COMPRESSED GLUINOS

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with
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1605.06479

Santa Fe Summer Workshop
07 July 2016

Weak Scale SUSY

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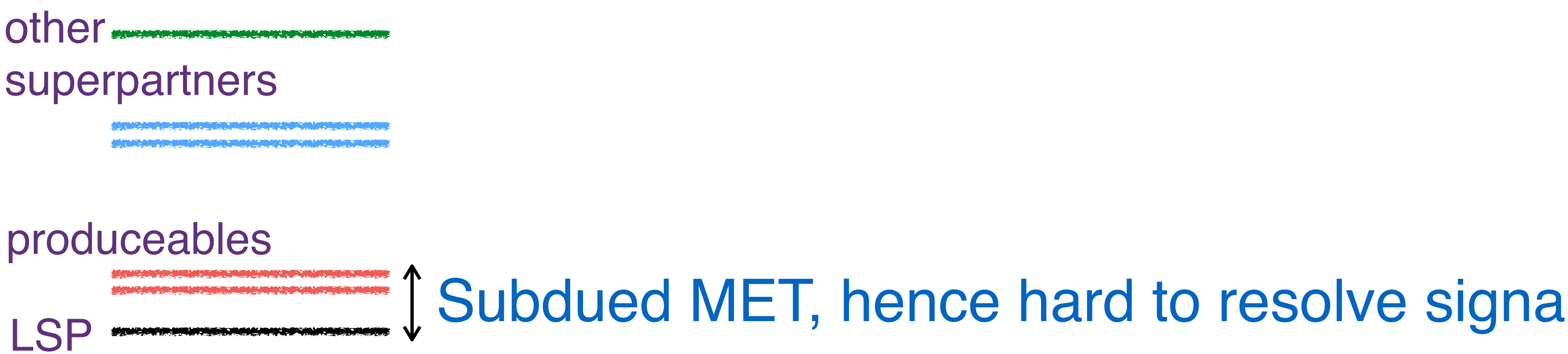
Weak Scale SUSY

- **Signal generator @ the LHC**

“Compressed”



The task is obvious —

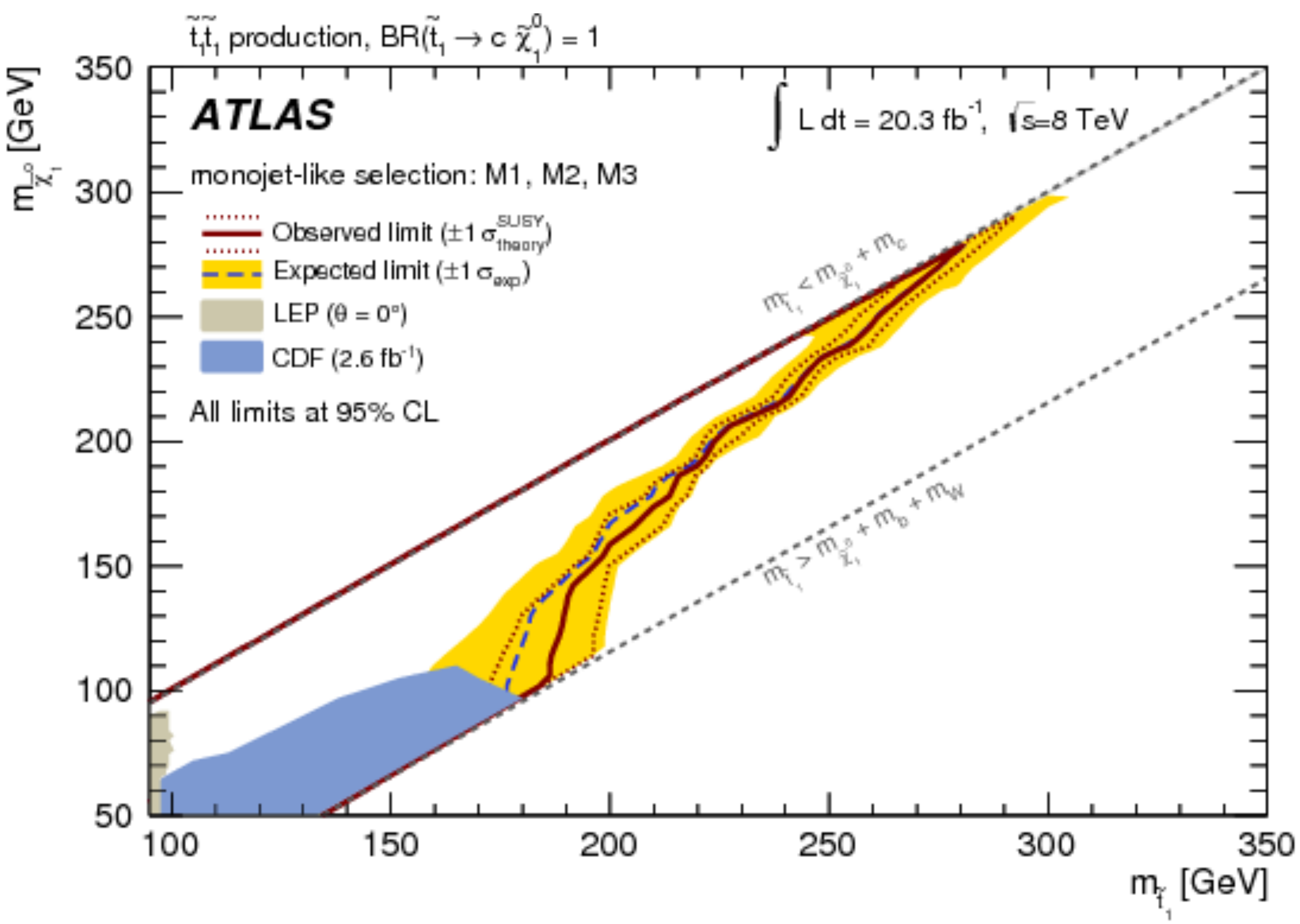
(a) Study unique kinematic features of these spectra,

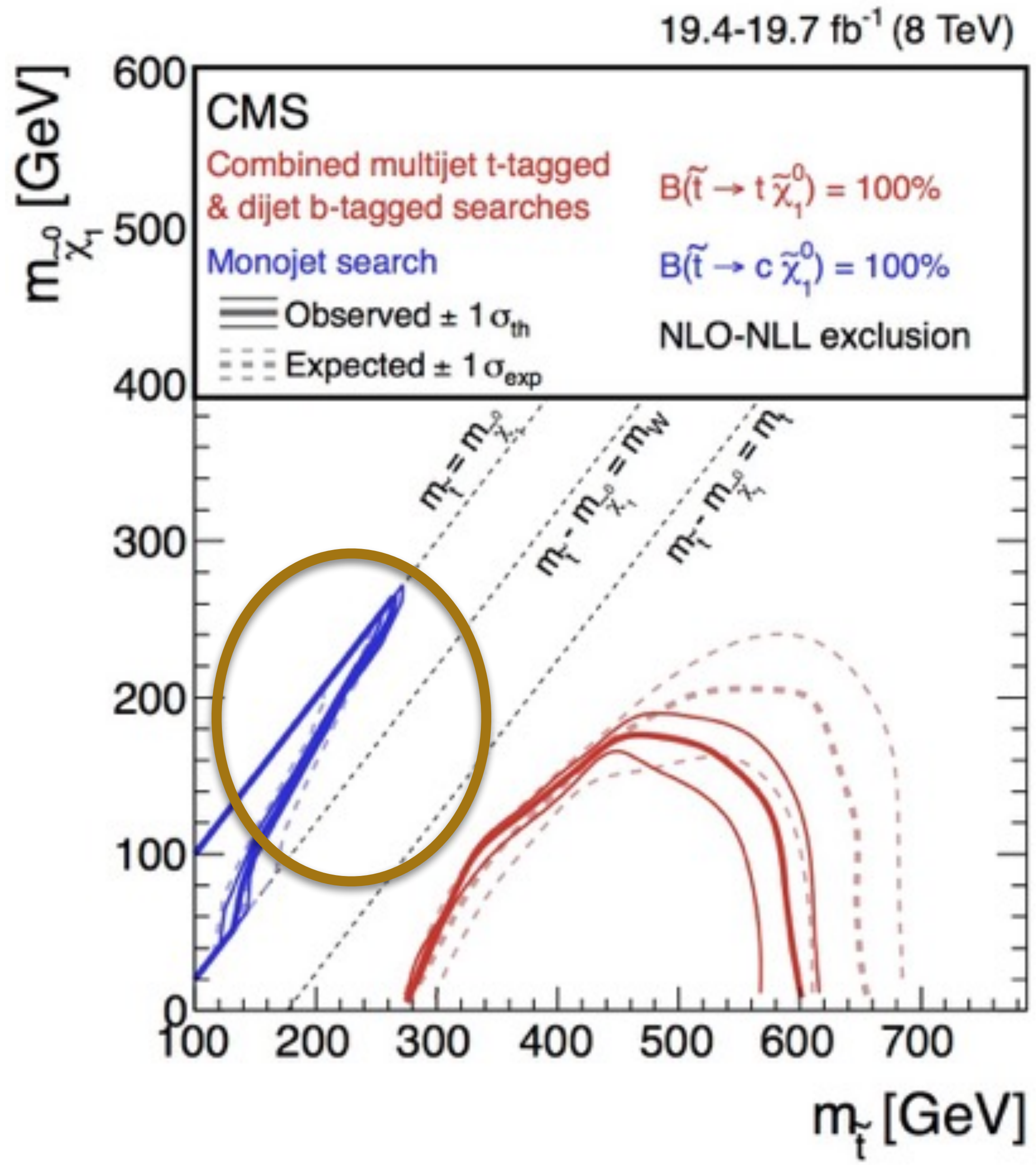
(b) build dedicated strategy to smoke out these features,

[(c) worry about trigger, pileup, …]

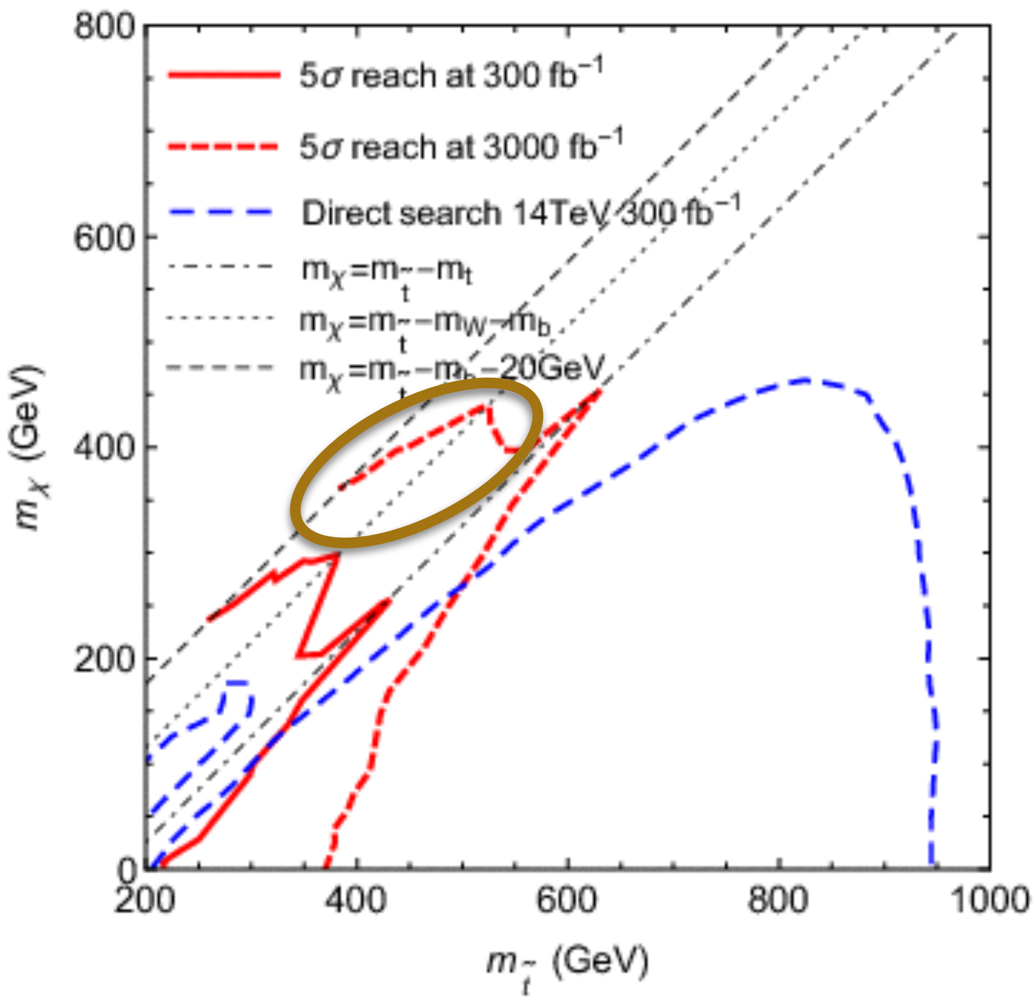
Monojet searches do this, but too bluntly;
sensitivity not fantastic.

