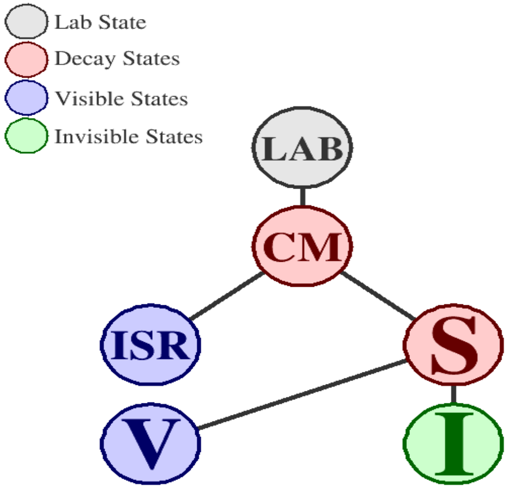
# A complete basis of variables

Kinematics observables to probe SUSY in the compressed regime

$p^{\mathrm{CM}}_{\mathbf{ISR},T}$ Magnitude of the jets vector-sum transverse momentum of **ISR**-system evaluated in the CM frame ( $\vec{p}^{\,\mathrm{CM}}_{\mathbf{ISR},T} = -\vec{p}^{\,\mathrm{CM}}_{\mathbf{S},T}$ )

$$R_{\mathrm{ISR}} \equiv \frac{\left|\vec{p}^{\,\mathrm{CM}}_{\mathbf{I},T} \cdot \hat{p}^{\mathrm{CM}}_{\mathbf{ISR},T}\right|}{p^{\mathrm{CM}}_{\mathbf{ISR},T}} \sim \frac{M_{\tilde{\chi}^0_1}}{M_{\tilde{P}}}$$

Variable sensitive to the mass ratio




$M^{\mathrm{S}}_{T}$ Transverse mass of **S** system (**V**+**I**)

$N^{V}_{jet}$ Number of jets assigned to the **V** system (i.e. not associated with the ISR system)

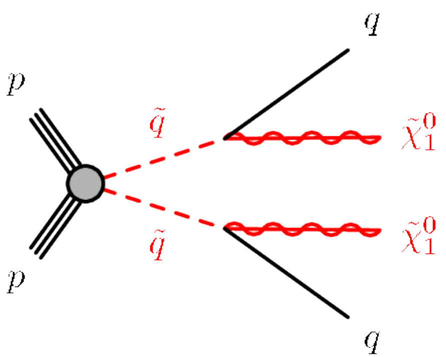
$\Delta\phi_{\mathbf{ISR},\mathbf{I}}$ Opening angle between the ISR system and the I system, evaluated in the CM frame.

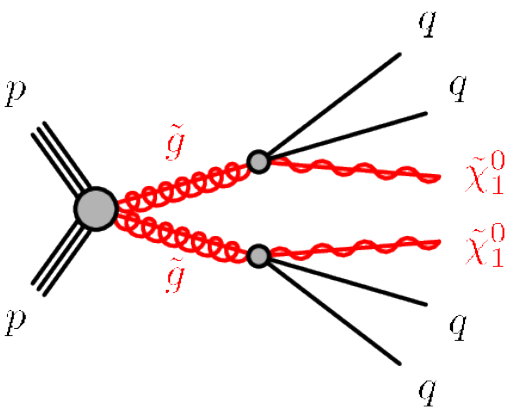
# The samples

- Samples of all major Standard Model backgrounds as part of the Snowmass study simulated at 14TeV (see arXiv:1308.1636 and 1309.1057 for details)

- All signal and BG samples are generated/simulated using same versions and data_cards Madgraph+Pythia+Delphes with jet-parton matching and corrections for next-to-leading order (NLO) contributions.

- ***Signals: Squark*** and ***Gluino pair production*** in the compressed-regime



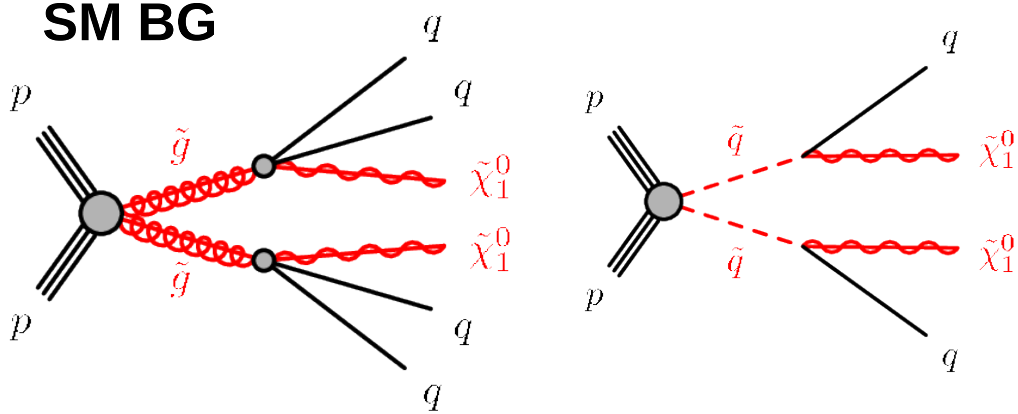

- Mass splittings: $M_{\tilde{P}} - M_{\tilde{\chi}_1^0} = 25, 50, 100, 200 \text{ GeV}$

- Squark mass $500 \text{ GeV} \leq M_{\tilde{q}} \leq 1000 \text{ GeV}$ Gluino Mass: $500 \text{ GeV} \leq M_{\tilde{g}} \leq 1400 \text{ GeV}$

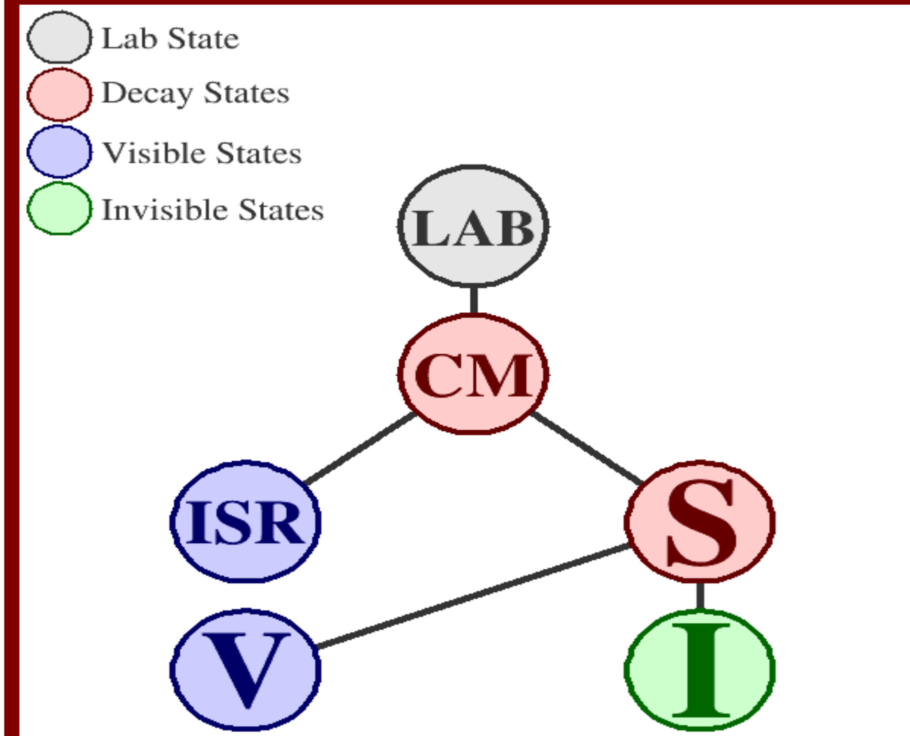
- All samples are scaled to a projection of $\int L = 100\text{fb}^{-1}$ arXiv:1607.08307 [hep-ph]

# The compressed RJR tree

**SM BG**

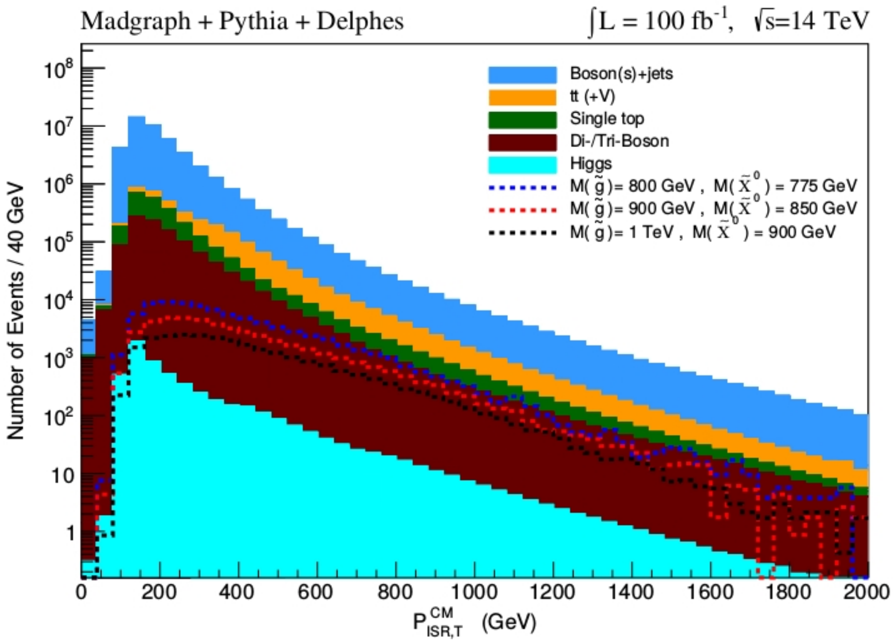


- Pre-selection criteria: final states with
  - Lepton veto (e and mu)
  - $\not{E}_T > 100\ \mathrm{GeV}$
  - $p_T(jet) > 20\ \mathrm{GeV}$




**Complete basis of RJR observables**

# Compressed kinematics for squark/gluino

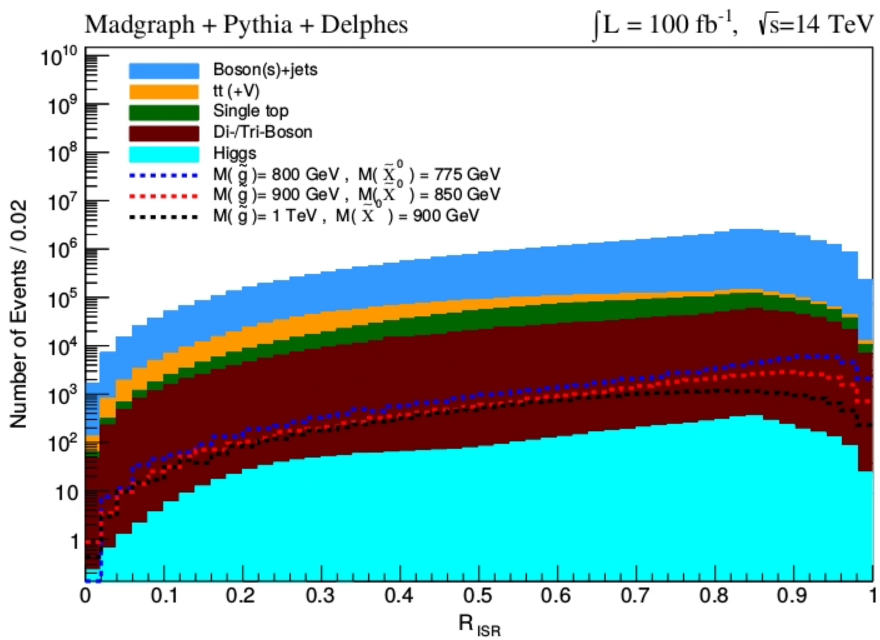



$p^{\mathrm{CM}}_{\mathbf{ISR},T}$ magnitude of vector-sum transverse momentum of all 'ISR' associated jets evaluated in CM frame

Little discrimination in the absence of other cuts

$$R_{\mathrm{ISR}} \equiv \left| \vec{p}^{\,\mathrm{CM}}_{\mathbf{I},T} \cdot \hat{p}^{\,\mathrm{CM}}_{\mathbf{ISR},T} \right| / p^{\mathrm{CM}}_{\mathbf{ISR},T}$$

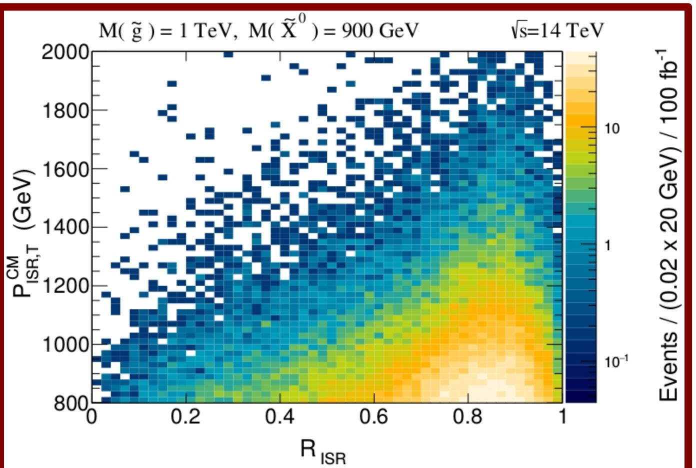
Our choice for $\dfrac{M_{\tilde{\chi}^0_1}}{M_{\tilde{P}}}$ sensitive variable

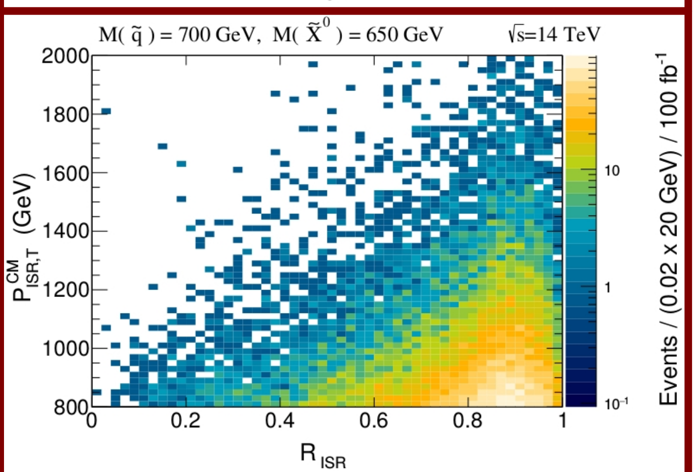


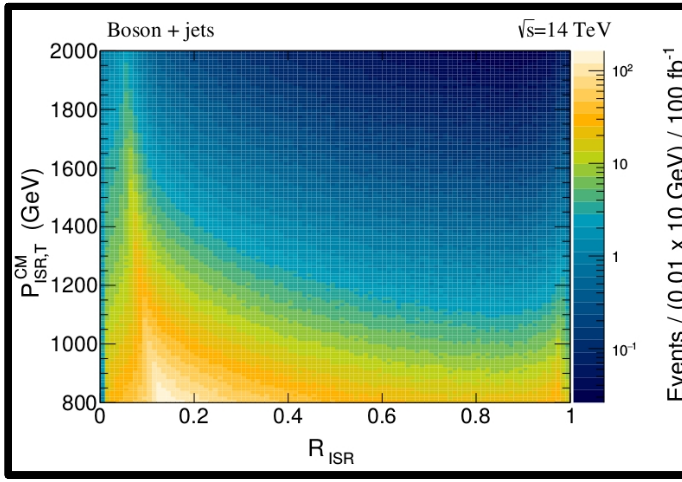
Backgrounds

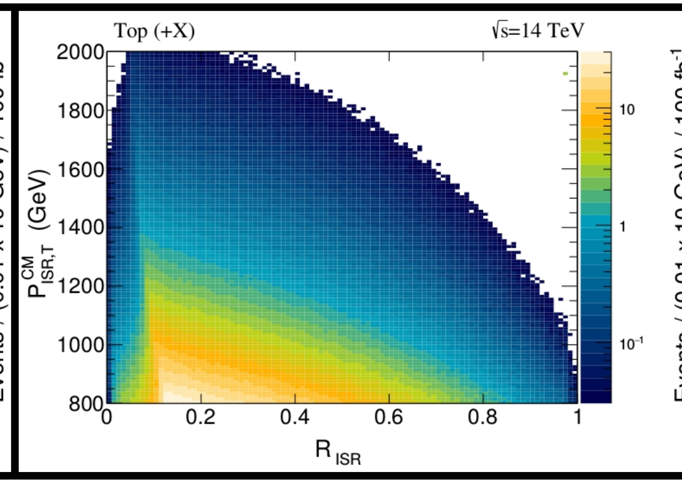
$R_{\text{ISR}}$ vs $p^{\text{CM}}_{\textbf{ISR},T}$

Signal



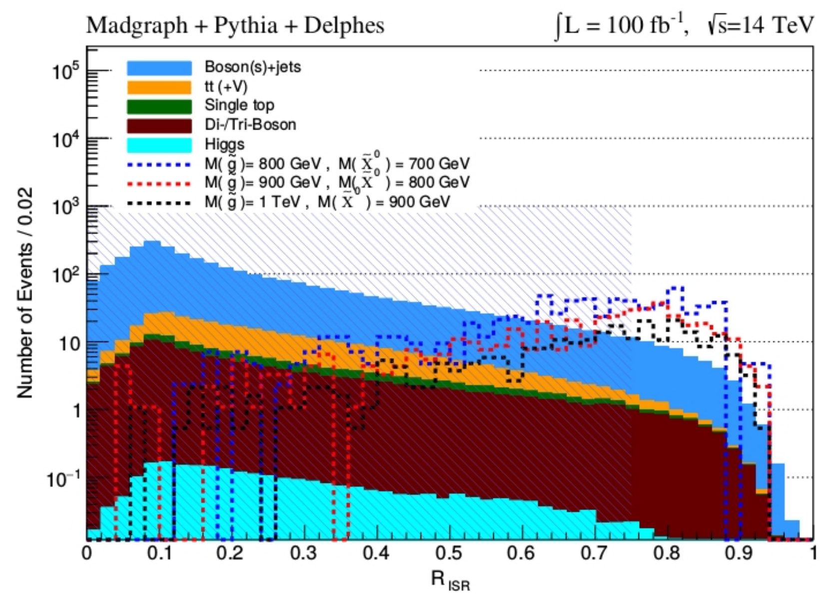



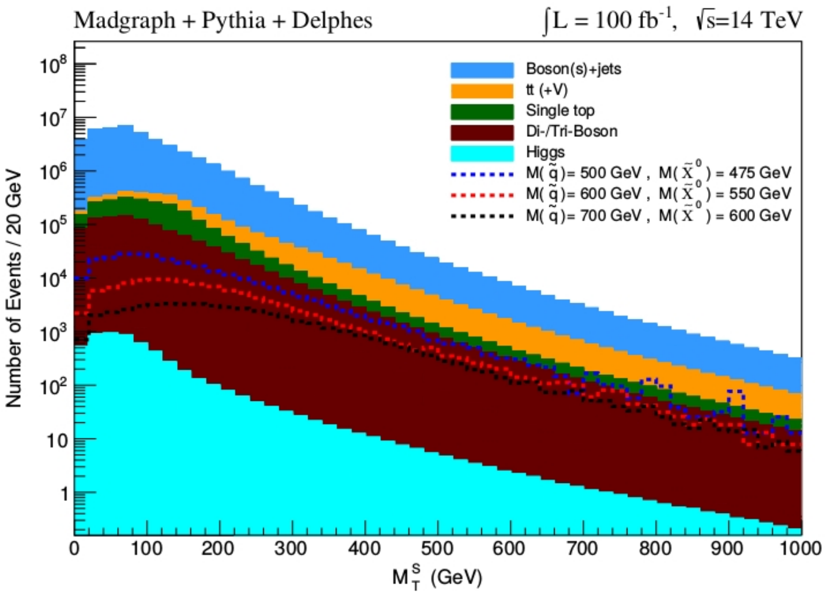

Increasingly hard for backgrounds to have large $R_{\text{ISR}}$ for higher $p^{\text{CM}}_{\textbf{ISR},T}$

$R_{\text{ISR}}$

**Great discrimination in the high ISR-regime**



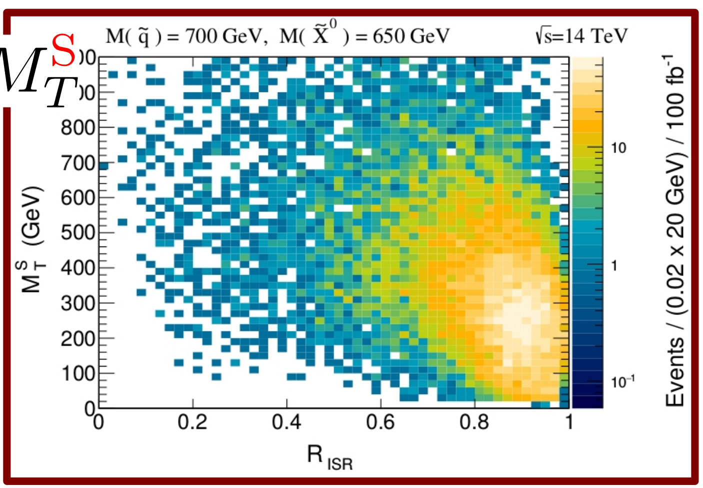
# Transverse mass of the S-system

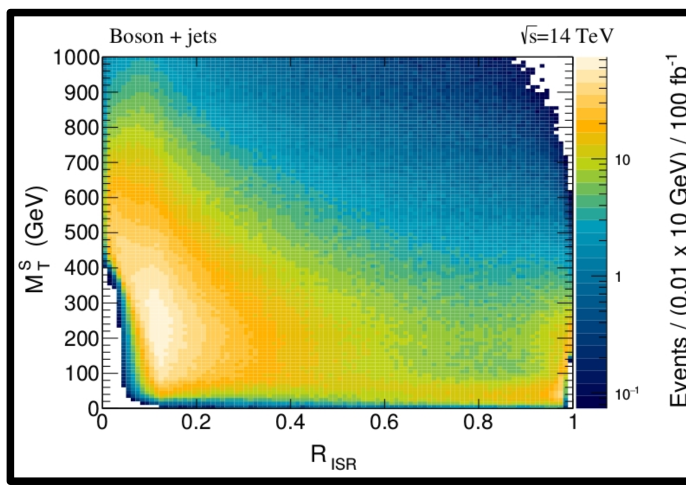


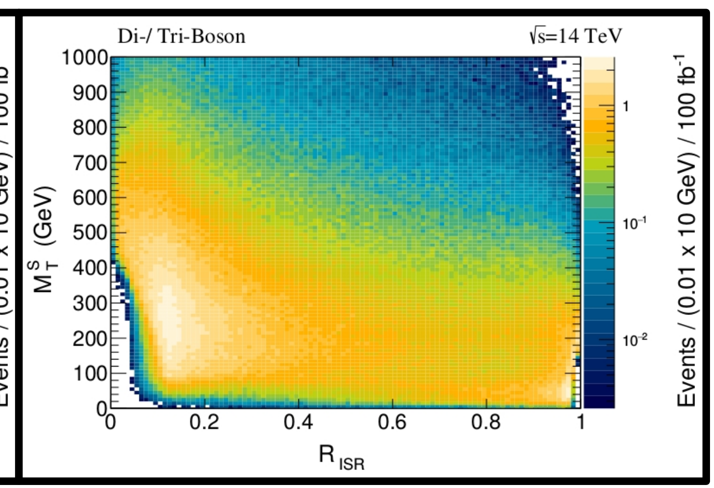

$M_T^S$ Transverse mass of **S** (**V**+**I**) system

- Largely uncorrelated: complementary with other variables
- Good discrimination particularly against V+jets