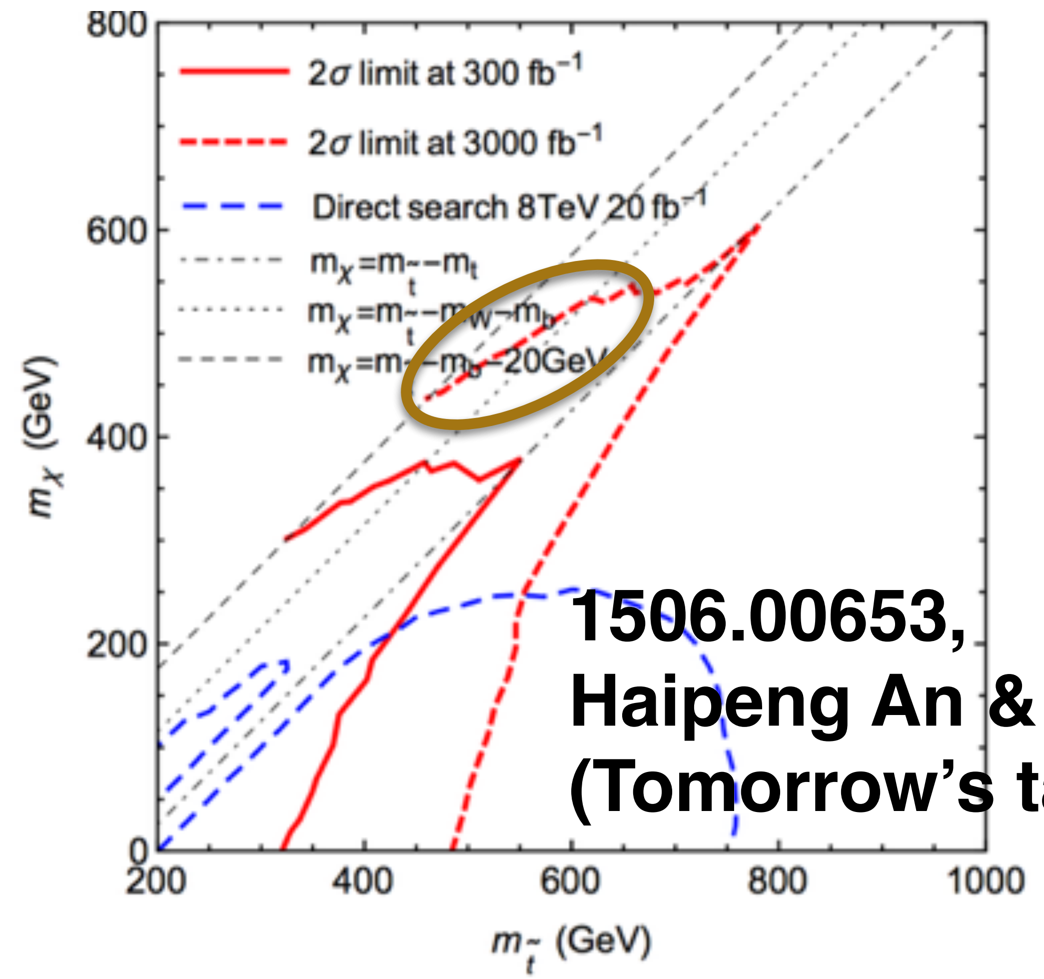
LHC compressed frontier



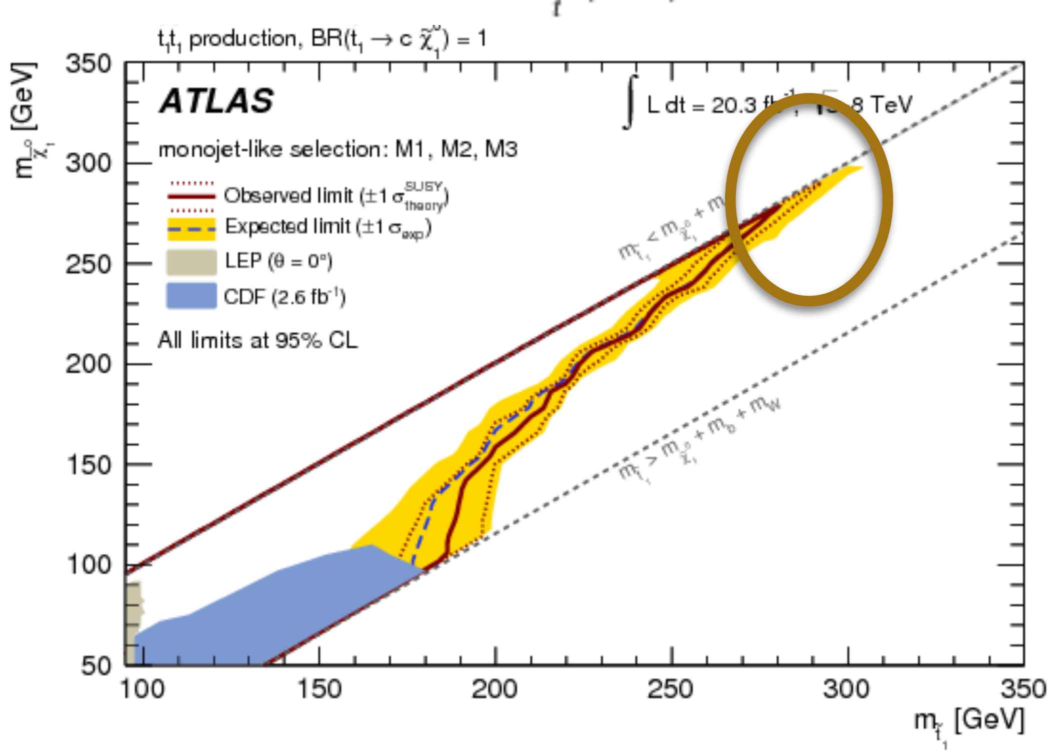


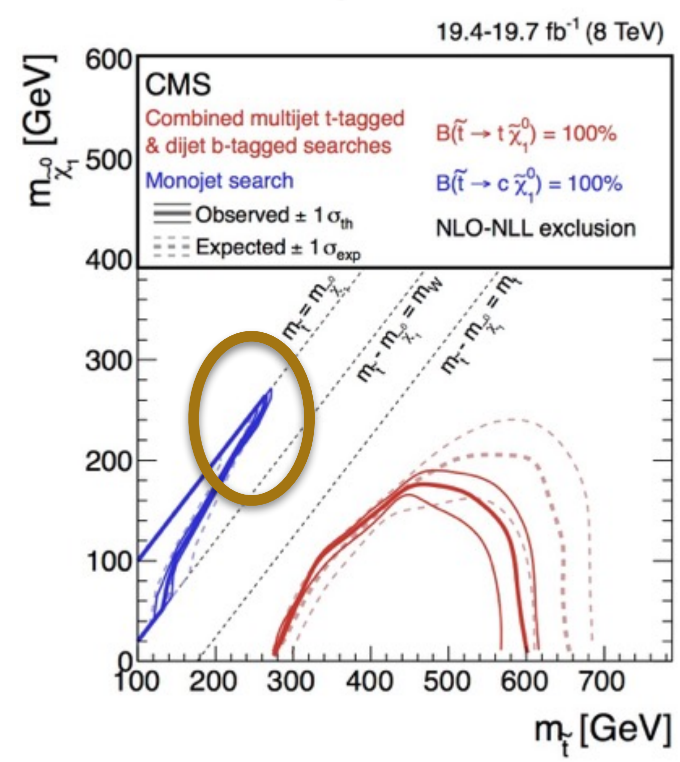
Ditto, with dedicated cuts





1506.00653, Haipeng An & L.T. Wang (Tomorrow's talk)





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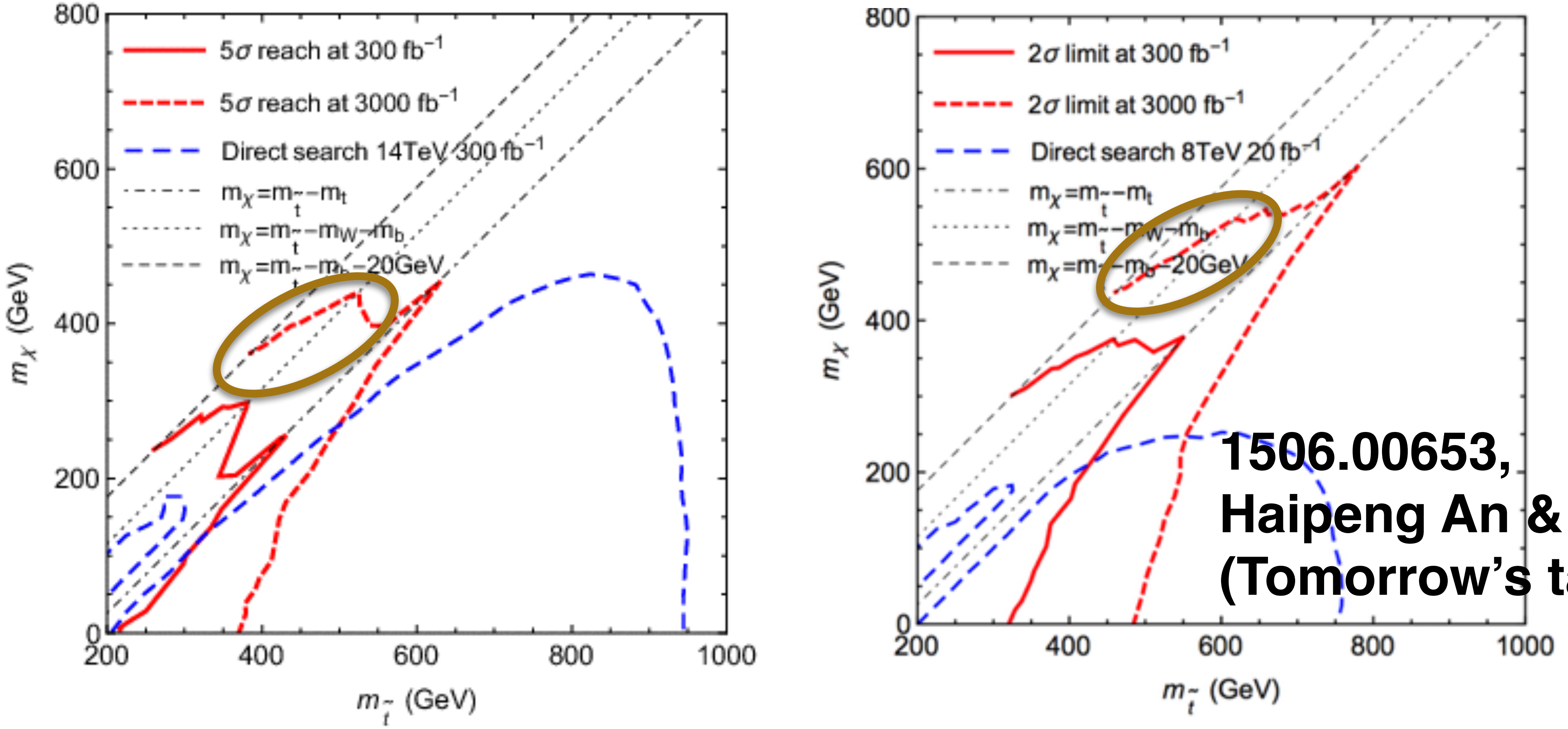


1506.00653, Haipeng An & L.T. Wang (Tomorrow's talk)

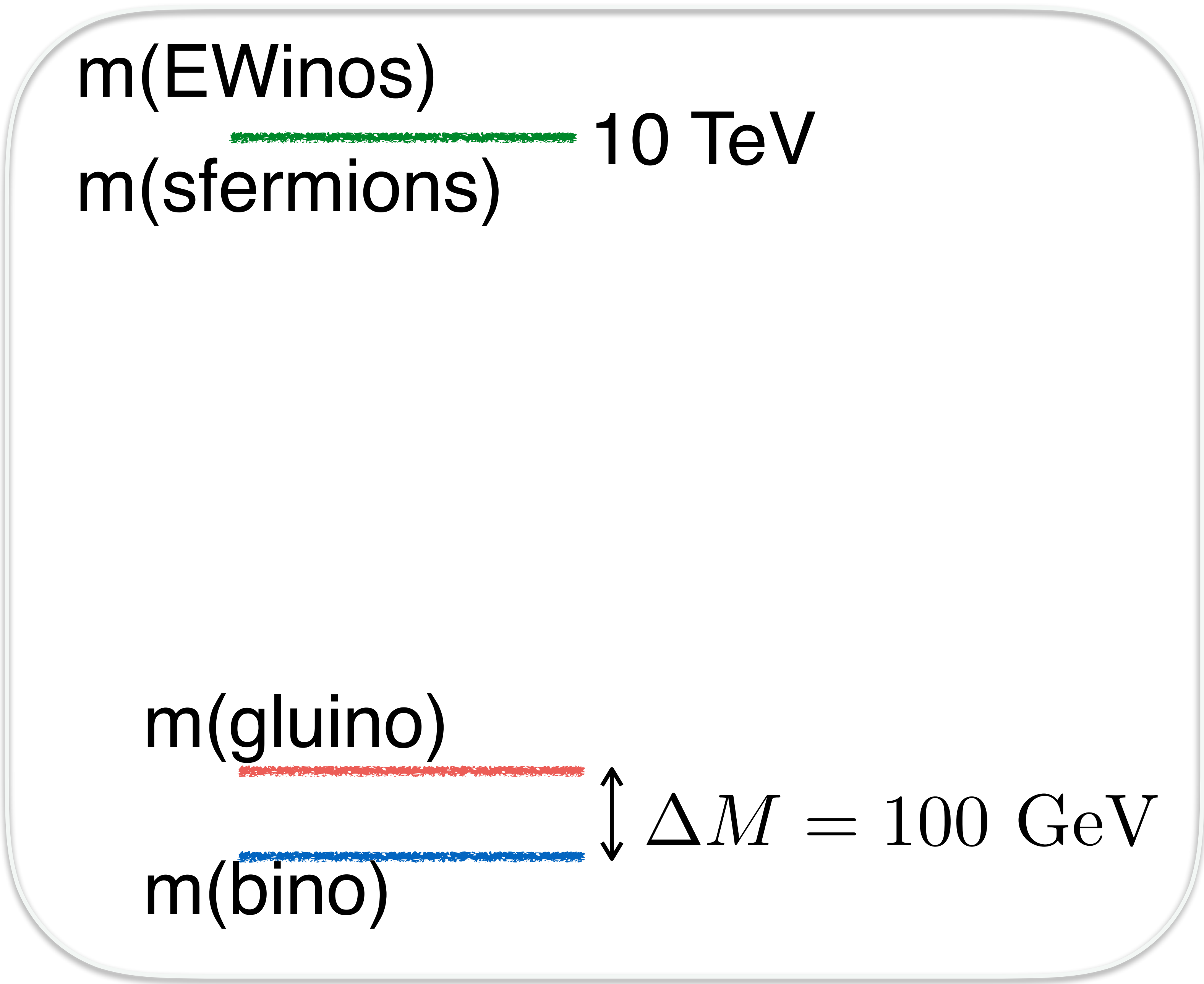
Similar variables, similar results for compressed stops

1307.1553; K Hagiwara, T Yamada

1506.07885; Macaluso, Park, Shih, Tweedie

1604.00007; H-C Cheng, C. Gao, L. Li

Spectrum of interest



Bino relatively safe from direct detection limits

Spectrum of interest

m(EWinos)

10 TeV

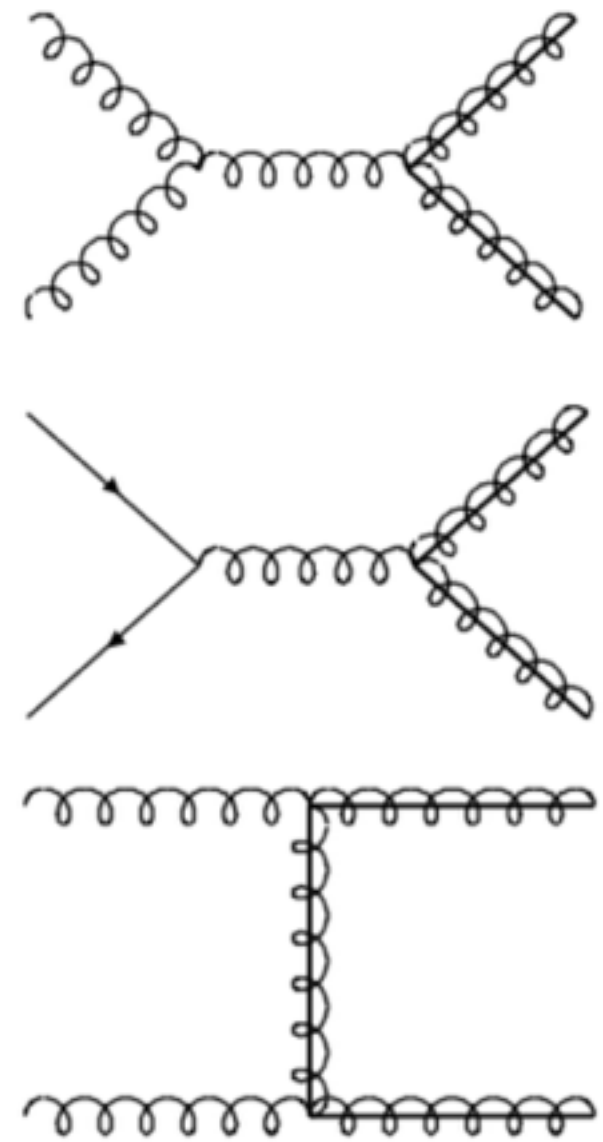
m(sfermions)

m(gluino)