$M_T^S$

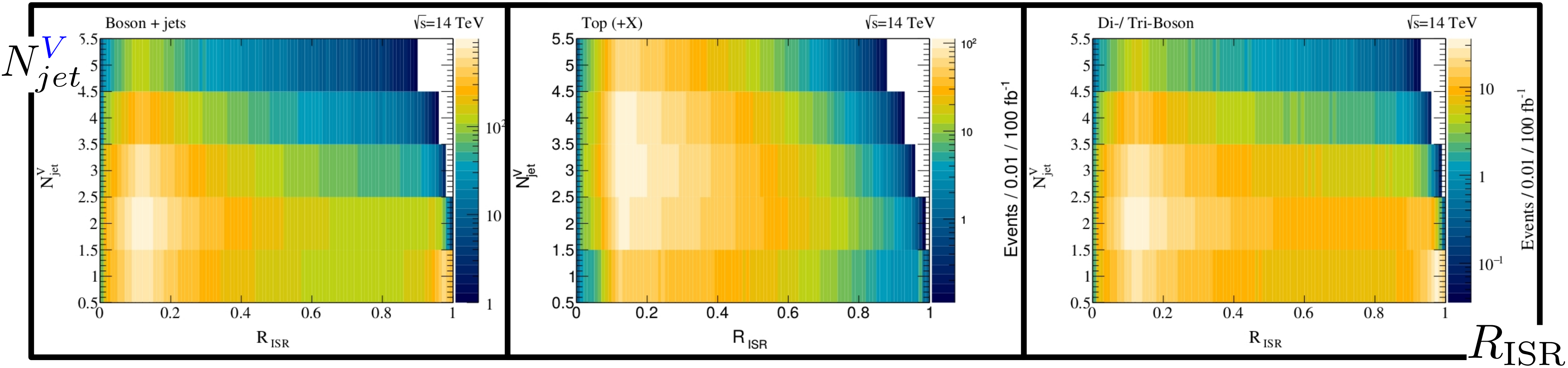


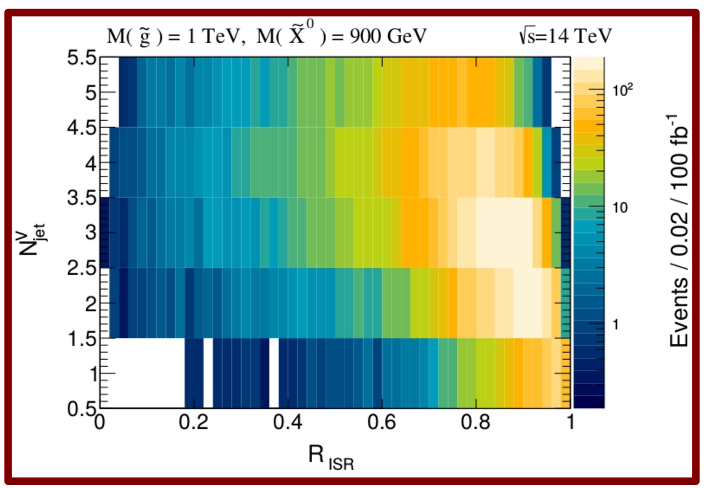




$R_{\text{ISR}}$

# Jet multiplicity in the V-system

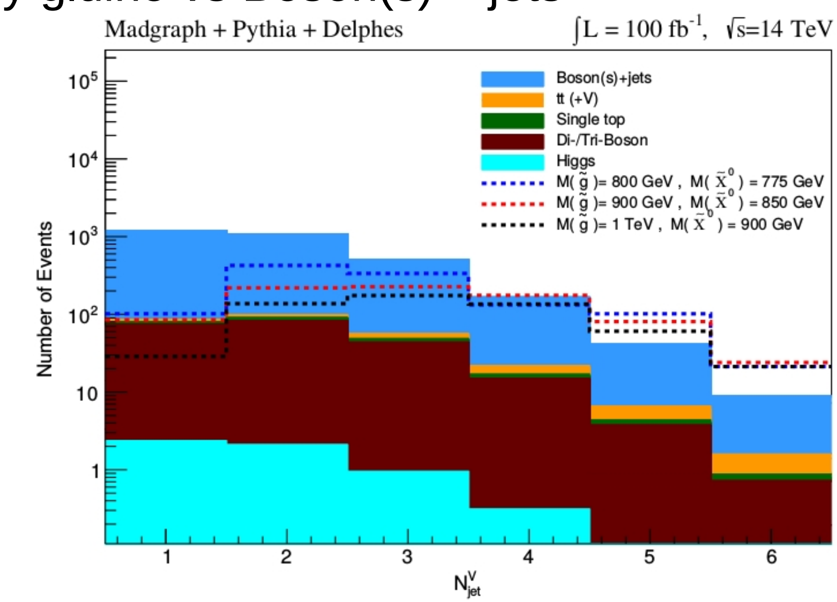



After the high $p^{\rm CM}_{{\bf ISR},T}$ selection criterion, we get excellent performances cutting harder on the jet multiplicity together with the ratio: particularly gluino vs Boson(s) + jets




$N^{V}_{jet}$

Number of jets
in V-system



# Inclusive gluino (squark) signal regions

A set of selection criteria for signal regions in the analysis of gluino (squark) pair-production defined targeting the mass splittings.

| Variable \ Mass splitting [GeV] | $\Delta M = 25$ | $\Delta M = 50$ | $\Delta M = 100$ | $\Delta M = 200$ |
|---|---|---|---|---|
| Preselection criteria | Lepton (e and mu) and *b*-jet veto, $\not{E}_T > 100$ GeV, $p_T(jet) > 20$ GeV | | | |
| $p^{\mathrm{CM}}_{\mathbf{ISR},T}$ [GeV] | > 1000 | | | |
| $R_{\mathrm{ISR}}$ | > 0.9 | > 0.85 | > 0.75 | > 0.65 |
| $M_T^{\mathrm{S}}$ [GeV] | - | 100 | 250 | 400 |
| $N^{V}_{jet}$ | ≥ 3 (≥ 2) | | ≥ 4 (≥ 2) | |
| $p_T^{jet3,V}$ $(p_T^{jet2,V})$ [GeV] | > 20 (> 40) | > 30 (> 60) | > 40 (> 120) | > 50 (> 140) |
| $\Delta\phi_{\mathbf{ISR},\mathbf{I}}$ | > 3.0 | | | |

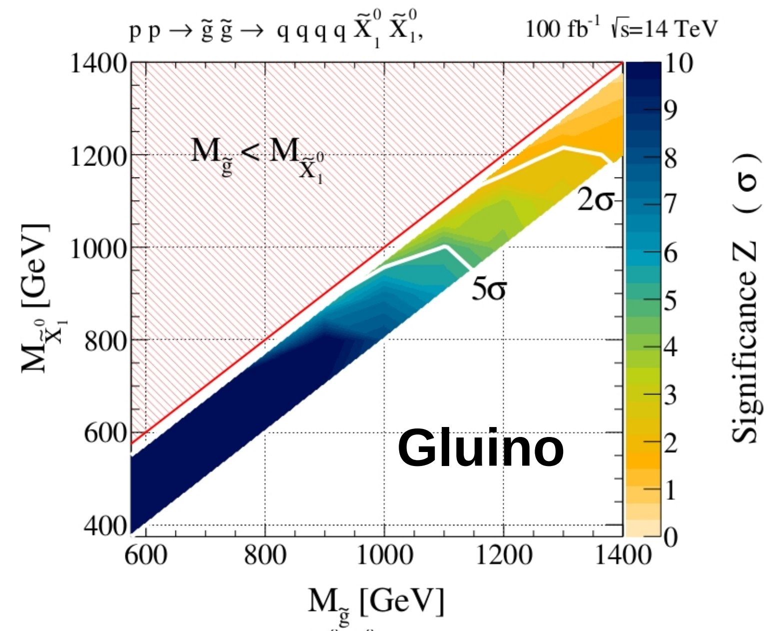
# Results

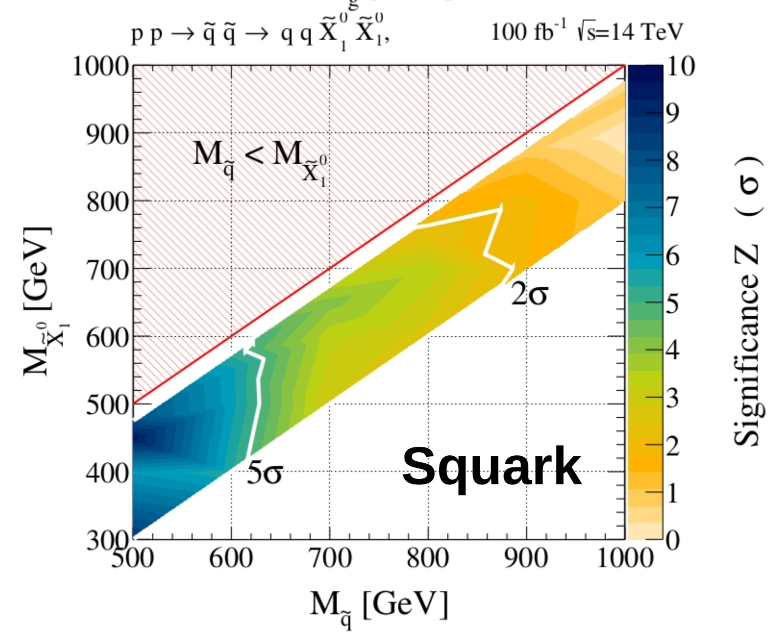
- Z-score from the RJR inclusive signal regions
- We assume **15%** for the background systematic uncertainty
- **Gluino** *Discover:* above 1 TeV
  *Exclusion:* up to 1.4 TeV
- **Squark** *Discover:* above 600 GeV
  *Exclusion:* between 800 and 900 GeV
- Optimisation can be improved using different signal regions for squark and gluino

RJR technique is used by ATLAS collaboration.

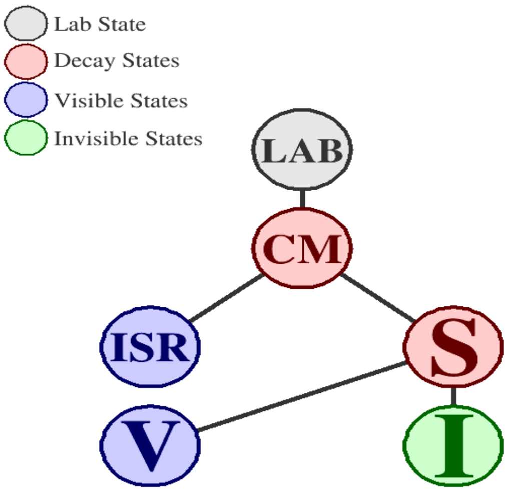
Compressed gluino-squark:

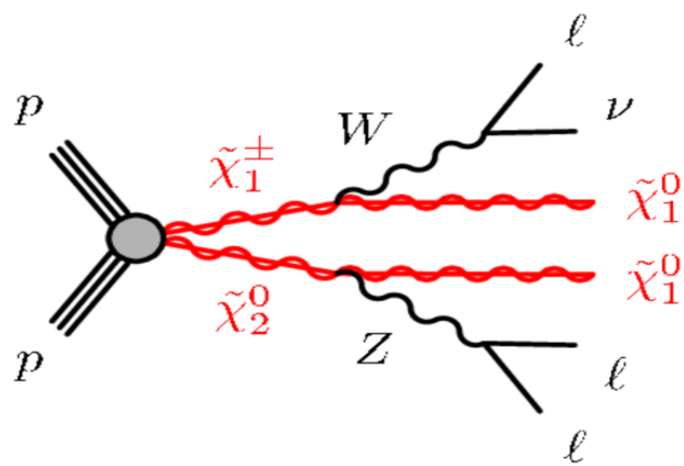
*ATLAS-CONF-2016-078 - ATLAS-CONF-2016-077*

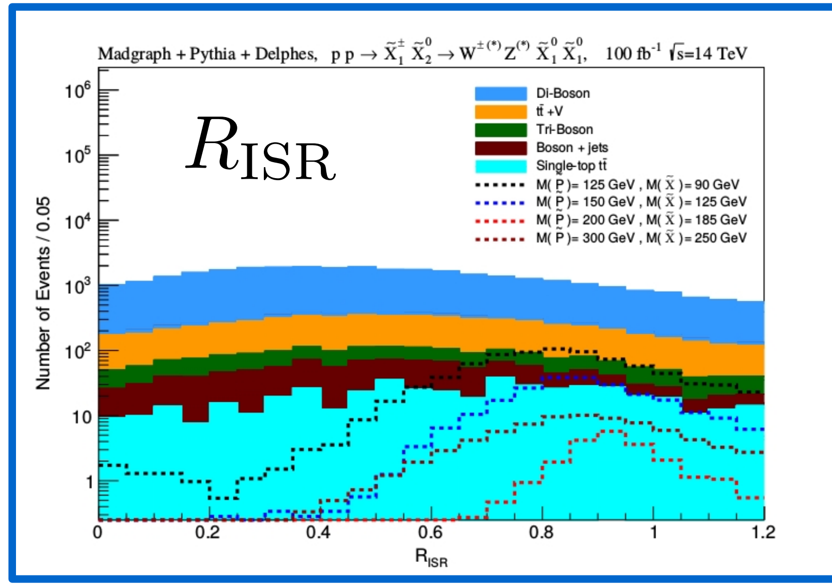


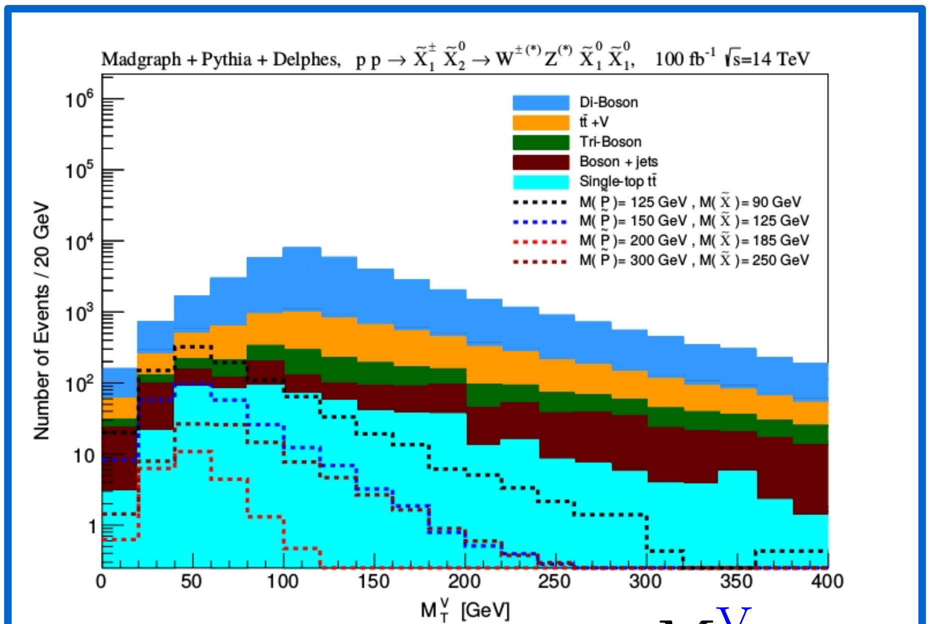



# SUSY EWK : associated neutralino chargino production




$M_T^V$

No ambiguity in the assignment

**V**-system = leptons

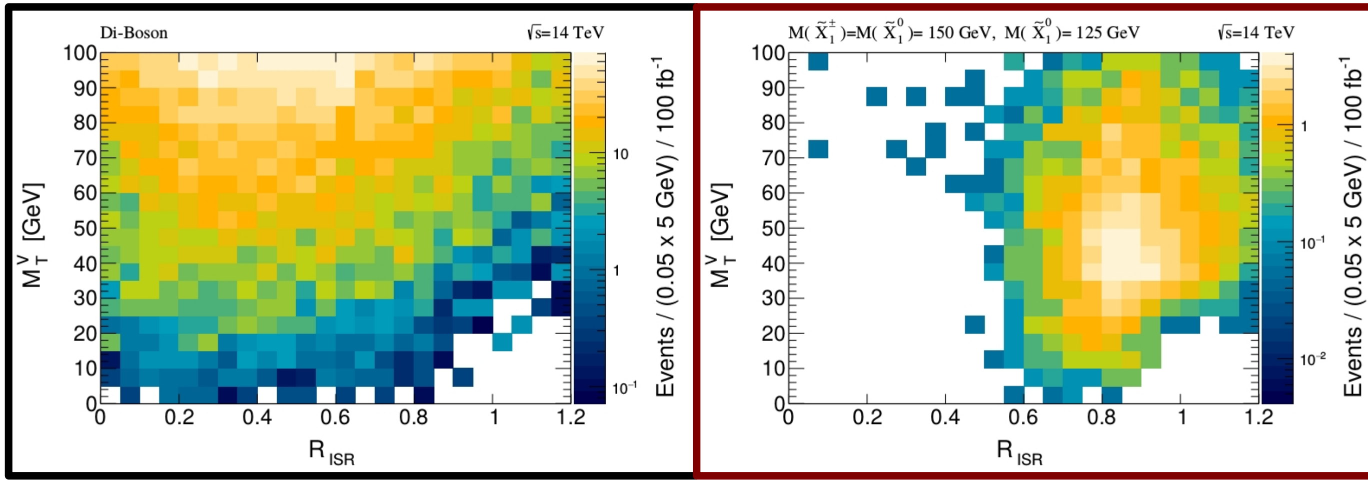
**ISR**-system = jets

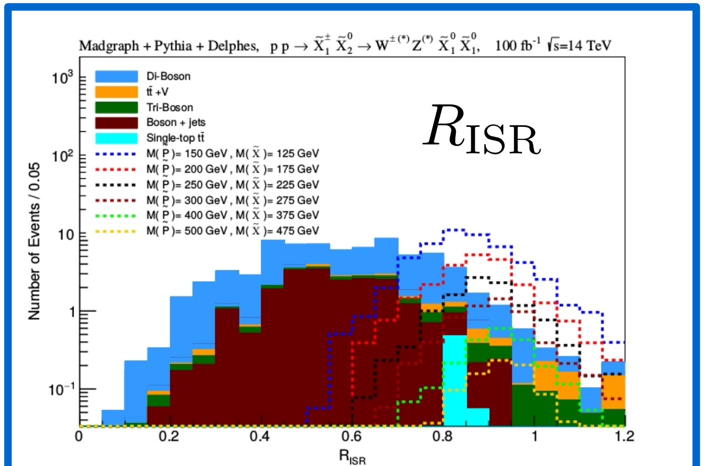
$M_T^V$ : Transverse Mass of the Visible system

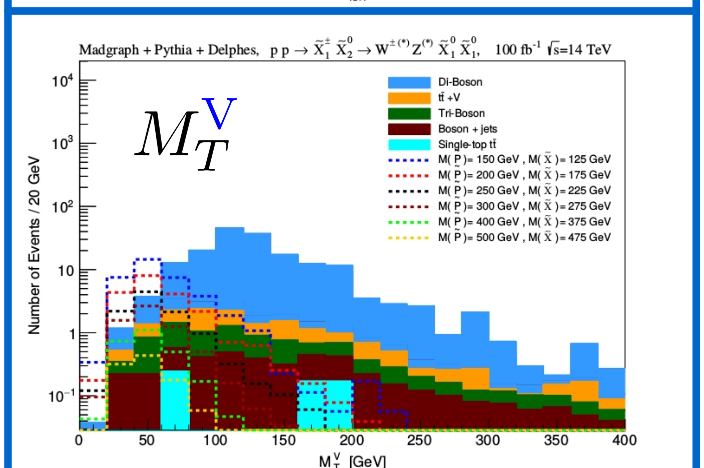
$$M_{\tilde{P}} - M_{\tilde{\chi}_1^0} = 15, 25, 35, 50, 75\ \mathrm{GeV}$$