$\Delta M = 100 \text{ GeV}$

m(bino)

Production



Thus, sole free parameter:
m(gluino)

Bino relatively safe from direct detection limits

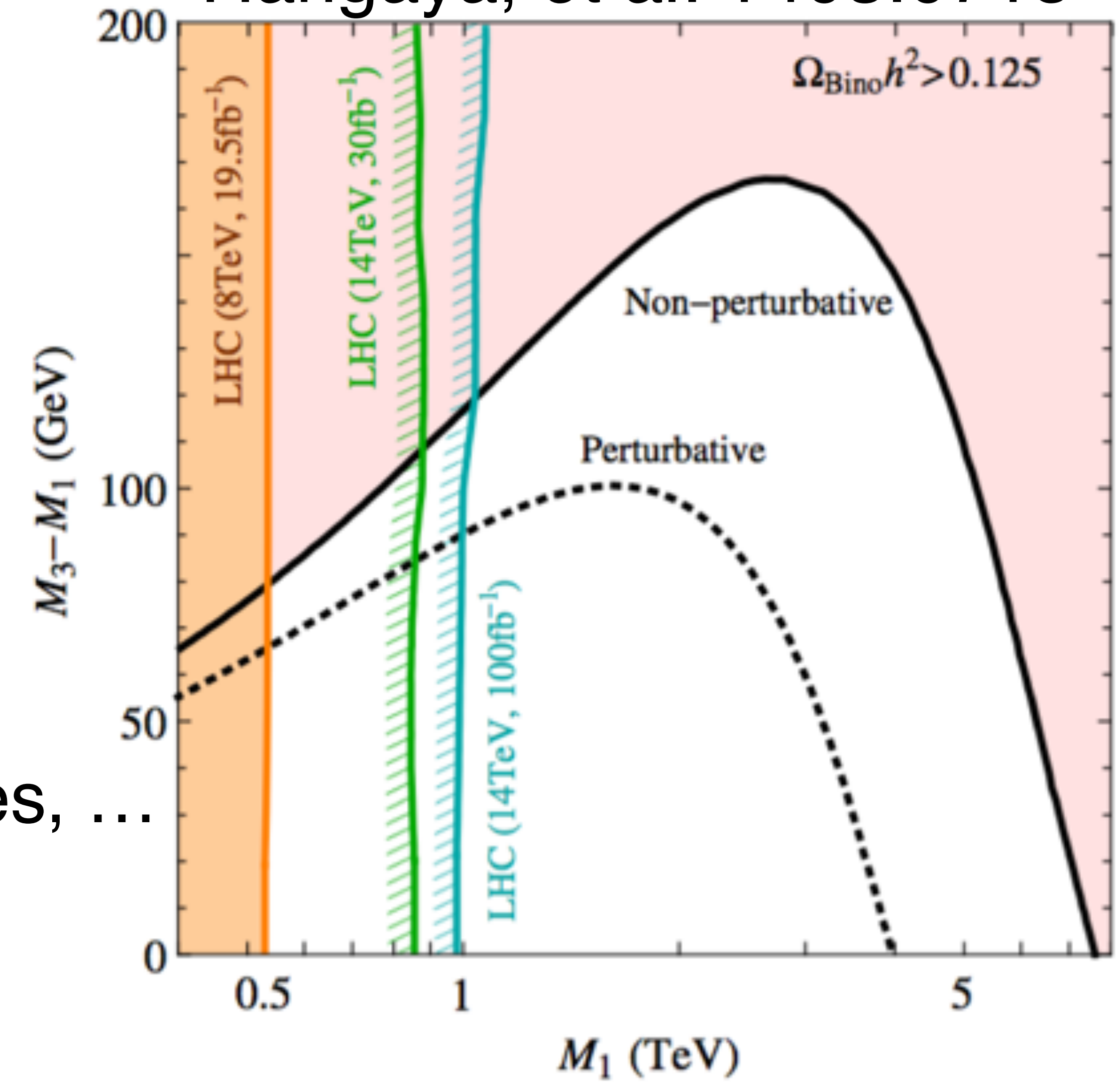
[Cosmological motivation]

m(gluino)

$\updownarrow \Delta M$

m(bino)

Harigaya, et al: 1403.0715



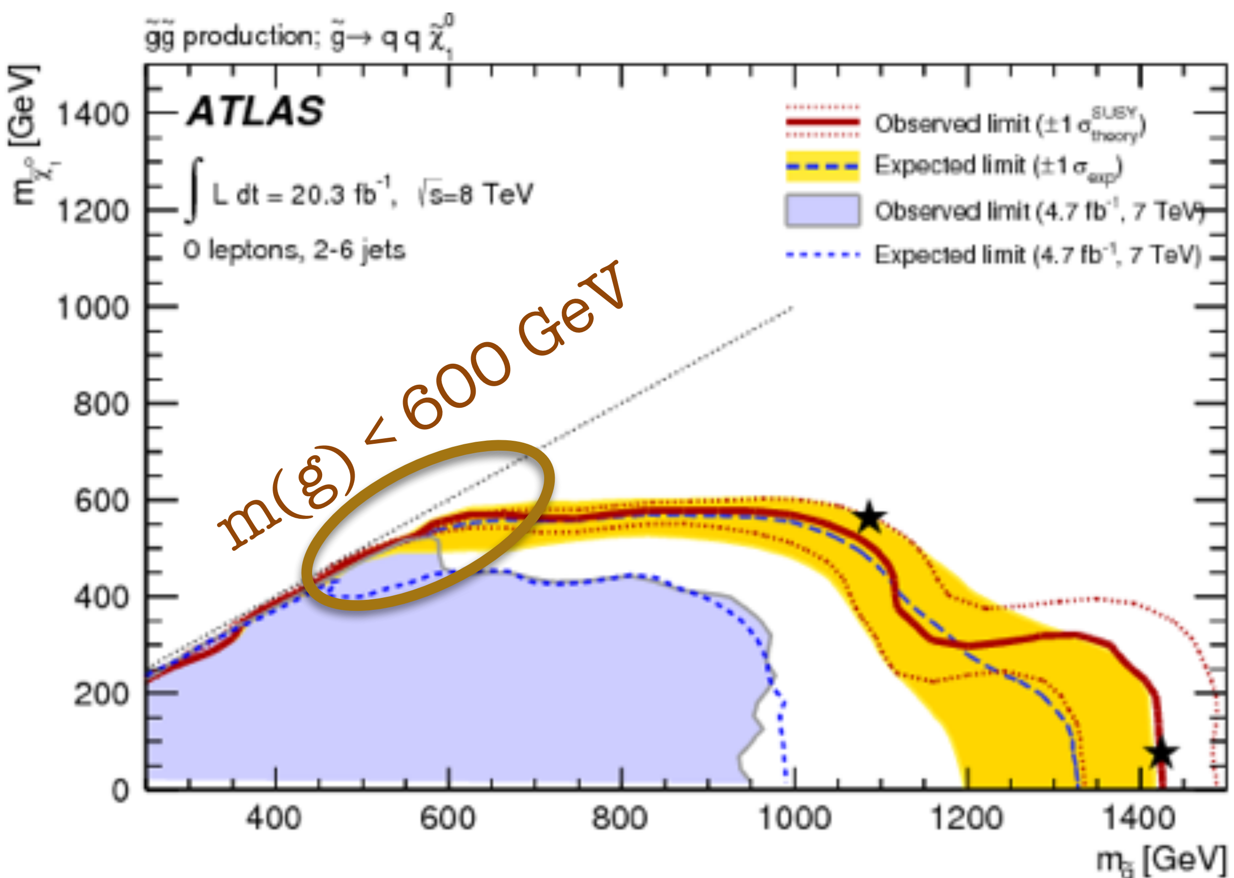
Bino self-annihilates inefficiently,
but gluino annihilation dilutes relic density.

Exact calculation — Sommerfeld, bound states, …
(J Ellis, et al: 1503.07142)

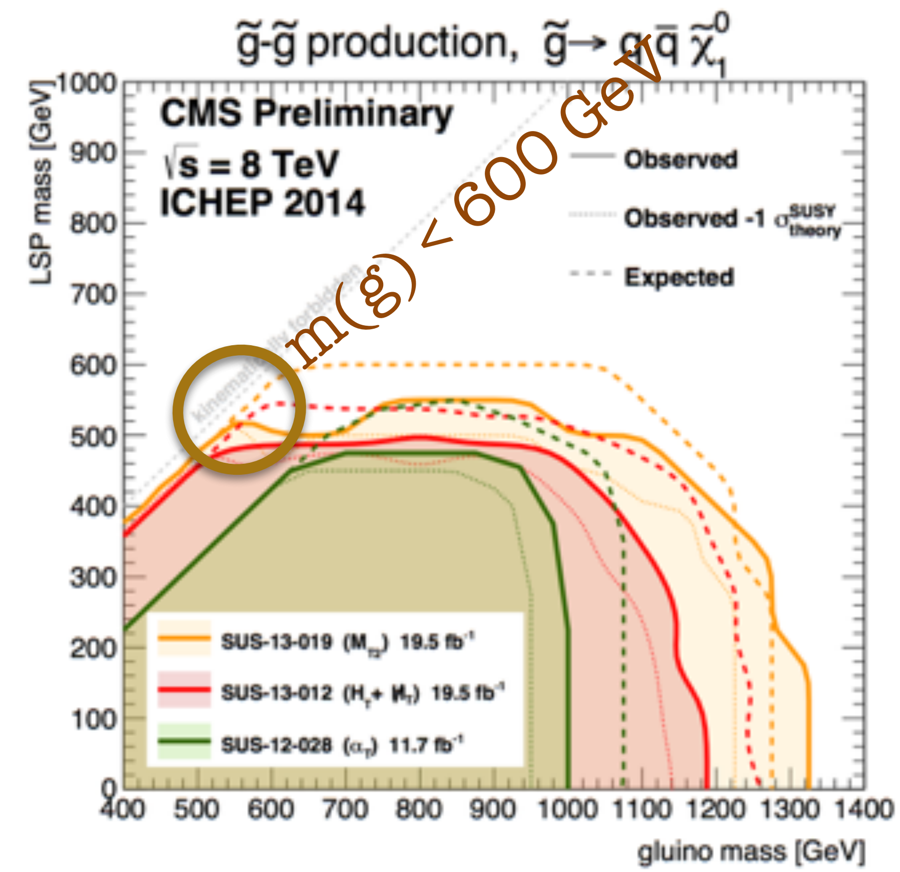
[Also, Profumo, et al: hep-ph/0402208,
Strumia, et al: 1402.6287.]

Here, collider focus. Therefore, $\boxed{\Delta M = 100\ \text{GeV}}$.

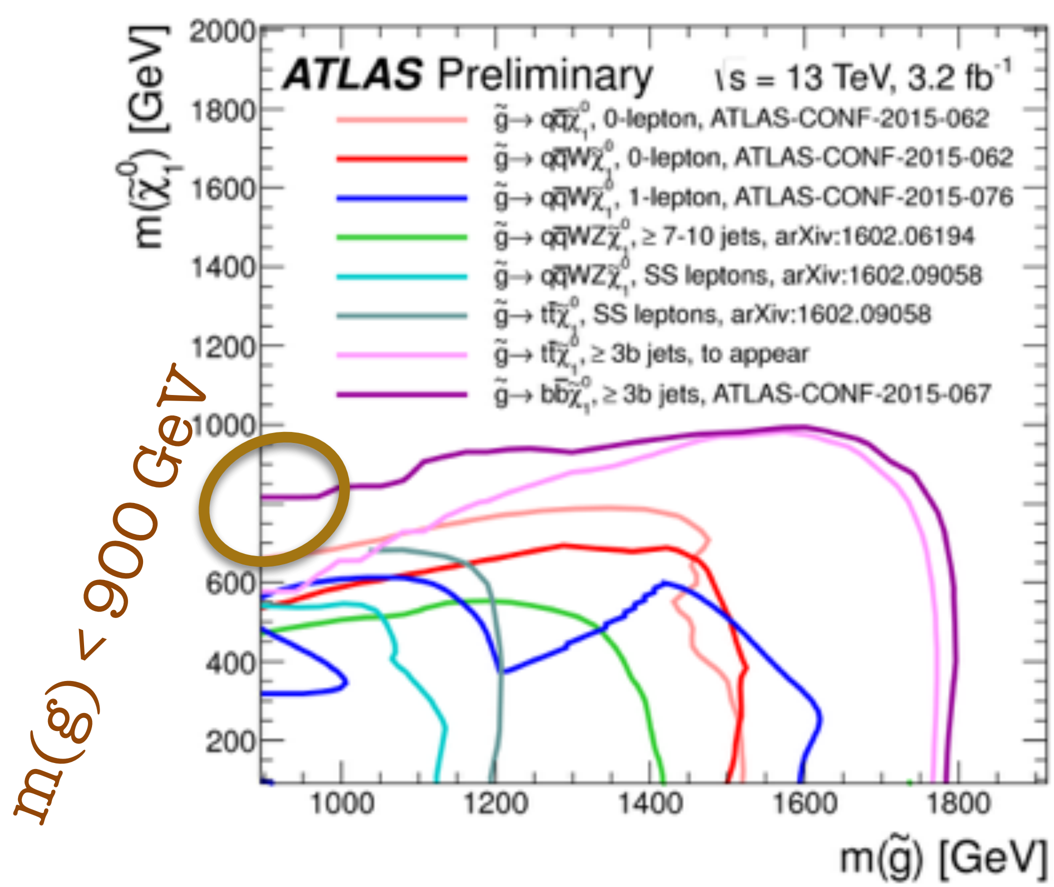
Status



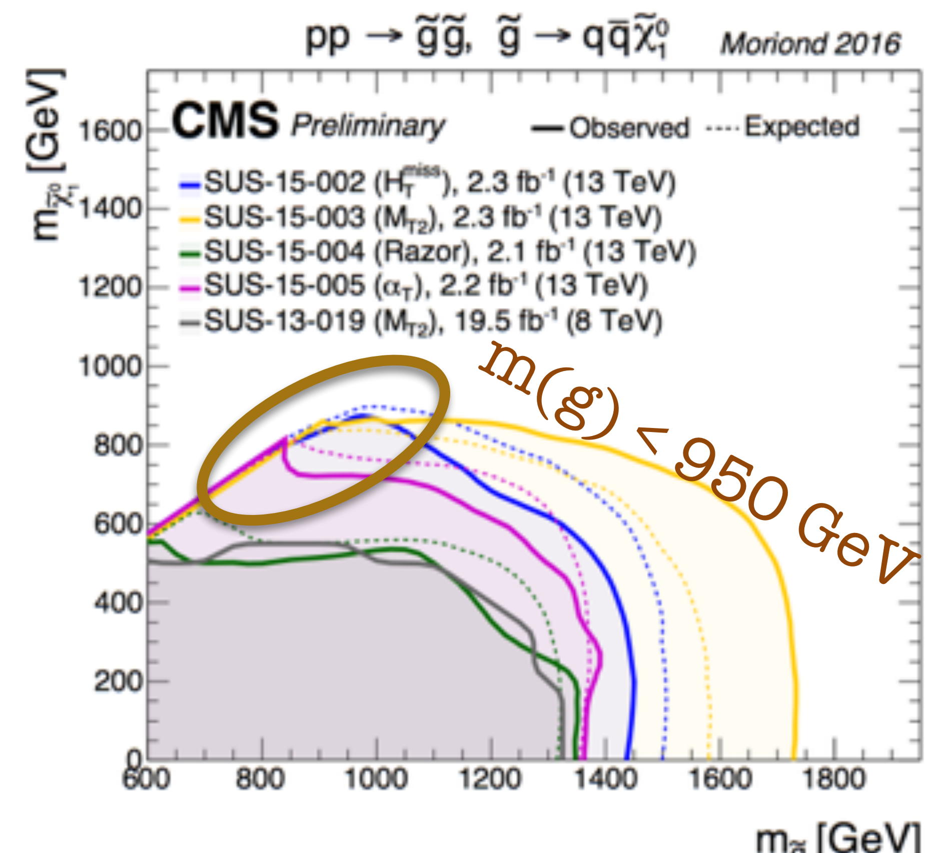
g̃g̃ production; g̃→ q q χ̃₁⁰
ATLAS
∫ L dt = 20.3 fb⁻¹, √s=8 TeV
0 leptons, 2-6 jets
Observed limit (±1 σ theory SUSY)
Expected limit (±1 σ exp)
Observed limit (4.7 fb⁻¹, 7 TeV)
Expected limit (4.7 fb⁻¹, 7 TeV)
m(g) < 600 GeV
m g̃ [GeV]



g̃-g̃ production, g̃→ q q̄ χ̃₁⁰
CMS Preliminary
√s = 8 TeV
ICHEP 2014
Observed
Observed -1 σ theory SUSY
Expected
m(g) < 600 GeV
SUS-13-019 (M_T2) 19.5 fb⁻¹
SUS-13-012 (H_T+ H̸_T) 19.5 fb⁻¹
SUS-12-028 (α_T) 11.7 fb⁻¹
LSP mass [GeV]
gluino mass [GeV]