# EWKino: associated neutralino chargino production

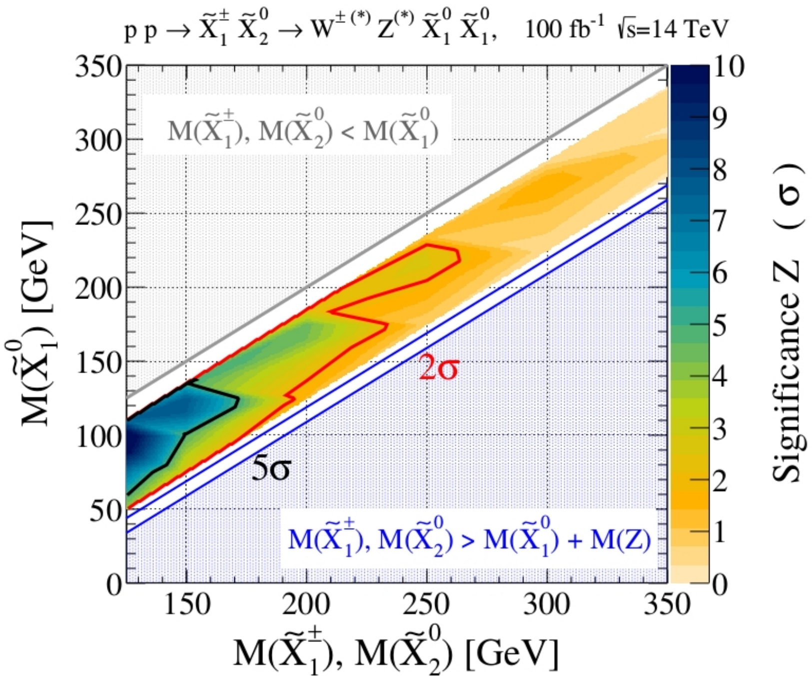
$R_{\mathrm{ISR}}$ vs $M_T^{V}$ →



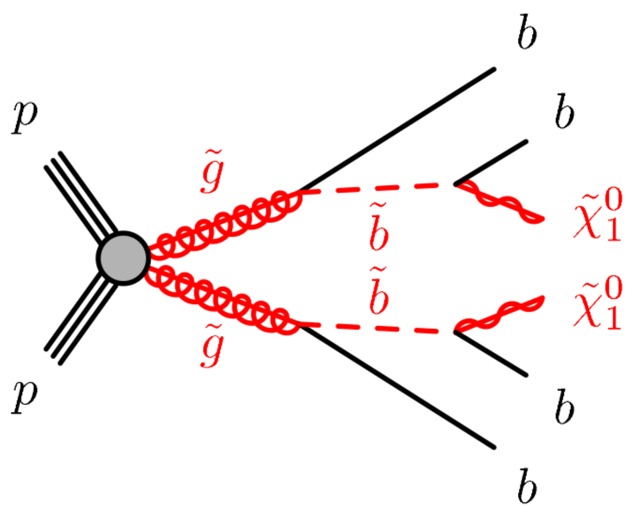

← Applying selection criteria based on RJR observables

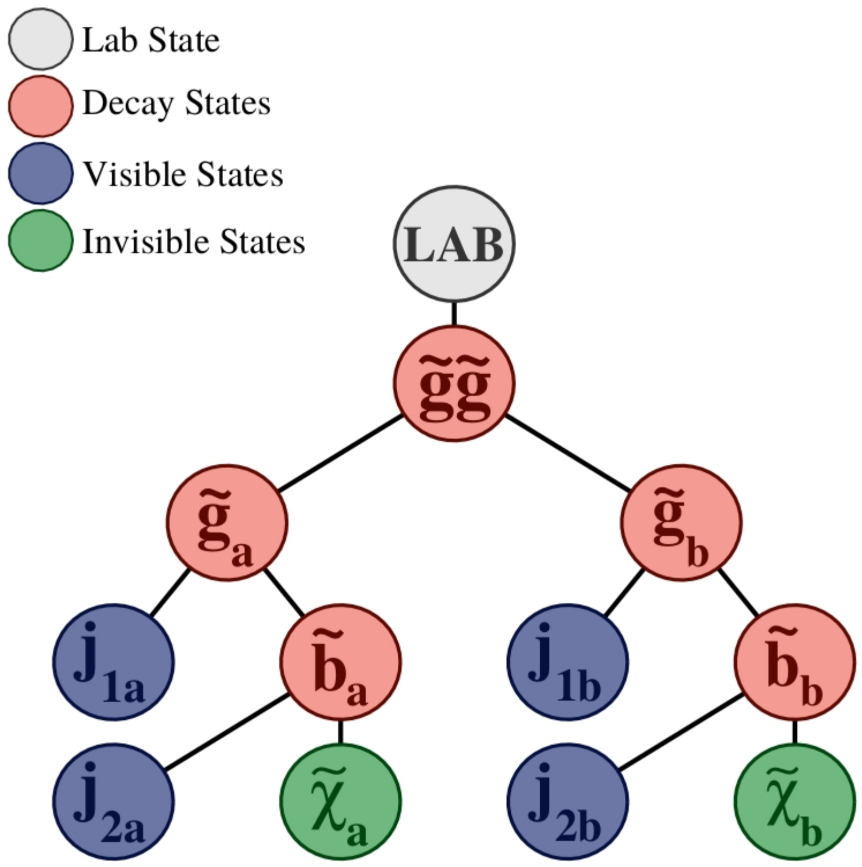



Z-value assuming **15%** of systematic uncertainty and

$$\int L = 100\text{fb}^{-1}$$

# Gluino mediated sbottom pair production



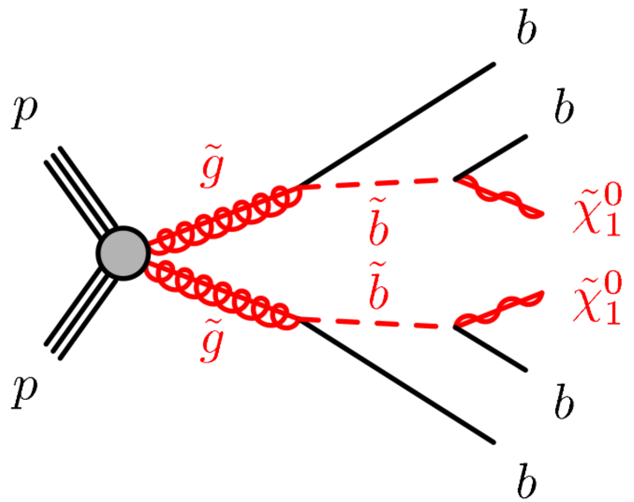



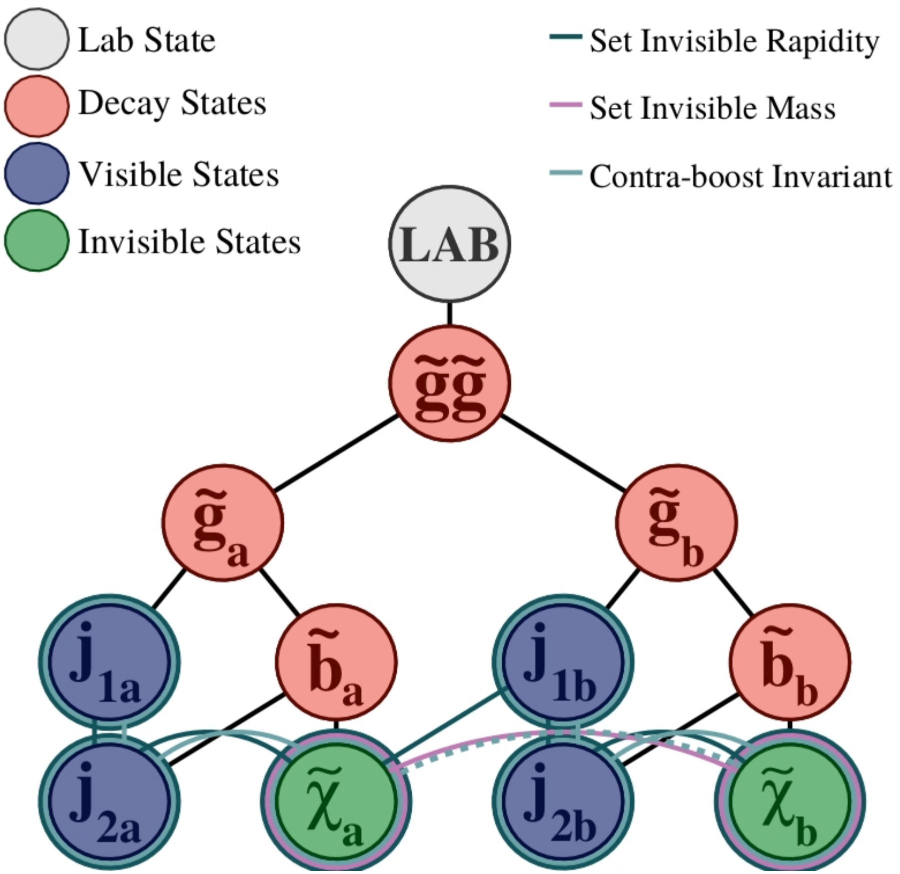

- Open mass spectra: RJR tree describes the SUSY substructure
- Jigsaw rules: **unknown d.o.f. + combinatoric** travelling recursively through the frames
- Complete basis of scale and angular variables computed in the appropriate frame

$$\mathrm{M}_{\tilde{g}\tilde{g}} \quad \mathrm{E}(\mathrm{j}_{1a}) \; \mathrm{E}(\mathrm{j}_{2a}) \; \mathrm{E}(\mathrm{j}_{1b}) \quad \mathrm{E}(\mathrm{j}_{2b})$$

$$\cos\theta_{\tilde{g}\tilde{g}} \quad \cos\theta_{\tilde{g}_a} \quad \cos\theta_{\tilde{g}_b} \quad \cos\theta_{\tilde{b}_a} \quad \cos\theta_{\tilde{b}_b} \quad \triangle\varphi_{\tilde{g}_a\tilde{g}_b} \quad \triangle\varphi_{\tilde{g}_a\tilde{b}_a} \quad \triangle\varphi_{\tilde{g}_b\tilde{b}_b}$$

# Gluino mediated sbottom pair production

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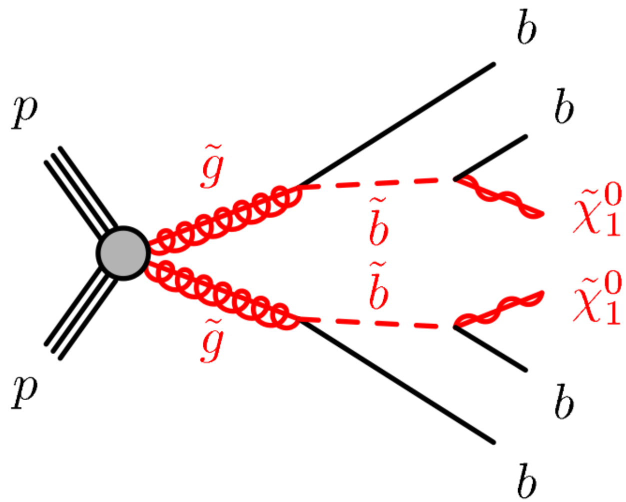
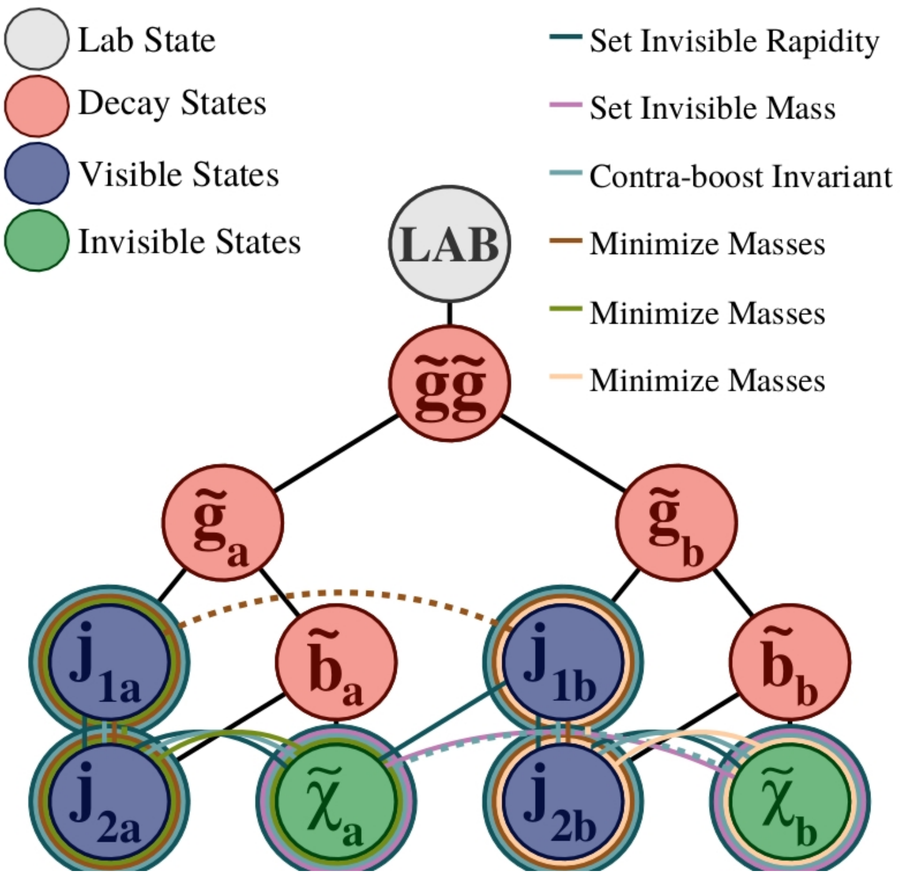
# Gluino mediated sbottom pair production