ATLAS Preliminary
√s = 13 TeV, 3.2 fb⁻¹
g̃→ qq̄χ̃₁⁰, 0-lepton, ATLAS-CONF-2015-062
g̃→ qq̄Wχ̃₁⁰, 0-lepton, ATLAS-CONF-2015-062
g̃→ qq̄Wχ̃₁⁰, 1-lepton, ATLAS-CONF-2015-076
g̃→ qq̄WZχ̃₁⁰, ≥ 7-10 jets, arXiv:1602.06194
g̃→ qq̄WZχ̃₁⁰, SS leptons, arXiv:1602.09058
g̃→ tt̄χ̃₁⁰, SS leptons, arXiv:1602.09058
g̃→ tt̄χ̃₁⁰, ≥ 3b jets, to appear
g̃→ bb̄χ̃₁⁰, ≥ 3b jets, ATLAS-CONF-2015-067
m(χ̃₁⁰) [GeV]
m(g̃) [GeV]
m(g) < 900 GeV



pp → g̃g̃, g̃ → qq̄χ̃₁⁰
Moriond 2016
CMS Preliminary
Observed
Expected
SUS-15-002 (H_T^miss), 2.3 fb⁻¹ (13 TeV)
SUS-15-003 (M_T2), 2.3 fb⁻¹ (13 TeV)
SUS-15-004 (Razor), 2.1 fb⁻¹ (13 TeV)
SUS-15-005 (α_T), 2.2 fb⁻¹ (13 TeV)
SUS-13-019 (M_T2), 19.5 fb⁻¹ (8 TeV)
m(g) < 950 GeV
m χ̃₁⁰ [GeV]
m g̃ [GeV]

Status: Theory

1603.04854; Pran Nath, Andrew Spisak

Used experimentalists' variables: M_{eff}, $E_T^{\rm miss}$, and $E_T^{\rm miss}/\sqrt{H_T}$.

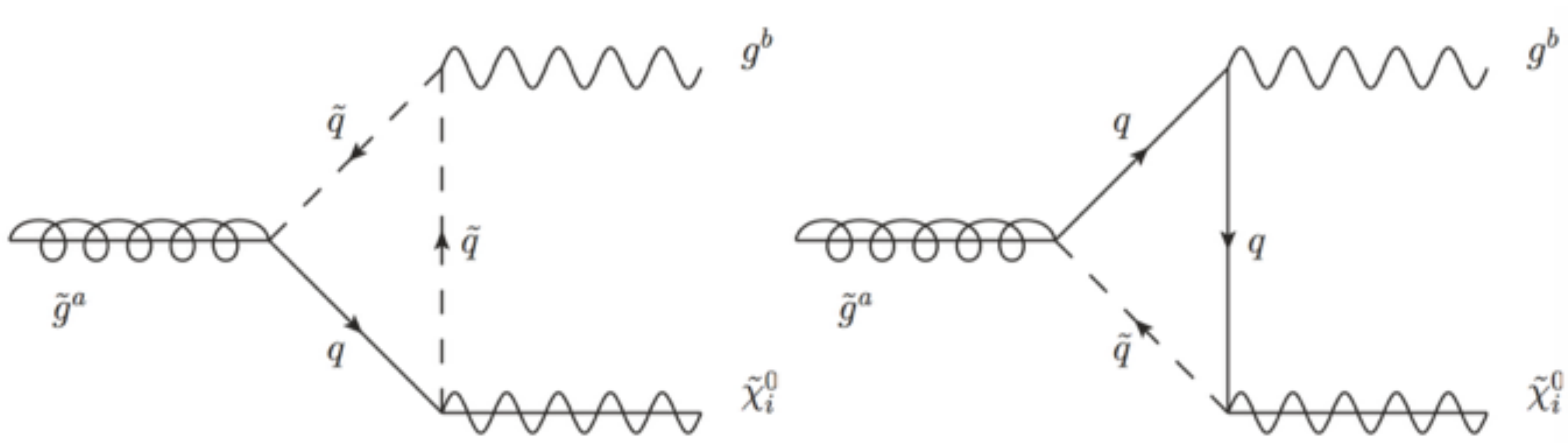
Bino

Model	Gluino	Neutralino	Stop	Higgs	$\Omega_{\rm LSP}h^2$	m_0	A_0	$m_1 = m_2$	m_3
(i)	706	634	2124	123.8	0.122	5000	−7000	1400	250
(ii)	836	755	3497	124.1	0.110	7000	−8000	1650	300
(iii)	955	868	2367	125.5	0.112	6000	−9000	1900	350
(iv)	1057	975	2754	123.2	0.102	5500	−5500	2150	400
(v)	1129	1046	2910	123.5	0.101	5800	−5800	2300	430
(vi)	1201	1107	2932	126.7	0.110	7500	−11500	2400	450
(vii)	1252	1167	3459	124.1	0.101	6800	−6800	2550	480

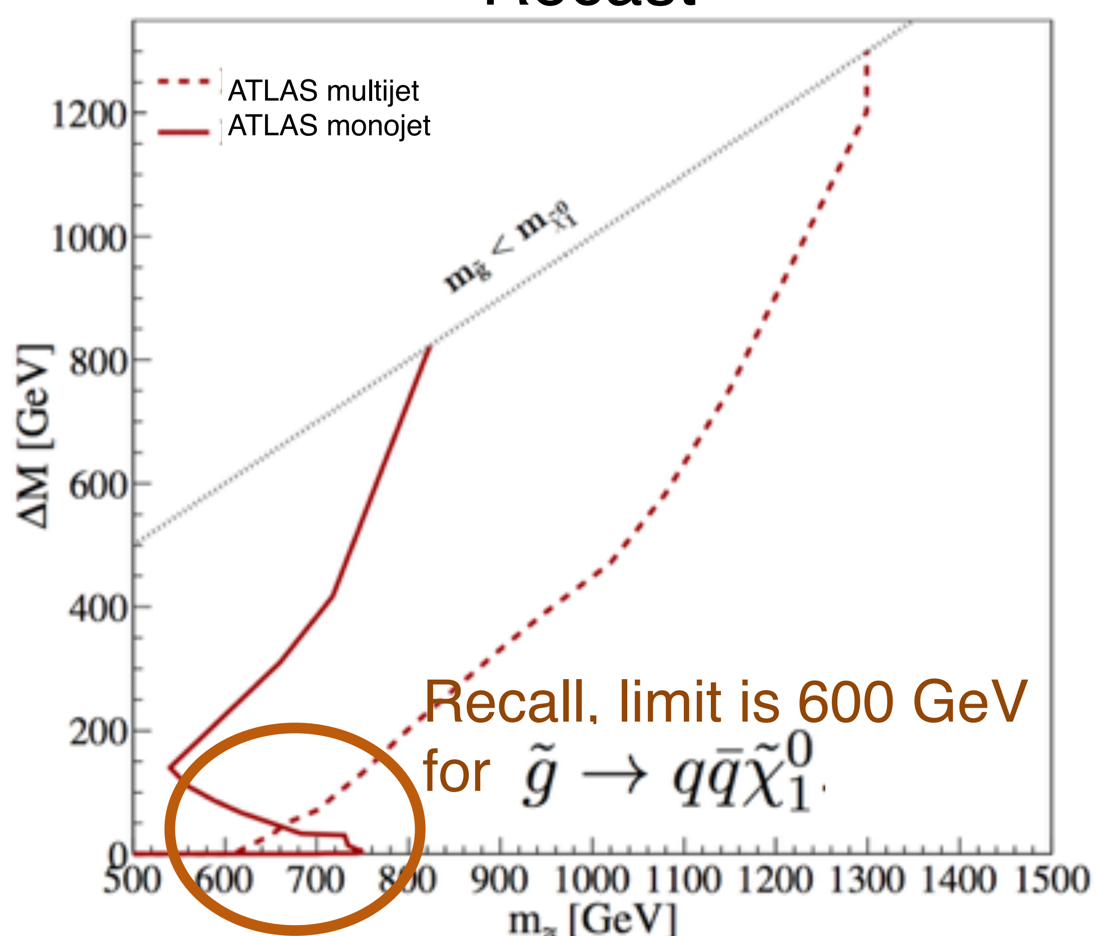
Discoverable with 3 ab^{-1} @ Run II

Status: Theory

JHEP12 (2015) 129; G. Chalons, D. Sengupta



Recast



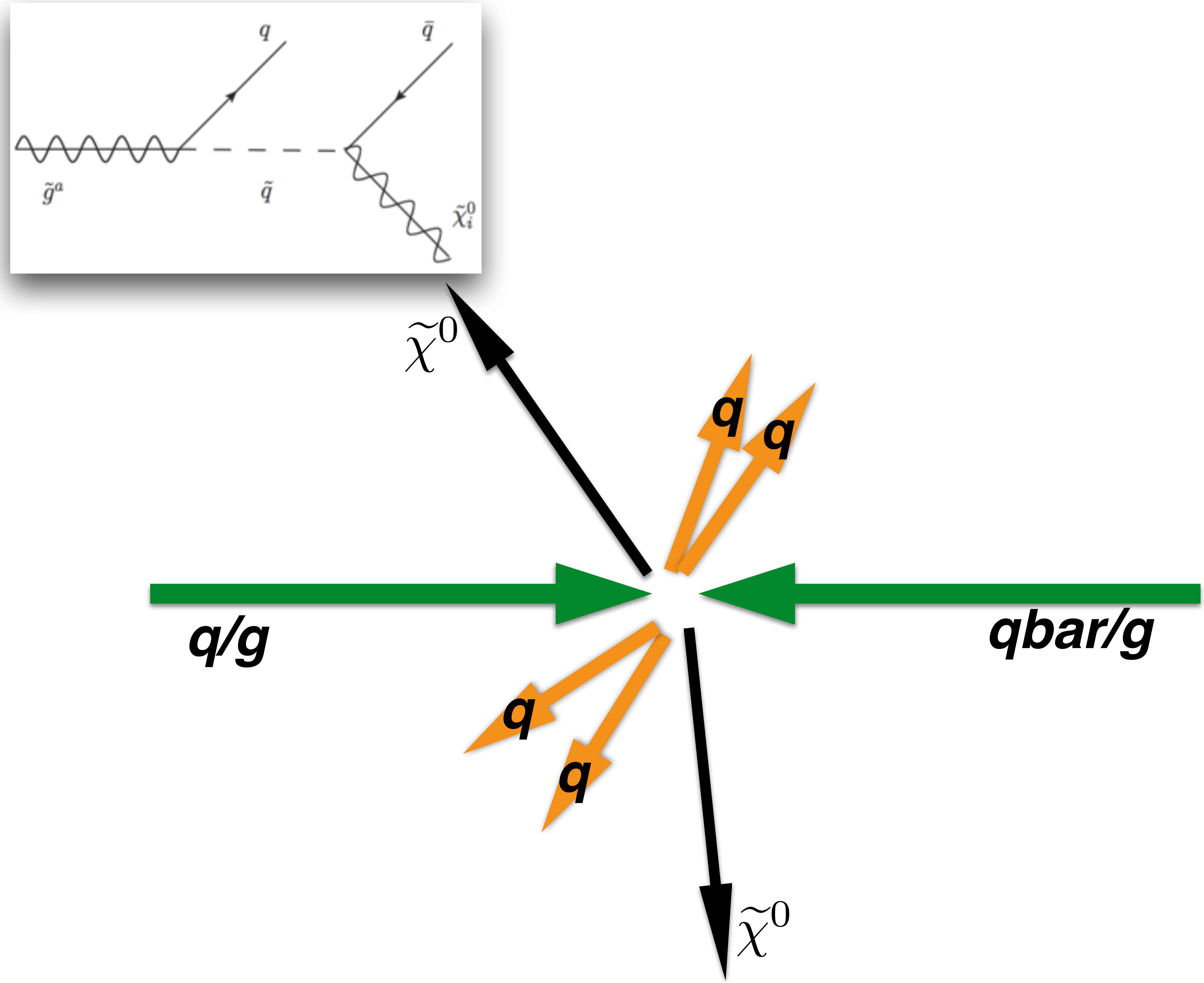
Recall, limit is 600 GeV for $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$