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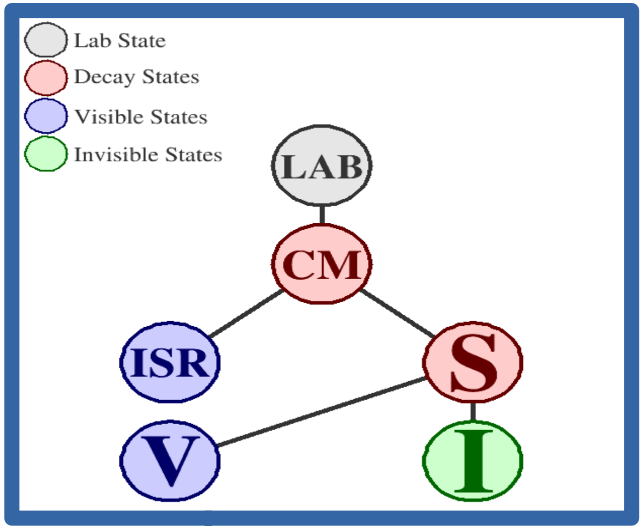
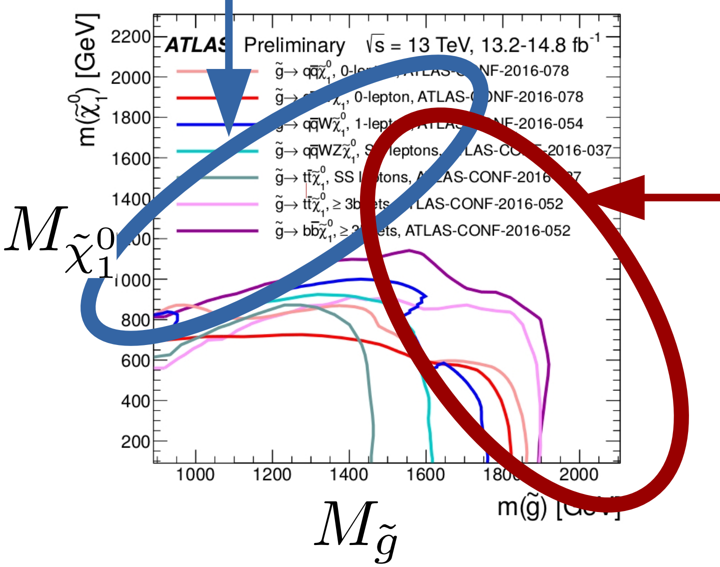
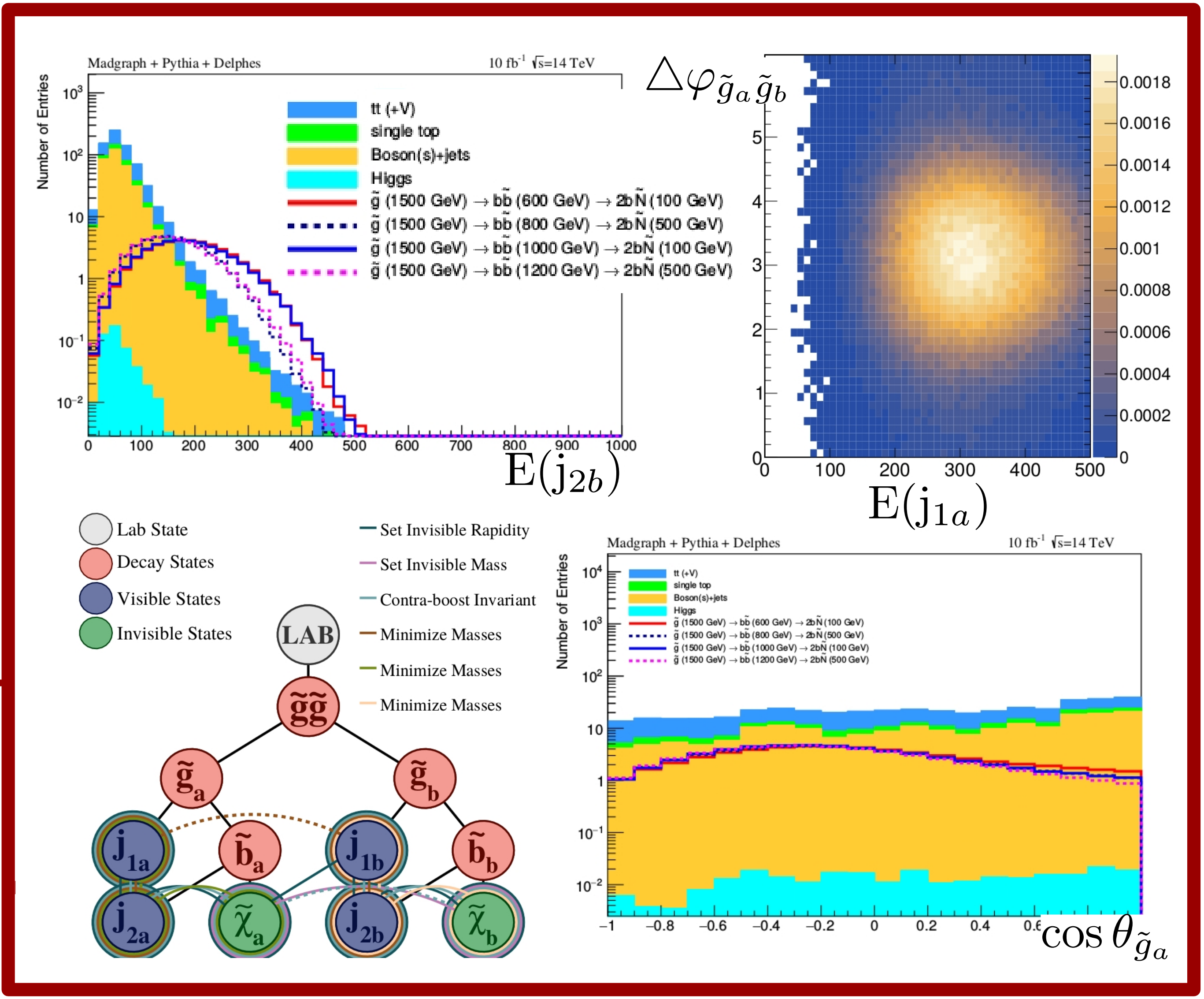
$$M_{\tilde{g}\tilde{g}} \quad E(j_{1a}) \quad E(j_{2a}) \quad E(j_{1b}) \quad E(j_{2b})$$

$$\cos\theta_{\tilde{g}\tilde{g}} \quad \cos\theta_{\tilde{g}_a} \quad \cos\theta_{\tilde{g}_b} \quad \cos\theta_{\tilde{b}_a} \quad \cos\theta_{\tilde{b}_b} \quad \triangle\varphi_{\tilde{g}_a\tilde{g}_b} \quad \triangle\varphi_{\tilde{g}_a\tilde{b}_a} \quad \triangle\varphi_{\tilde{g}_b\tilde{b}_b}$$

# Gluino mediated sbottom production

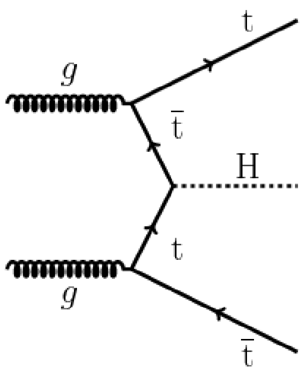



Work in progress with Paul Jackson and Chris Rogan

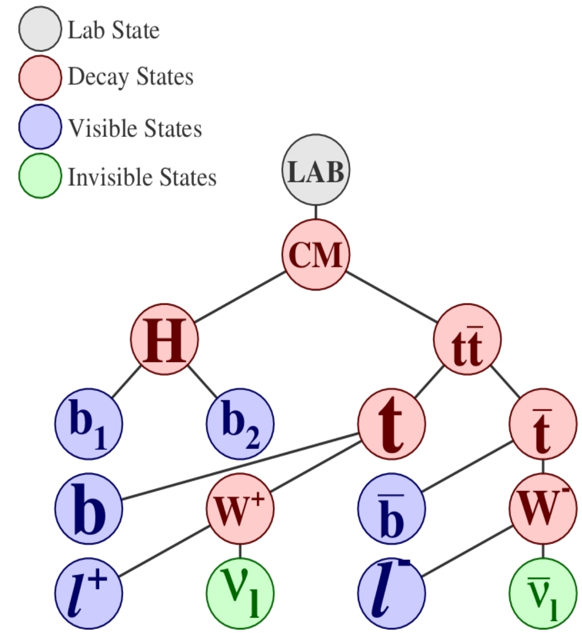
# Higgs + top pair production in di-leptonic channel

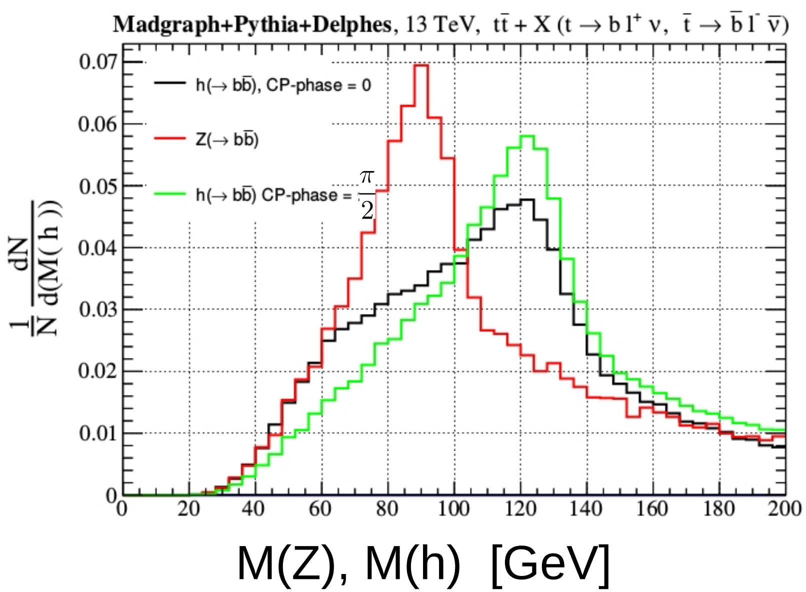


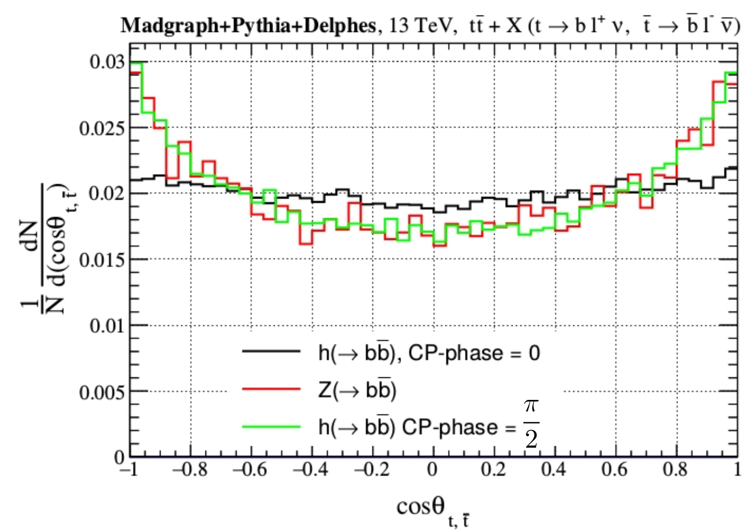

RJR tree →

Compare the observables that are sensitive to the CP nature of the Higgs

Demonstrate the feasibility of the di-leptonic channel of $t\bar{t} + h$ at LHC with the RJR method




Work in progress with Lei Wu and Jason Yue

# Summary - Outlook

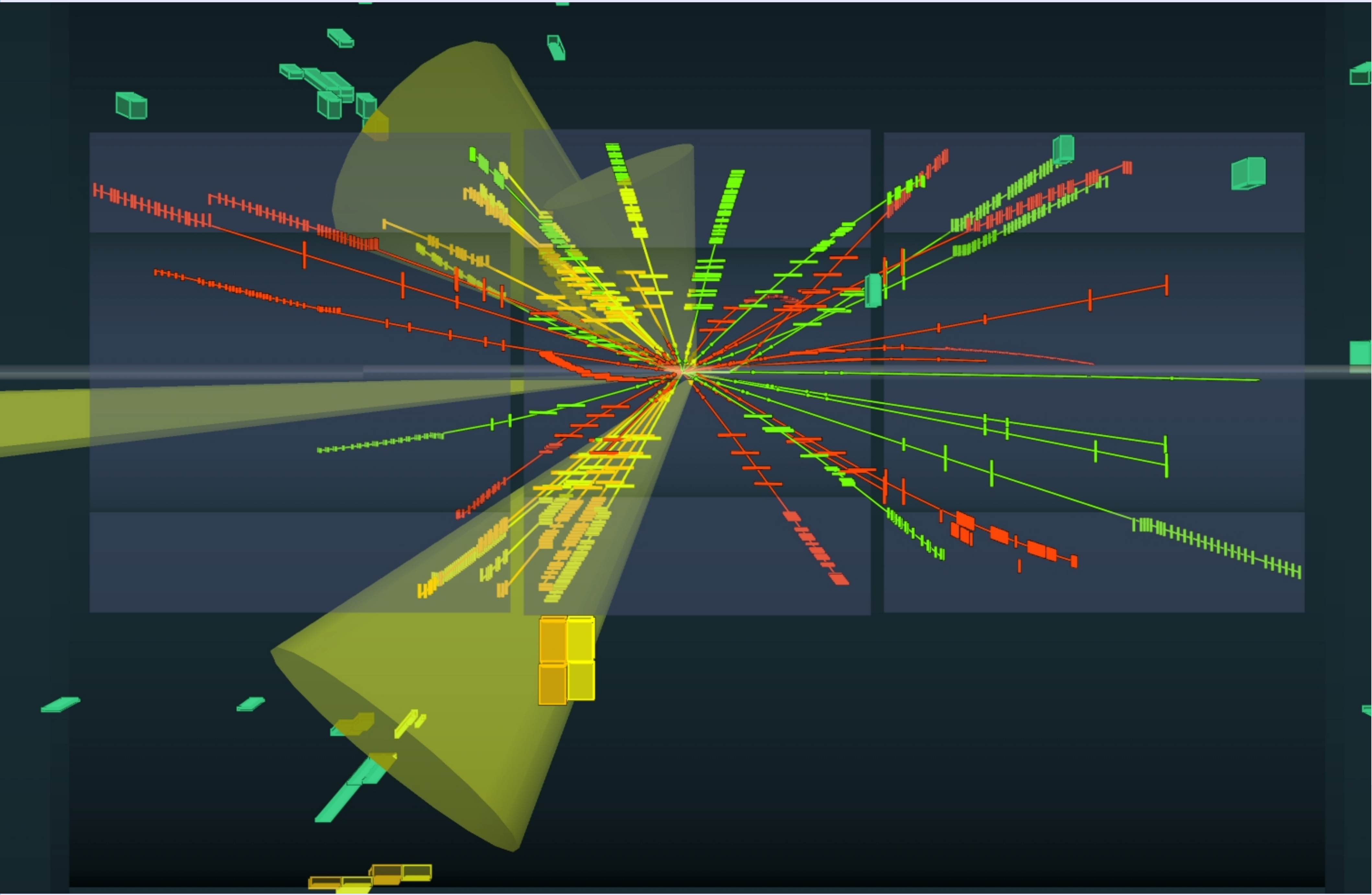
- Demonstrated a new approach for **open** and **compressed** analyses based on the Recursive Jigsaw Reconstruction technique

- Compressed gluino - squark scenarios: excellent performance for all mass-splittings and final state topologies studied (arXiv:1607.08307 [hep-ph])
- Compressed EWKino: No ambiguity in assignment of leptons and jets to ISR-V system:
  - Excellent performance for associated neutralino chargino production
  - In preparation → chargino pair production

- RJR can be applied in principle to any open final states: SUSY and beyond
  - Gluino mediated sbottom production
  - Top pair (in di-leptonic channel) + Higgs
  - …

- The method is already being used by the ATLAS collaboration

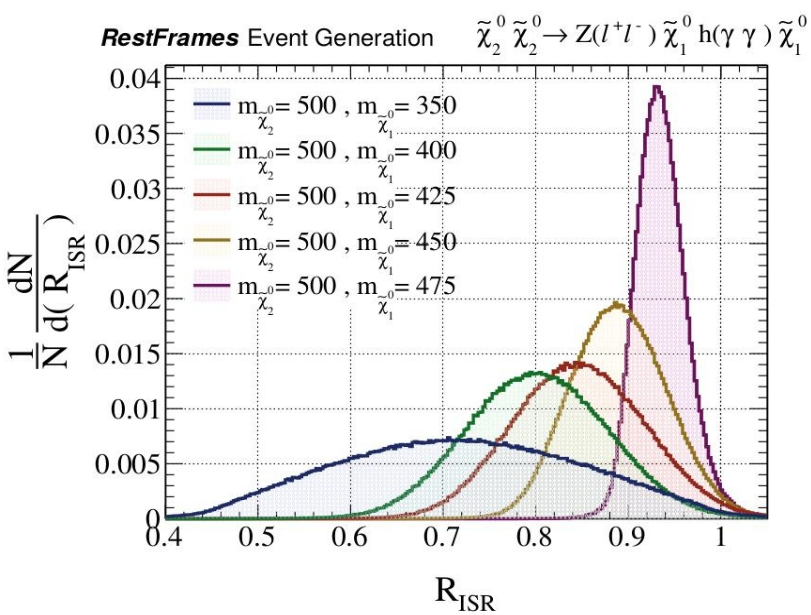
# THANKS FOR YOUR ATTENTION

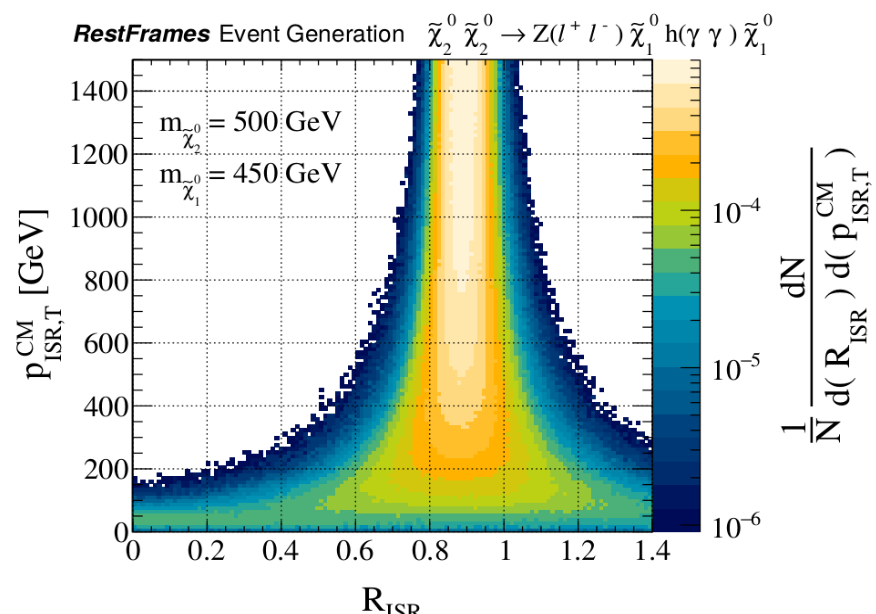


- In the limit of soft momentum of the LSPs in the sparents frame:

$$R_{\mathrm{ISR}} \sim \left|\not{E}_T \cdot \hat{p}_{\mathbf{ISR},T}\right| / p_{\mathbf{ISR},T} \sim \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{P}}} \left[ 1 + \mathcal{O}\left(\frac{p^{\tilde{P}}_{\tilde{\chi}_1^0}}{2m_{\tilde{P}}}\right) \left(\frac{\sqrt{p^2_{\mathbf{ISR},T} + m^2_{\tilde{P}\tilde{P}}}}{p_{\mathbf{ISR},T}}\right) \sin\Omega \right]$$

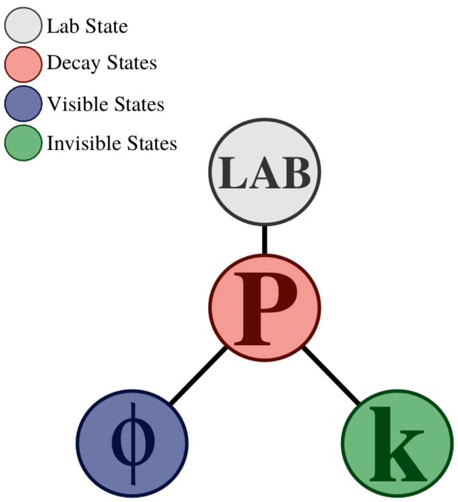
- R scales nicely with the mass ratio - Width depends on DM - Resolution improves with PTISR



# Backup slides: set rapidity of the invisible particles

$$\beta_z\,(Lab \rightarrow Tra) \qquad 0 = \frac{\partial E_{\phi}^{Tra}}{\partial \beta_z}$$

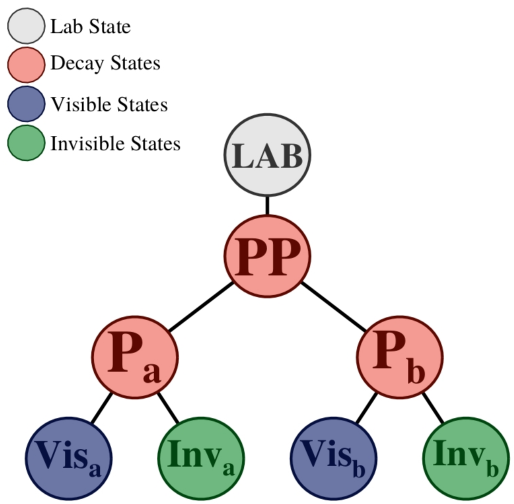



$$0 = \left(1-\beta_z^2\right)^{-3/2}\left(\beta_z E_{\phi} - p_z(\phi)\right)$$

$$\beta_z = \frac{p_z(\phi)}{E_{\phi}}$$

The guess for $p_z^{Tra}(P) = 0$

Being $p_z^{Tra}(\phi) = 0 \rightarrow p_z^{Tra}(k) = 0$




All the observables in the transverse frame and any frames that recursively follow from it are independent from the true value → Generalization

$$\beta_z = \frac{p_z(Vis_a) + p_z(Vis_b)}{E_{Vis_a} + E_{Vis_b}}$$

# Backup slides: NC signal regions

| $\downarrow$ Variable $\backslash \Delta M$ [GeV] $\rightarrow$ | $\Delta M = 15$ | $\Delta M = 25$ | $\Delta M = 35$ | $\Delta M = 50$ | $\Delta M = 75$ |
|---|---|---|---|---|---|
| Objects criteria | 3 Leptons (e and mu) $p_T(lep) > 10$ GeV, | | | | |
| | At least one jet, $p_T(jet) > 20$ GeV, $N^{\rm ISR}_{b-jet} = 0$ | | | | |
| $p^{\rm CM}_{{\rm ISR},T}$ ($\not{E}_T$) [GeV] | $> 50$ | | | $> 70$ | $> 100$ |
| $N^{\rm ISR}_{jet}$ | $< 3$ | $< 4$ | | $< 3$ | |
| $M_T^{\rm V}$, for 3 SFL [GeV] | $< 40$ | $< 50$ | $< 60$ | $< 70$ | $< 80$ |
| $M_{l^+l^-}$, for 2 SFL [GeV] | $< \Delta M$ with $M_T^{\rm V} < 100$ GeV | | | | |
| $\Delta\phi_{\rm CM,I}$ | $> 2$ | | | | |
| $\Delta\phi_{\rm ISR,I}$ | $> 3$ | | | | |

# Backup slides NC signal regions

$$R_{\rm ISR} \sim \left| \not{E}_T \cdot \hat{p}_{\mathbf{ISR},T} \right| / p_{\mathbf{ISR},T} \sim \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{P}}} \left[ 1 + \mathcal{O}\left( \frac{p^{\tilde{P}}_{\tilde{\chi}_1^0}}{2 m_{\tilde{P}}} \right) \left( \frac{\sqrt{p^2_{\mathbf{ISR},T} + m^2_{\tilde{P}\tilde{P}}}}{p_{\mathbf{ISR},T}} \right) \sin\Omega \right]$$

| GeV $\rightarrow$ | $\Delta M = 15$ | $\Delta M = 25$ | $\Delta M = 35$ | $\Delta M = 50$ | $\Delta M = 75$ |
|---|---|---|---|---|---|
| $M_{\tilde{P}}$=125 GeV | 0.80 – 1.15 | 0.80 – 1.15 | 0.80 – 1.20 | 0.70 – 1.15 | 0.65 – 1.10 |
| $M_{\tilde{P}}$=150 GeV | 0.85 – 1.05 | 0.80 – 1.15 | 0.80 – 1.20 | 0.70 – 1.15 | 0.70 – 1.10 |
| $M_{\tilde{P}}$=200 GeV | 0.85 – 1.05 | 0.85 – 1.15 | 0.80 – 1.20 | 0.70 – 1.15 | 0.70 – 1.10 |
| $M_{\tilde{P}}$=250 GeV | 0.90 – 1.05 | 0.85 – 1.15 | 0.85 – 1.20 | 0.75 – 1.05 | 0.75 – 1.10 |
| $M_{\tilde{P}}$=300 GeV | 0.90 – 1.05 | 0.85 – 1.15 | 0.85 – 1.20 | 0.75 – 1.05 | 0.75 – 1.10 |
| $M_{\tilde{P}}$=400 GeV | 0.90 – 1.05 | 0.90 – 1.15 | 0.85 – 1.20 | 0.80 – 1.05 | 0.75 – 1.10 |
| $M_{\tilde{P}}$=500 GeV | 0.90 – 1.05 | 0.90 – 1.15 | 0.85 – 1.20 | 0.85 – 1.05 | 0.80 – 1.10 |

# Backup slides

- In order to distinguish between signal and backgrounds we need an ISR system to give our sparticles a transverse kick:the response of the sparticle decay products is sensitive to the mass of the LSP

- In the limit where the LSPs receive no momentum from their parents' decays:

$$\vec{\not{E}}_T \sim -\vec{p}_T^{\,\mathrm{ISR}} \times \frac{m_{\tilde{\chi}}}{m_{\tilde{P}}}$$

- Different proxies for pTISR in the recent literature

arXiV:1506.00653 $\frac{\not{E}_T}{p_T^{\text{lead jet}}}$ arXiV:1506.07885v1 $\frac{\not{E}_T}{\sqrt{H_T}}$

arXiv:1605.06479 final state jet hierarchy

- Rather than relying on a clean mono-ISR signal or a priori assumption of the sparticles masses we want to separate "ISR objects" from "sparticle objects"