<u>Reach @ Run II</u>

$$\Delta M = 10 \text{ GeV}$$

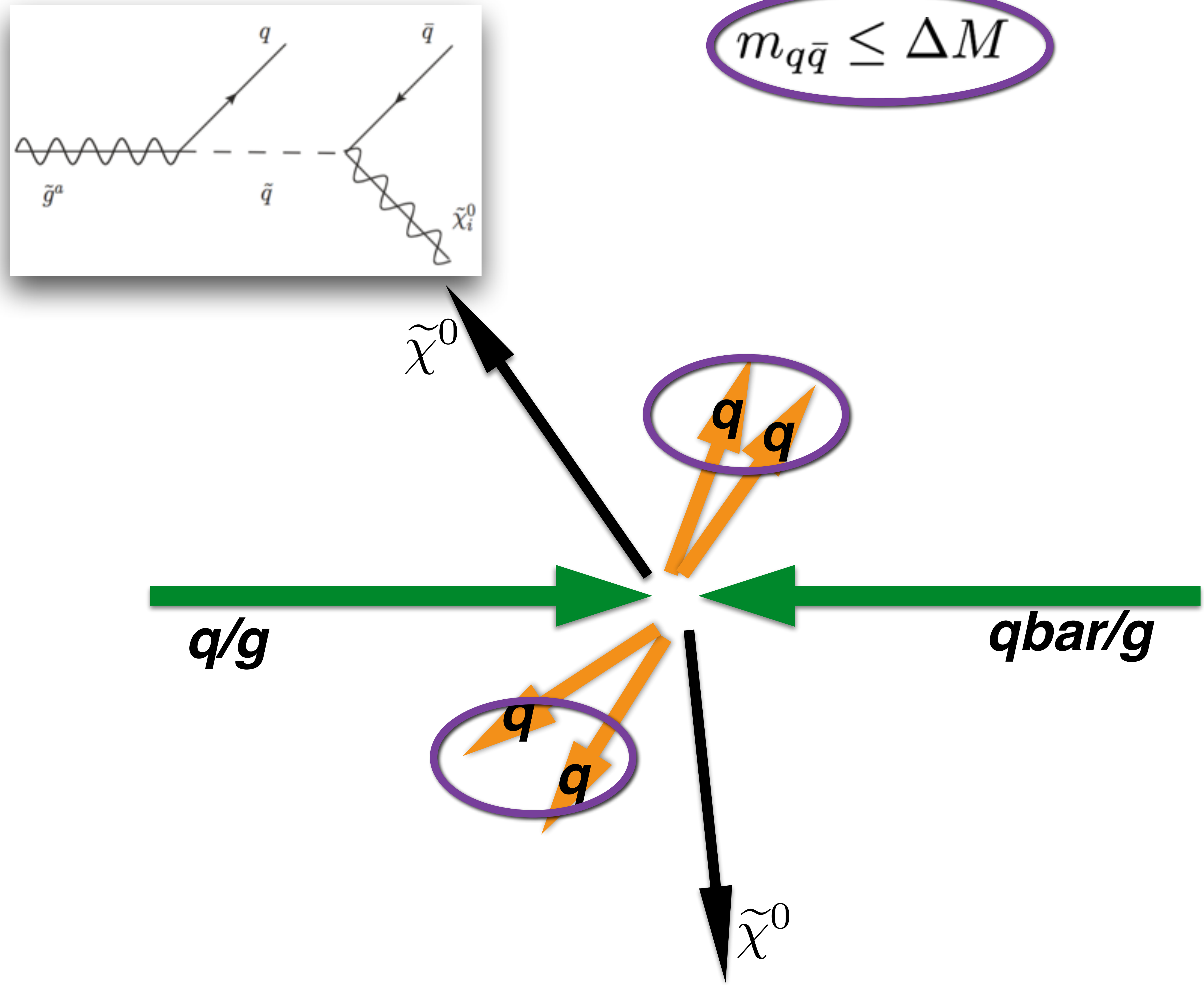
Discovery: m(gluino) 1.45 TeV
Exclusion: m(gluino) 1.55 TeV

Parton level

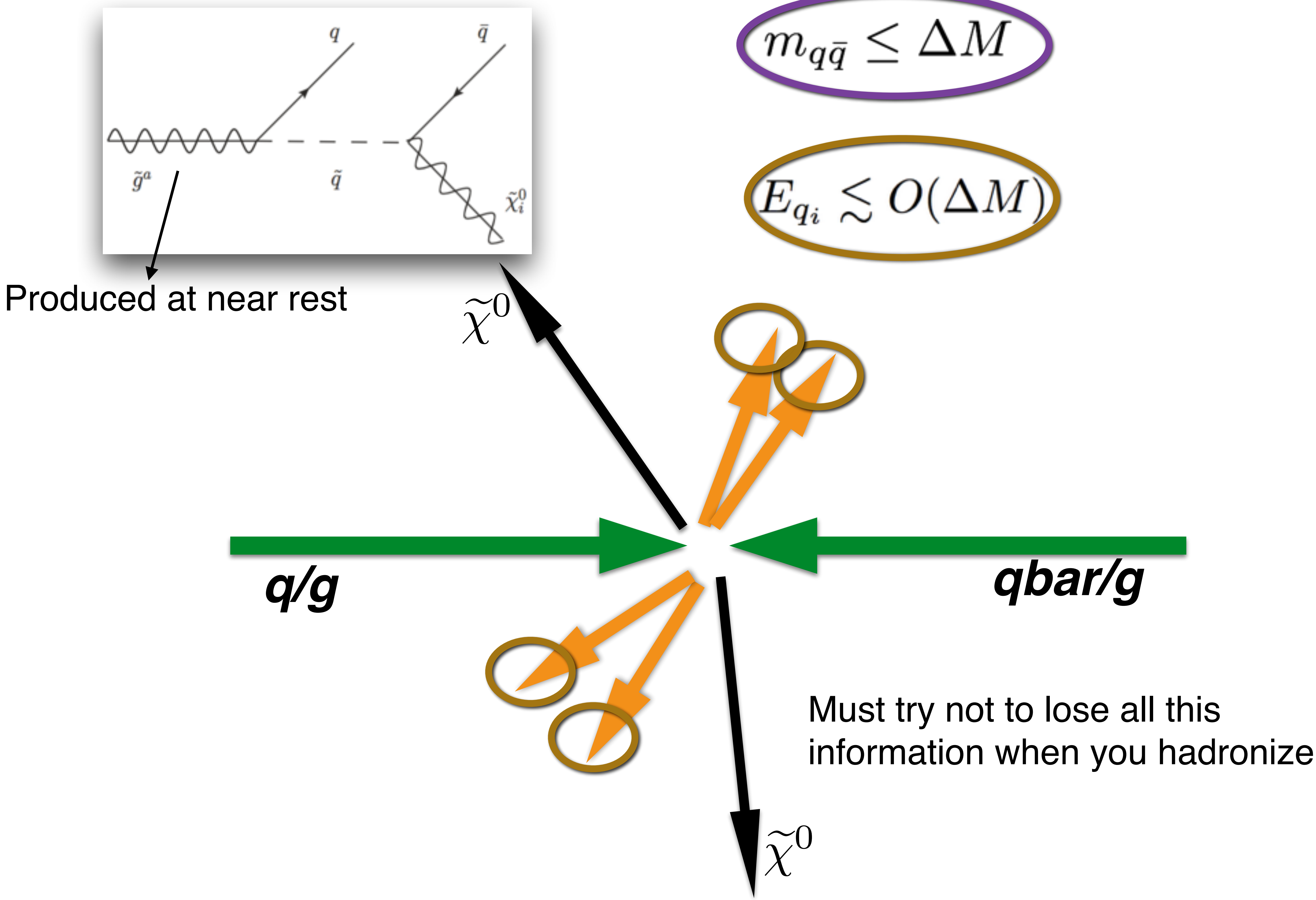


Parton level

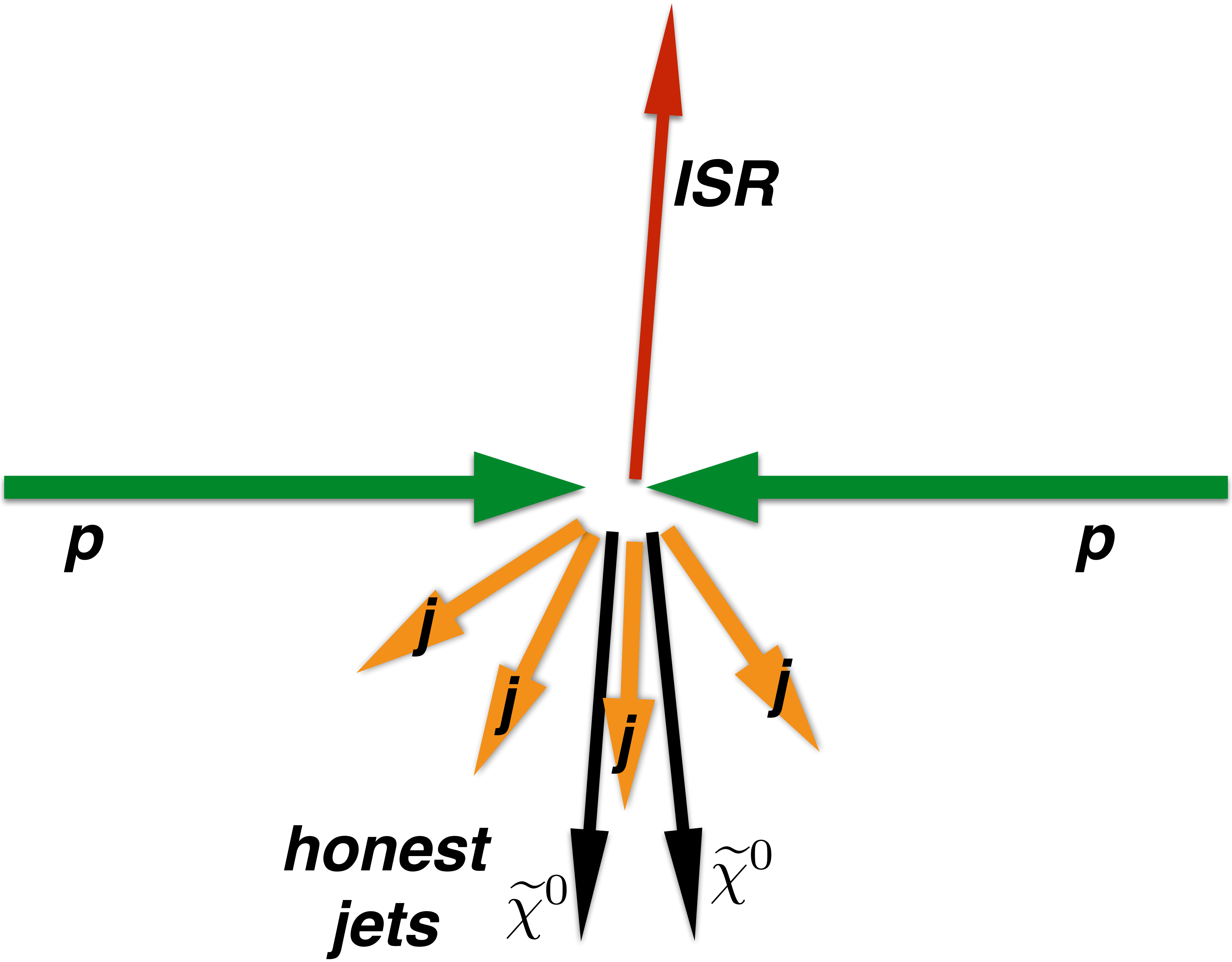
$m_{q\bar{q}} \leq \Delta M$



Parton level

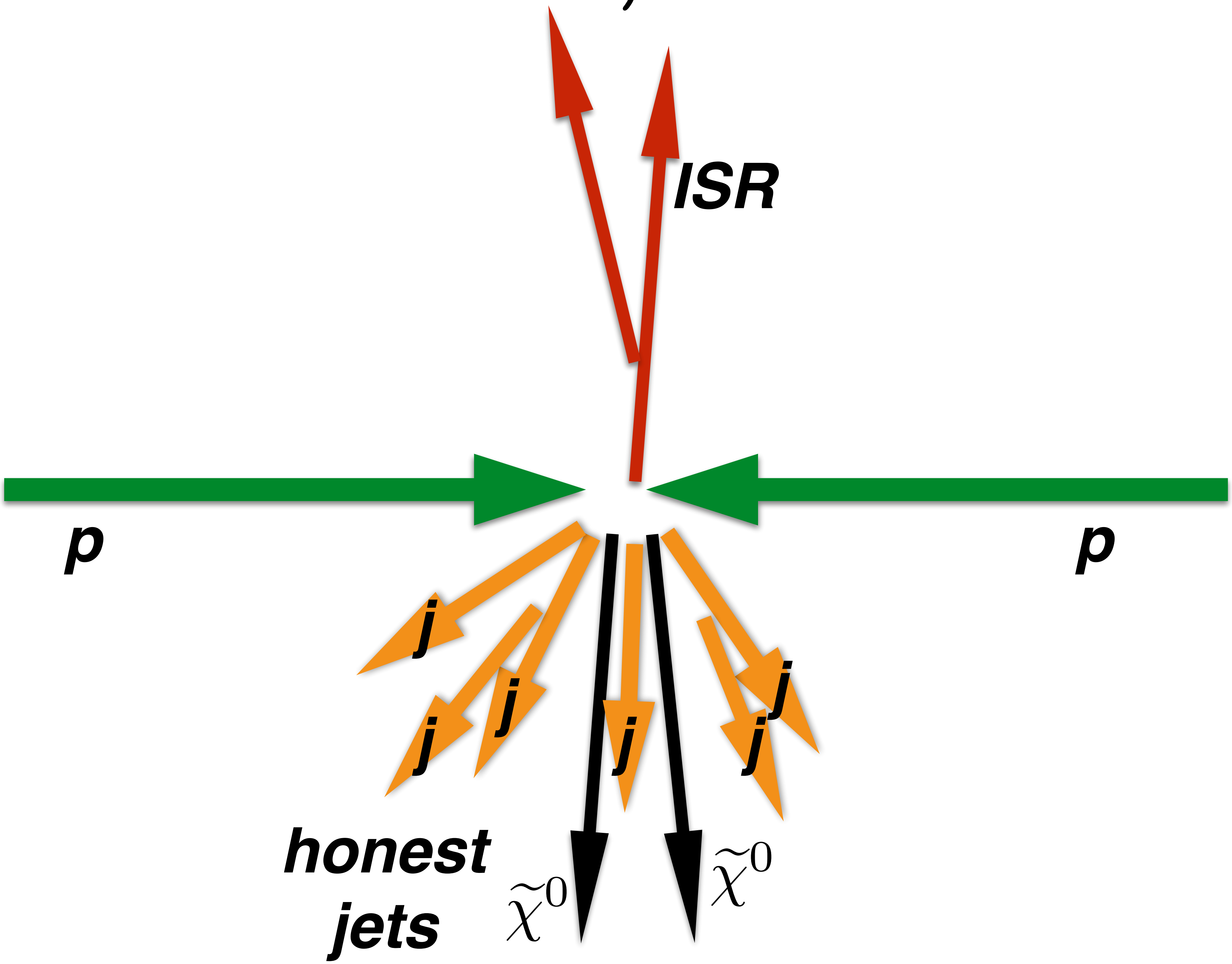


Hadron level



Monojet search takes advantage of this.

Hadron level, showered



Kinematic features

Parton level **Hadron level**

(a) At least two pairs of honest jets bounded in invariant mass

$m_{q\bar{q}} \leq \Delta M$

(b) Honest jets softer than ISR

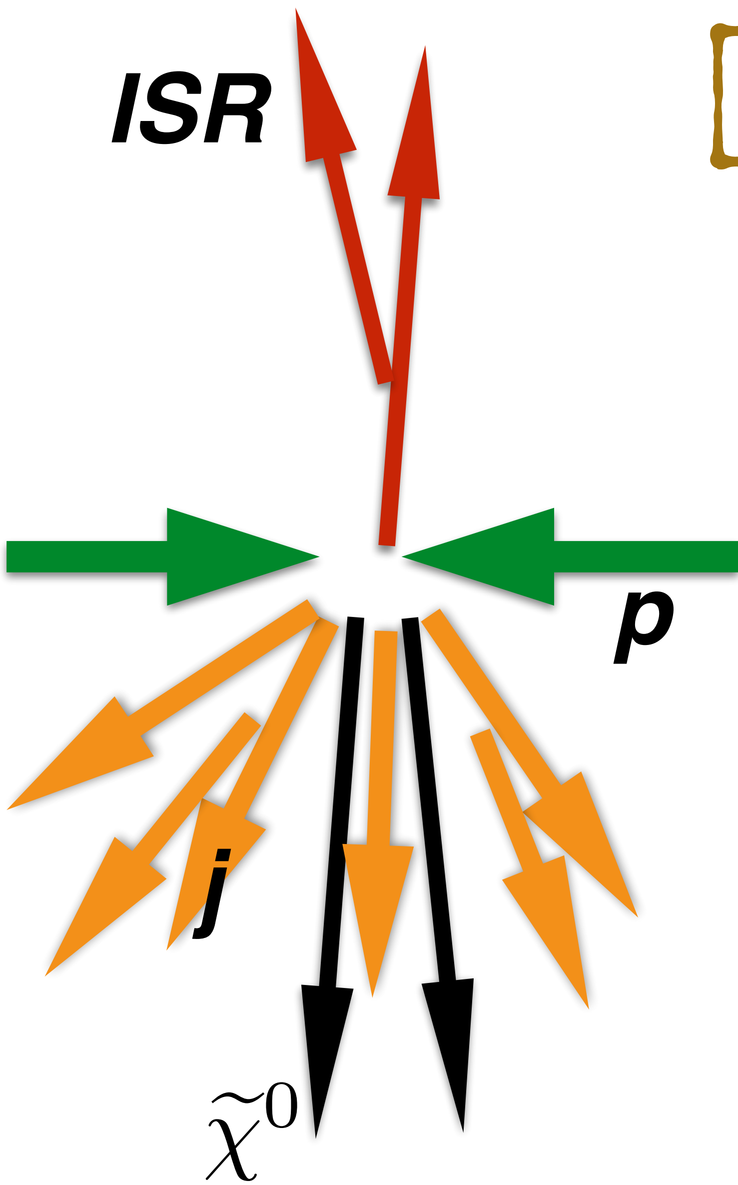
(c) Honest jets and binos recoil vs ISR

$E_{q_i} \lesssim O(\Delta M)$

(d) Honest jets outnumber ISR jets

(e) Binos slow (because gluinos are)

Slow creatures



(e) Binos slow (because gluinos are)

MET peaks at $\Delta M = 100\ \mathrm{GeV}$

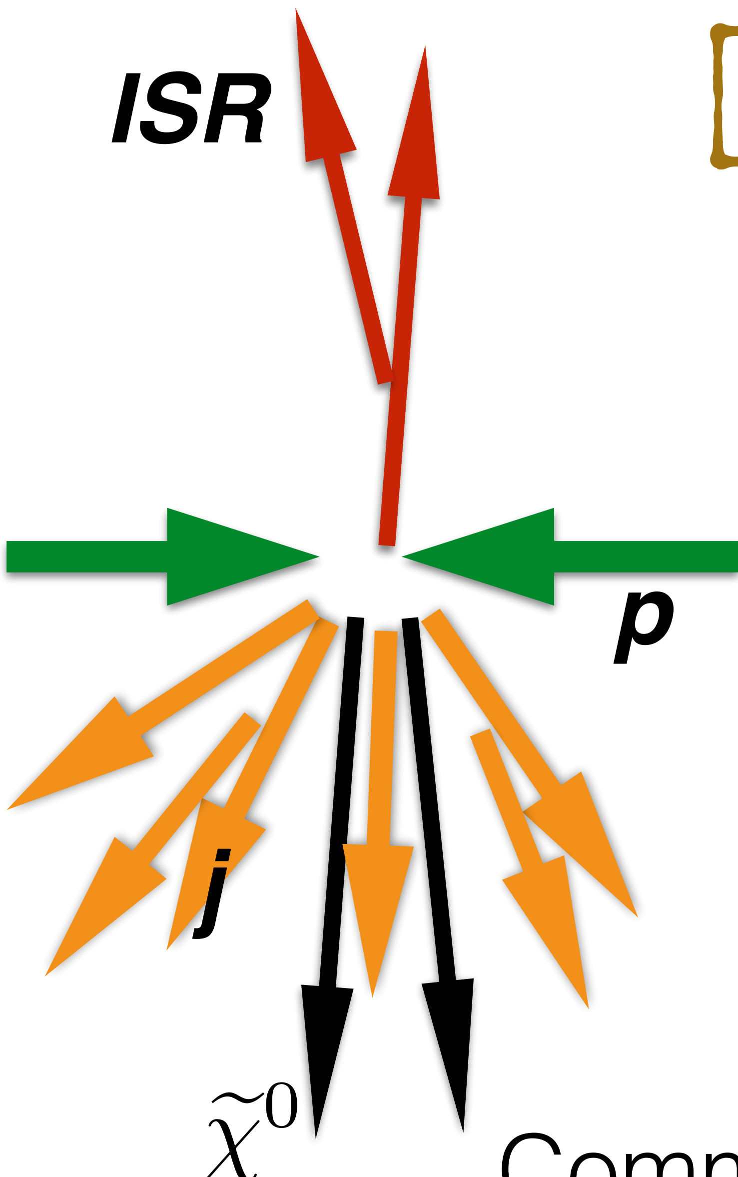
$$\mathrm{MET} = m_{\mathrm{bino}}\beta\gamma \approx 100\ \mathrm{GeV}$$

$$m_{\mathrm{gluino}} > 600\ \mathrm{GeV}\ \ (\mathrm{bounds})$$

=> $m_{\mathrm{bino}} > 500\ \mathrm{GeV}$

=> $\beta < 0.2$

Slow creatures



(e) Binos slow (because gluinos are)

MET peaks at $\Delta M = 100$ GeV

$\text{MET} = m_{\text{bino}}\beta\gamma \approx 100$ GeV

$m_{\text{gluino}} > 600$ GeV (bounds)

=> $m_{\text{bino}} > 500$ GeV

=> $\beta < 0.2$

Common boost factor => $p_{T_{\tilde{g}}}/\not{E}_T = m_{\tilde{g}}/m_{\tilde{\chi}^0}$

$p_{T_{\tilde{g}}} \simeq p_{T_{\text{ISR}}}$ => $p_{T_{\text{ISR}}}/\not{E}_T$ peaks at $m_{\tilde{g}}/m_{\tilde{\chi}^0} \simeq 1$

$\left.\begin{array}{l}\text{1307.1553, Hagiwara \& Yamada} \\ \text{1506.00653, H. An \& L.T. Wang}\end{array}\right\}$ compressed stops

Tagging, vetoes

(b) Honest jets softer than ISR

—> use as a (crude) **tag for ISR**

$\boxed{E_{\rm tag}^{\rm ISR} = \Delta M}$ — choice motivated by cuts

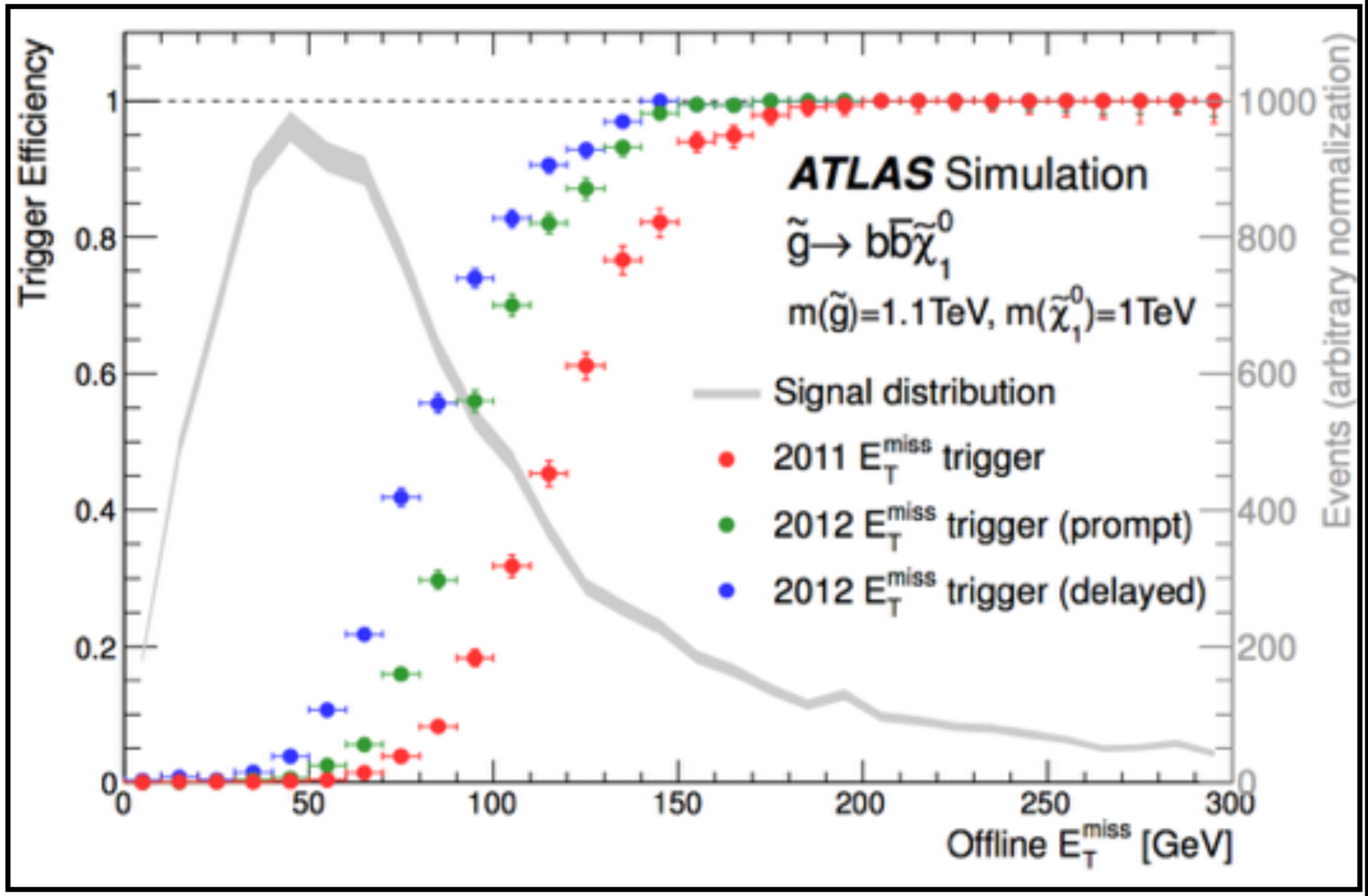
"Jet" = default anti-kT of PGS4 (distance param. = 0.5)

Veto
leptons, photons,
hadronically decaying taus,
b-tagged jets

Trigger

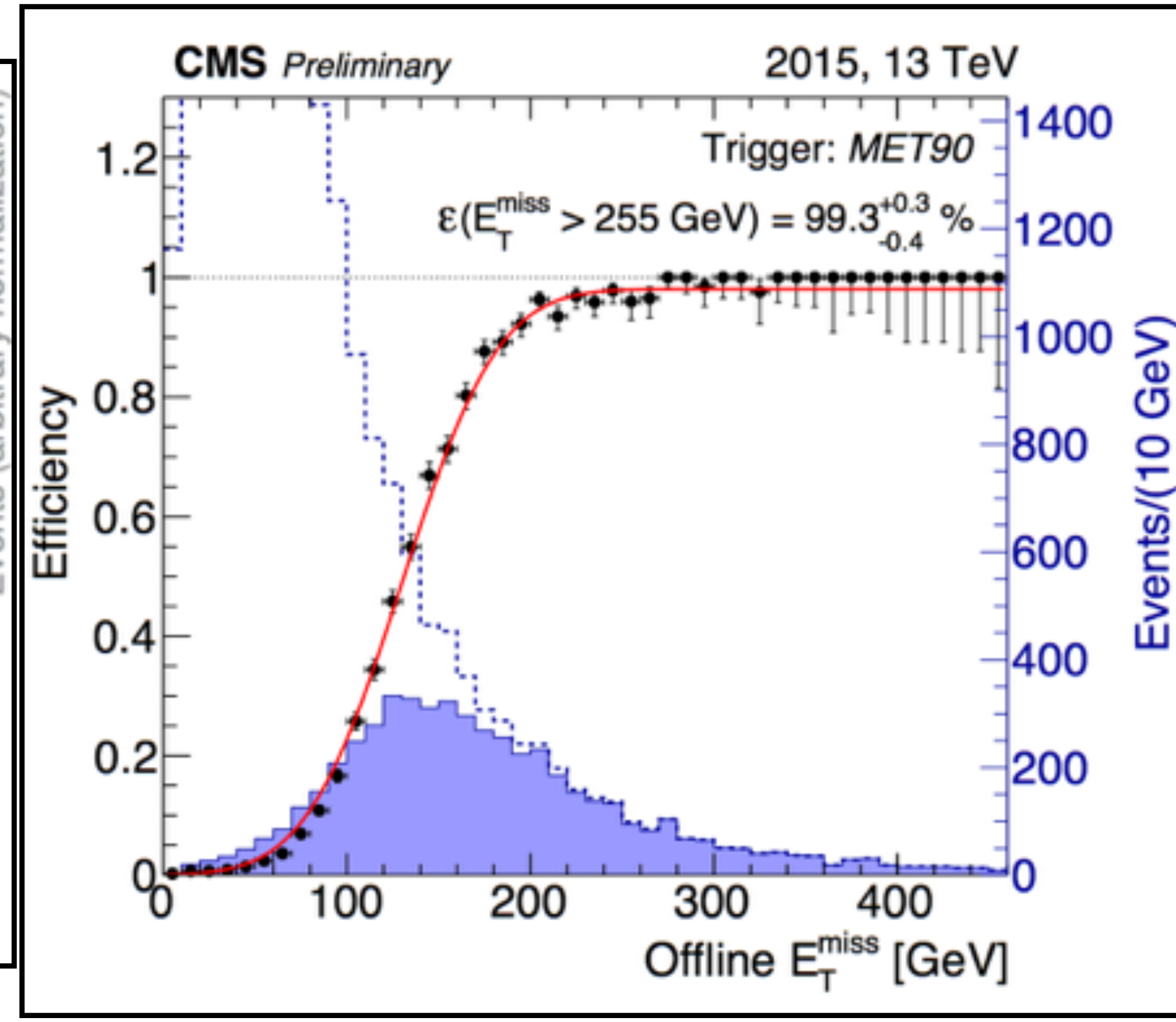
https://twiki.cern.ch/twiki/bin/view/CMSPublic/L1TriggerDPGResults