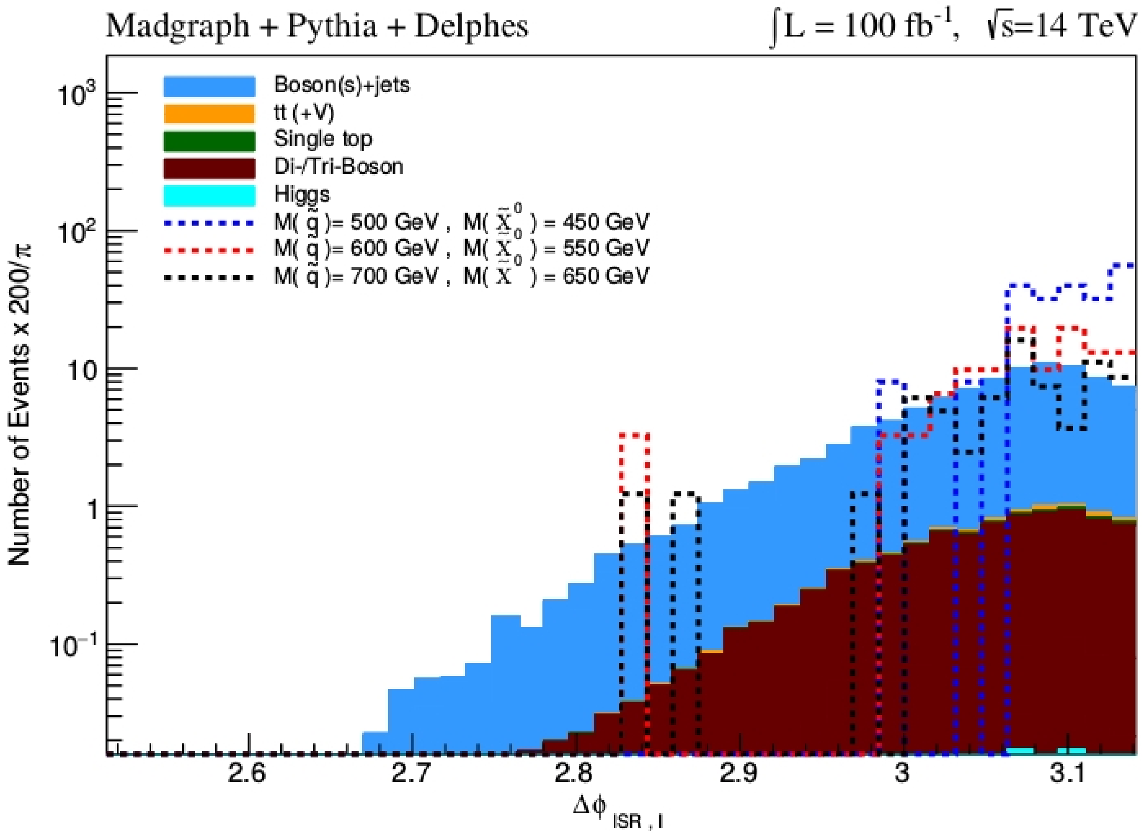
More discrimination from the angular variable

$$\Delta\phi_{\mathbf{ISR},\mathbf{I}}$$

N-1 distribution.

Although both signal and background distributions tend towards π the signal has a much stronger tendency to do so.

Good for optimisation



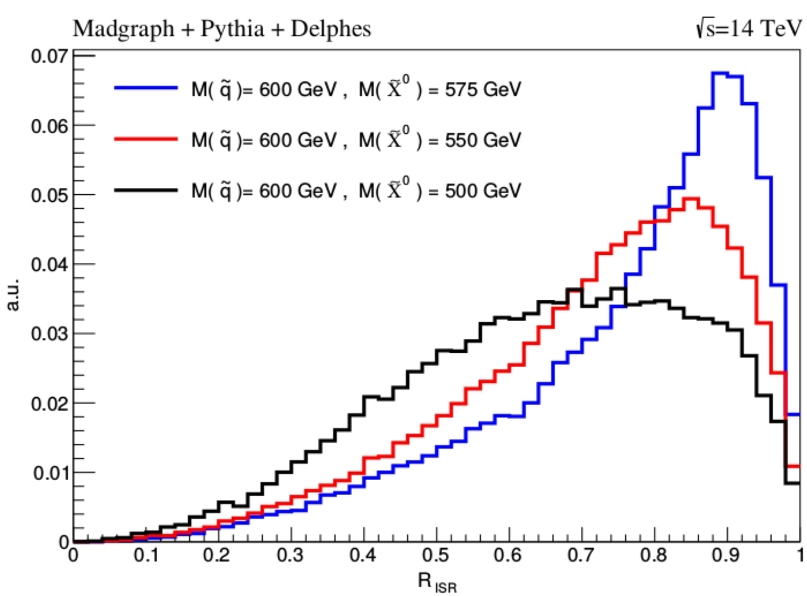
# Backup slides: sparticles in motion

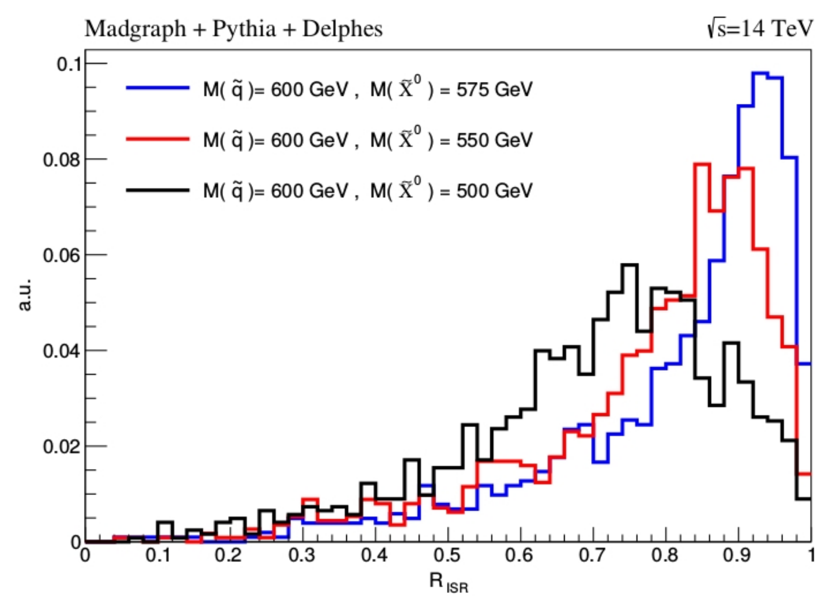
- In the limit of soft momentum of the LSPs in the sparents frame:

$$R_{\rm ISR} \sim \left|\not{E}_T \cdot \hat{p}_{\mathbf{ISR},T}\right| / p_{\mathbf{ISR},T} \sim \frac{m_{\tilde{\chi}^0_1}}{m_{\tilde{P}}} \left[ 1 + \mathcal{O}\left( \frac{p^{\tilde{P}}_{\tilde{\chi}^0_1}}{2m_{\tilde{P}}} \right) \left( \frac{\sqrt{p^2_{\mathbf{ISR},T} + m^2_{\tilde{P}\tilde{P}}}}{p_{\mathbf{ISR},T}} \right) \sin\Omega \right]$$

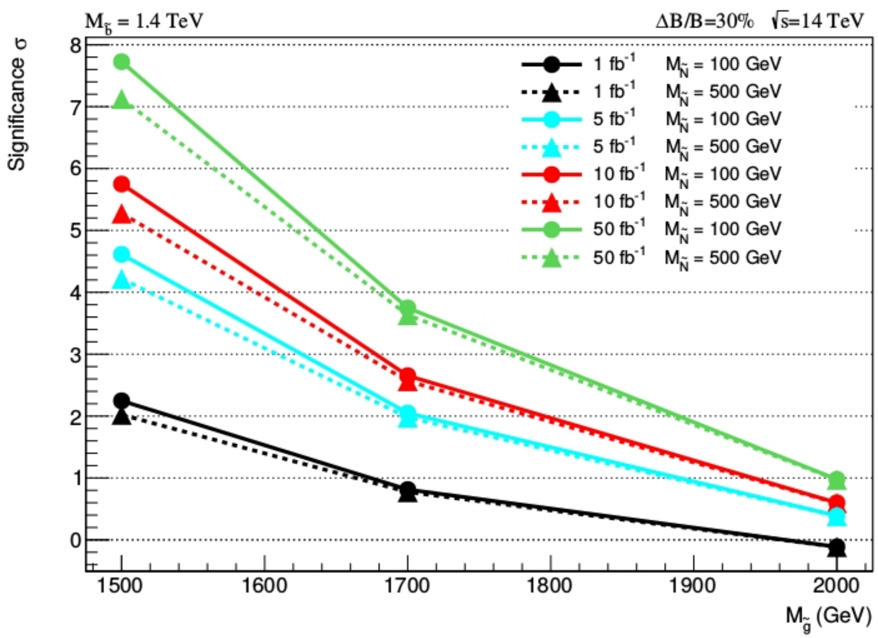
- R scales nicely with the mass ratio. Better after some PTISR requirement
- First term

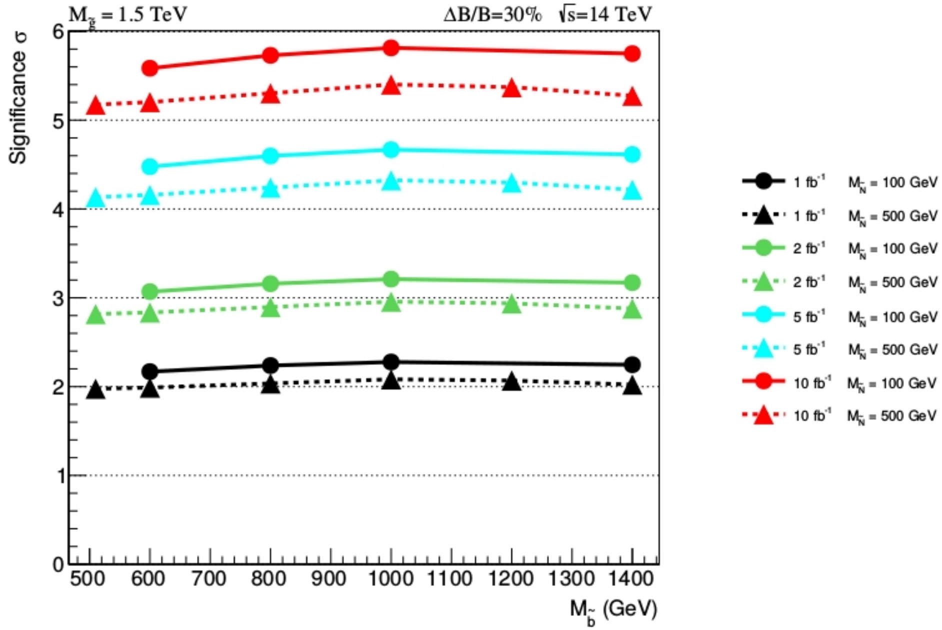
$$\vec{p}^{\,Lab}_{1\chi} + \vec{p}^{\,Lab}_{2\chi} \sim \frac{M_\chi}{M_{\tilde{P}}} \vec{p}^{\,Lab}_{1\tilde{P}} + \frac{M_\chi}{M_{\tilde{P}}} \vec{p}^{\,Lab}_{2\tilde{P}}$$



# Backup slides: preliminary ~gg→ ~bb




Sensitivity decreases with gluino-production cross section as expected

- But it’s pretty independent of LSP mass (till to the compressed regime)
- And very independent of sbottom mass (also off-shell sbottoms)
- Cutting hard on e.g. jet pTs or MET would have killed sensitivity for small mass splittings
- Preliminary, after 5 fb-1 of LHC14, >4σ sensitivity to a 1.5 TeV gluino for low gluino-sbottom and sbottom-LSP mass splittings (30% systematics)

Next → optimization for m(~g) 1.9- 2 TeV and large m(LSP)