8 TeV



ATL-DAQ-PUB-2012-002

13 TeV

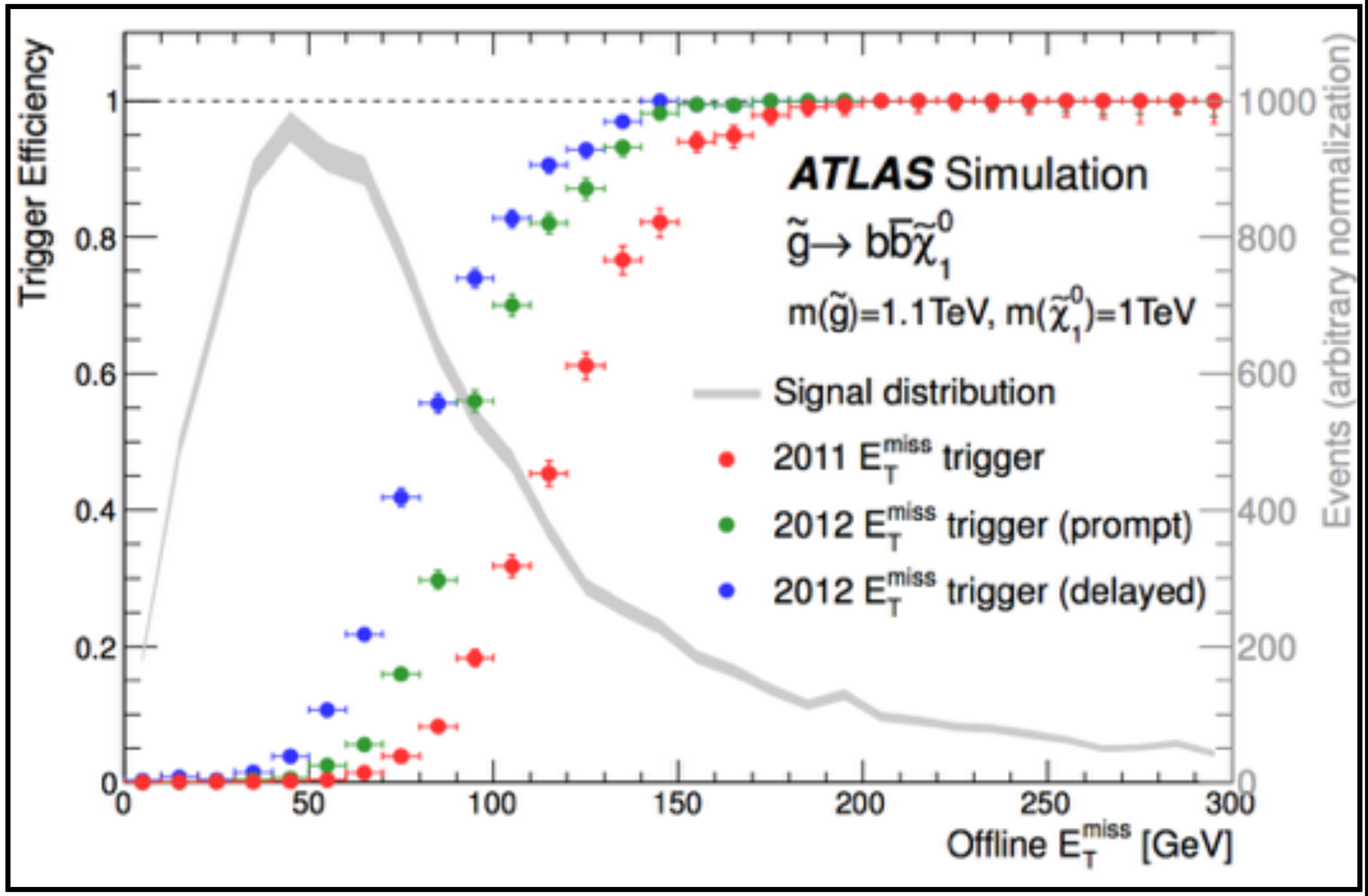


Trigger

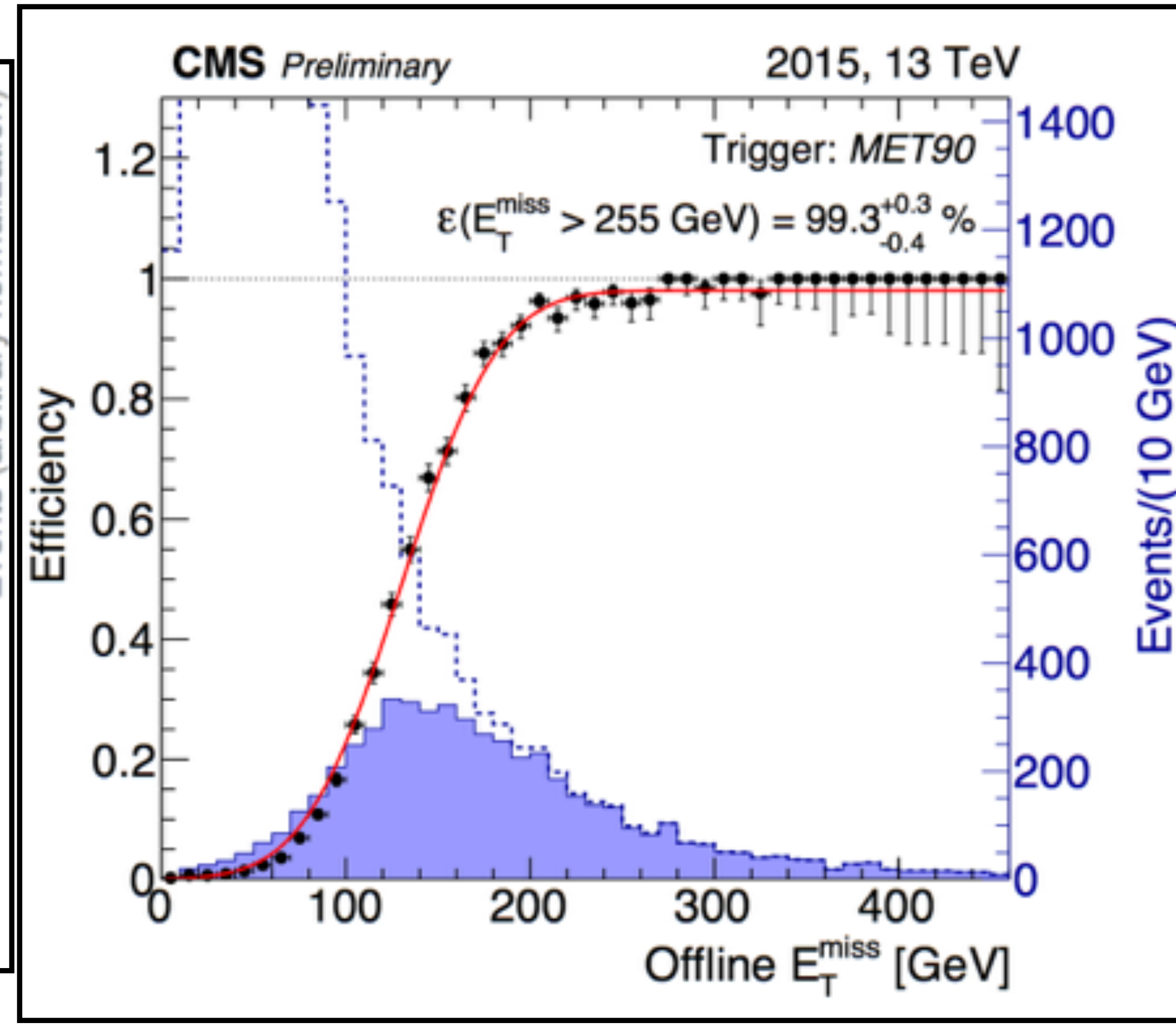
https://twiki.cern.ch/twiki/bin/view/CMSPublic/L1TriggerDPGResults

8 TeV

13 TeV



ATL-DAQ-PUB-2012-002



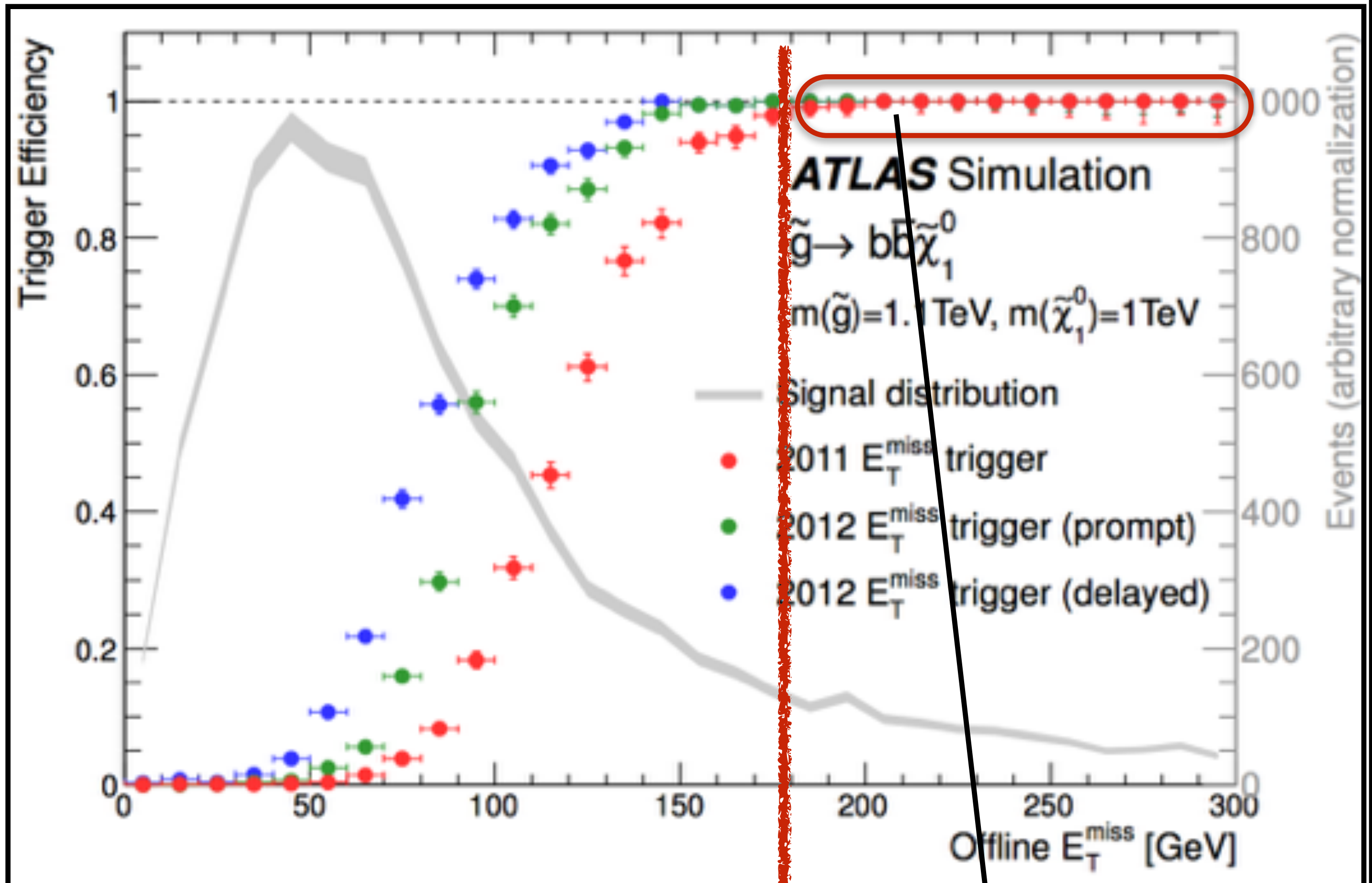
[Mined from ATLAS graveyard (not listed on InspireHEP)]

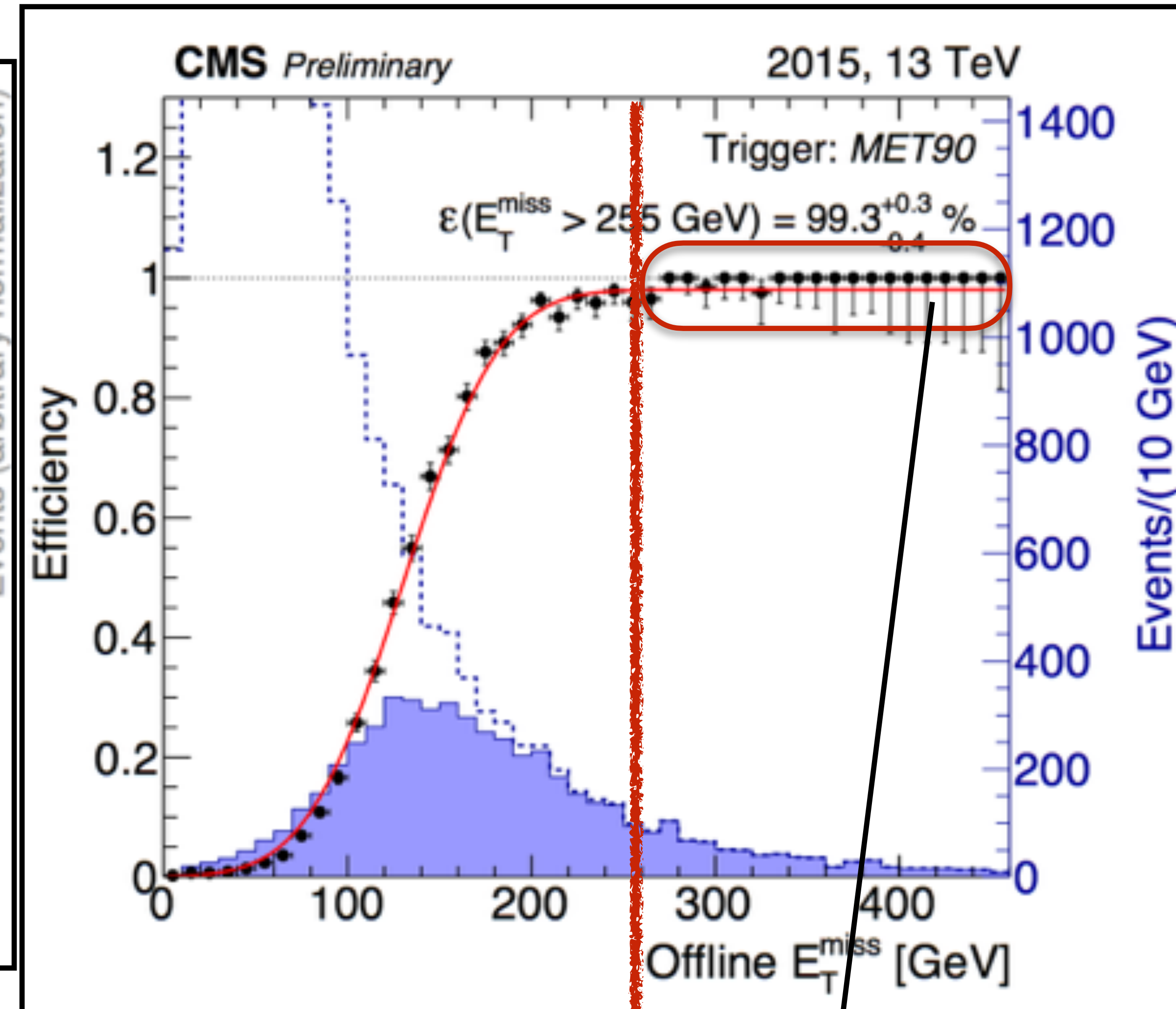
Dear searchers,
Kindly cite triggerers.
Yours,
Theorizers.

Trigger

8 TeV

13 TeV



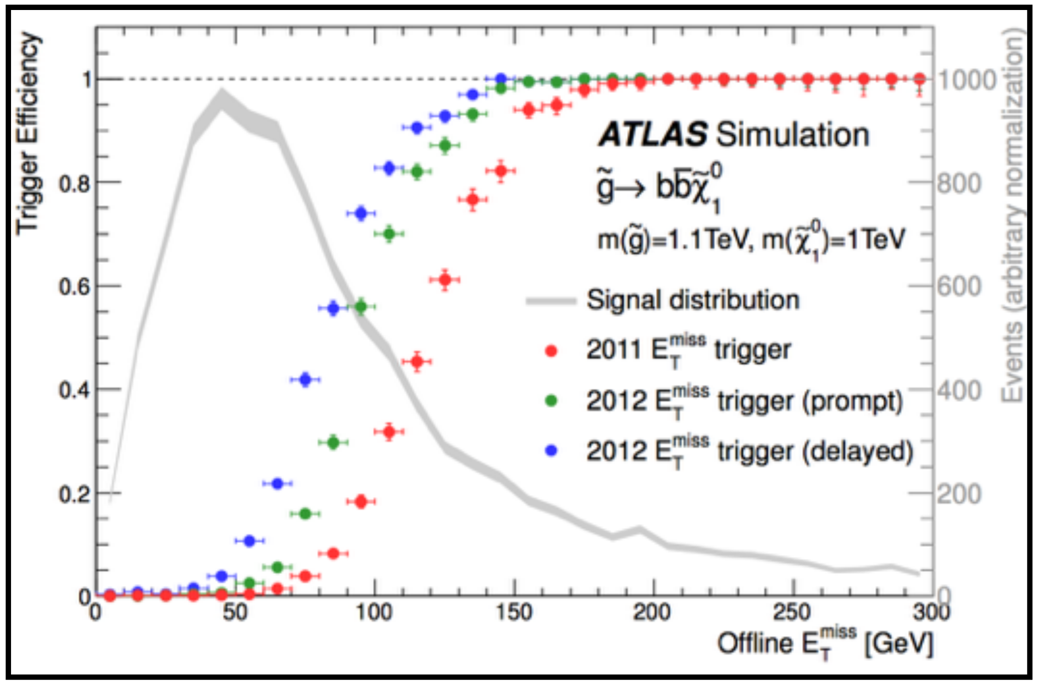


used in searches;
unfriendly to compressed region as MET there is subdued.

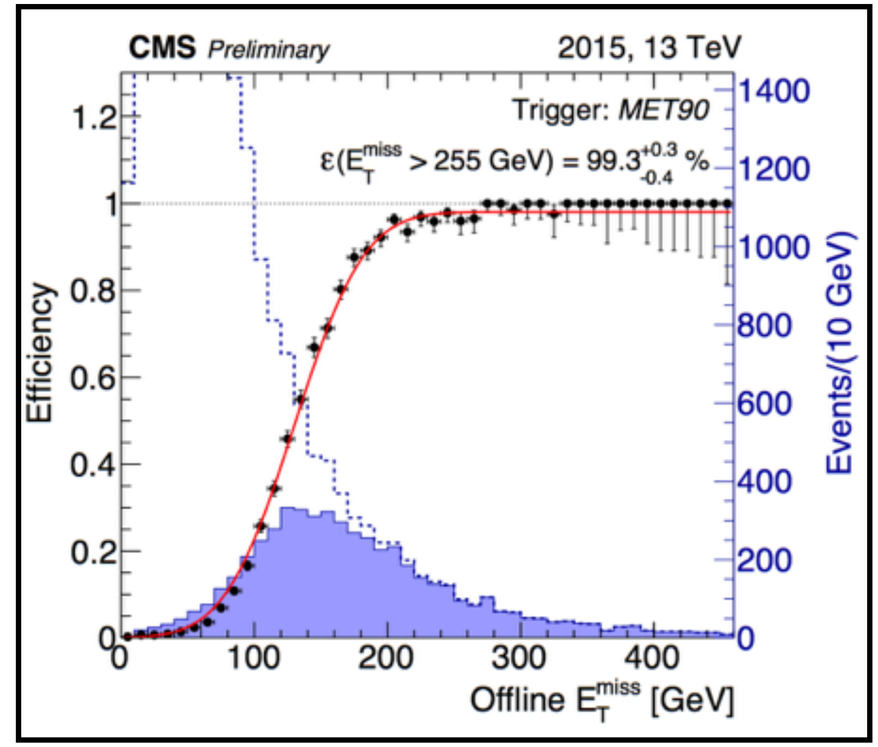
Without changing the analysis, experiments can set better limits by engaging the full trigger range.

Trigger

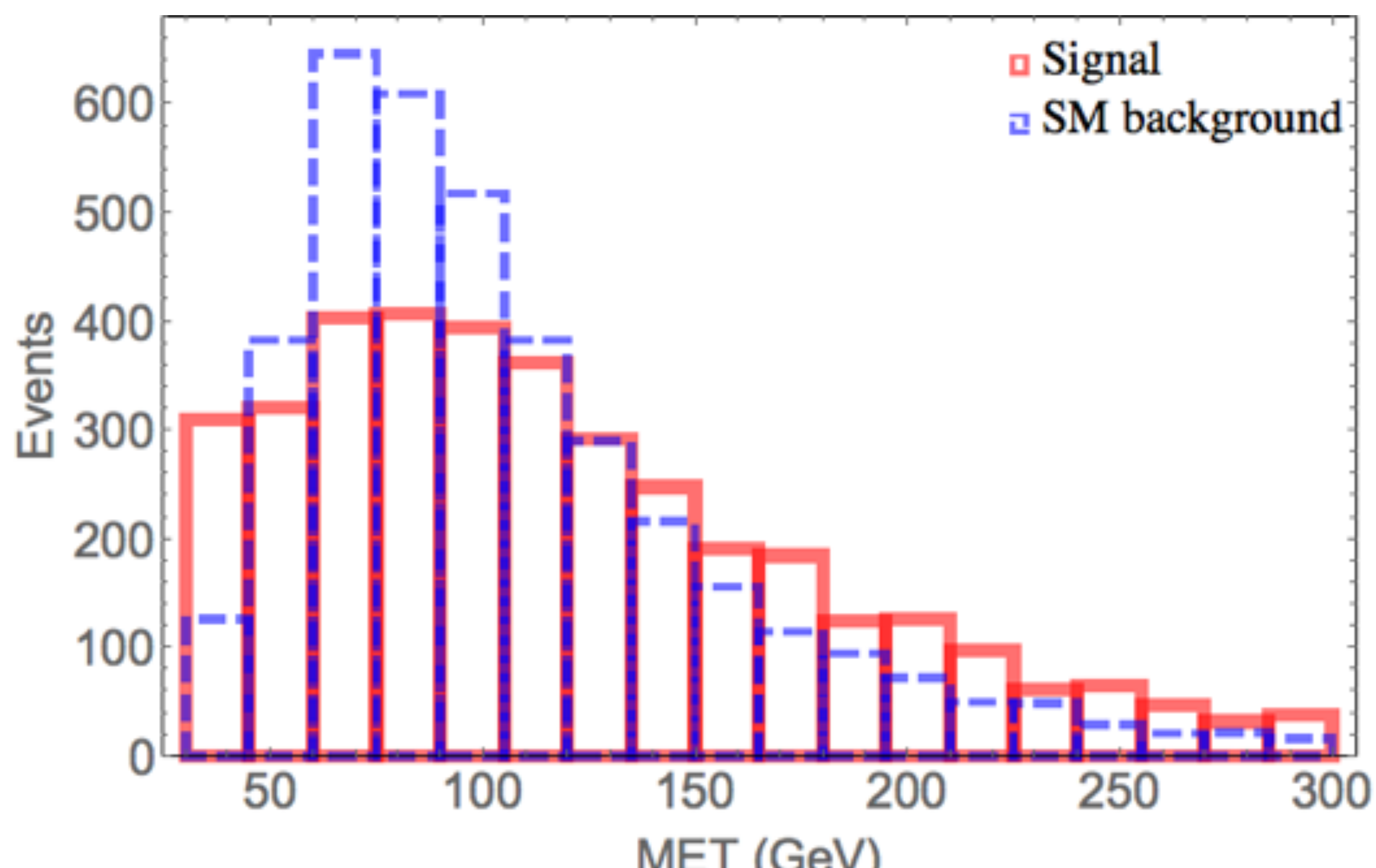
8 TeV



13 TeV

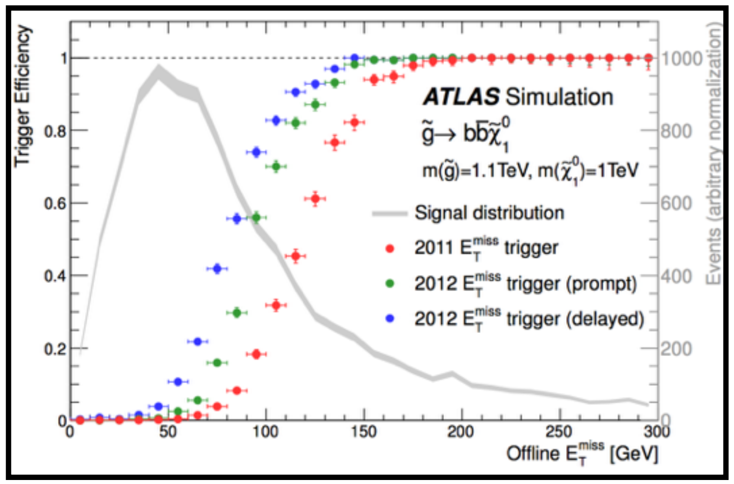


Convolve with MET distributions:

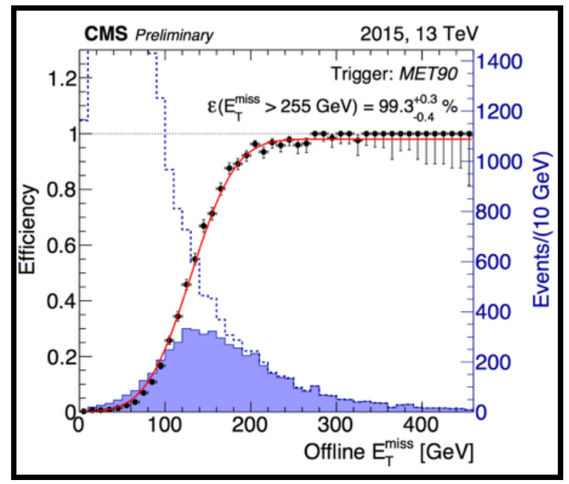


Trigger

8 TeV



13 TeV



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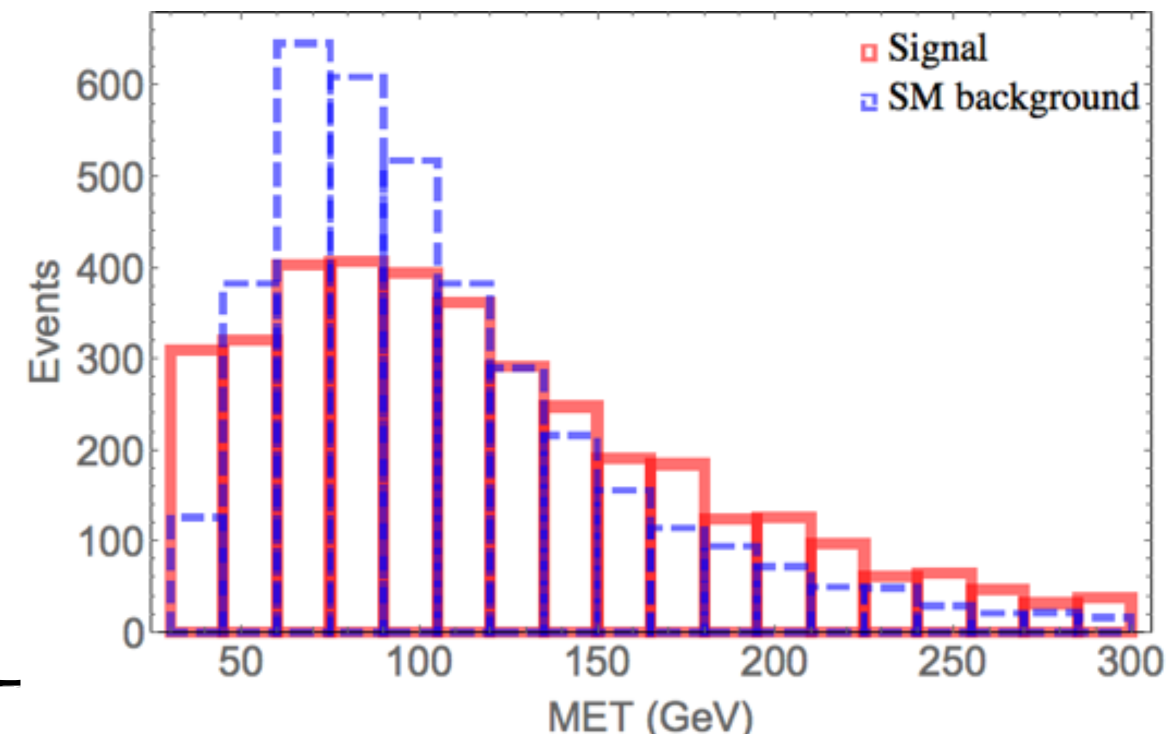

Profit/ forfeit

(i) If events selected from fully efficient region => significance loss: 50%
[ATLAS & CMS do this, plus cut hard on jets.]

(ii) Had trigger been ideal, significance gain: 10%

Backgrounds

Irreducible

$$jjjjZ \to jjjj\nu\bar{\nu}$$

"Lost" leptons

- **Failed isolation, reconstruction, acceptance**
- **Hadronically decaying taus**

$$jjjjW \to jjjj\nu\ell$$

$$t\bar{t} \to bbWW \to bbjj\nu\ell$$

$$jbt \to jbbW \to jbb\nu\ell$$

Other single top production modes

QCD multijets: jets mismeasured

High rates (millibarn cross-section), un-Monte Carlo-able.

QCD background

High rates (millibarn cross-section), un-Monte Carlo-able.

Cut cleverly and hope you have slain it.

QCD background

High rates (millibarn cross-section), un-Monte Carlo-able.

Cut cleverly and hope you have slain it.
E.g., in J Bramante, J Kumar, B Thomas (1109.6014) @ 7 TeV:

- No isolated charged leptons (e or μ) in the final state. ✓
- At least five ✓ jets with p_{T_j} ✓ > 40 GeV.
- Each jet must be isolated in the sense that ΔR_{jj} ✓ > 0.4 for every possible pairing of jets in the event, where ΔR_{jj} is the separation distance in the (η, ϕ) plane between a given pair of jets.
- An azimuthal-angle separation $\Delta\phi(p_{T_j}, \not{p}_T)$ X $> 11.5°$ between the missing-transverse-momentum vector and each of the leading three jets (ranked by p_{T_j}).
- $\not{E}_T > 100$ GeV. ✓

✓ ***We do something similar***
X ***We don't***

QCD background

High rates (millibarn cross-section), un-Monte Carlo-able.

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- $\not{E}_T > 100$ GeV. ✓

✓ ***We do something similar***
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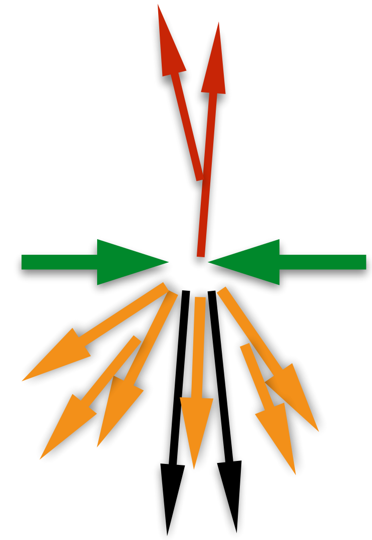
We look at what happens for different basic MET cuts —

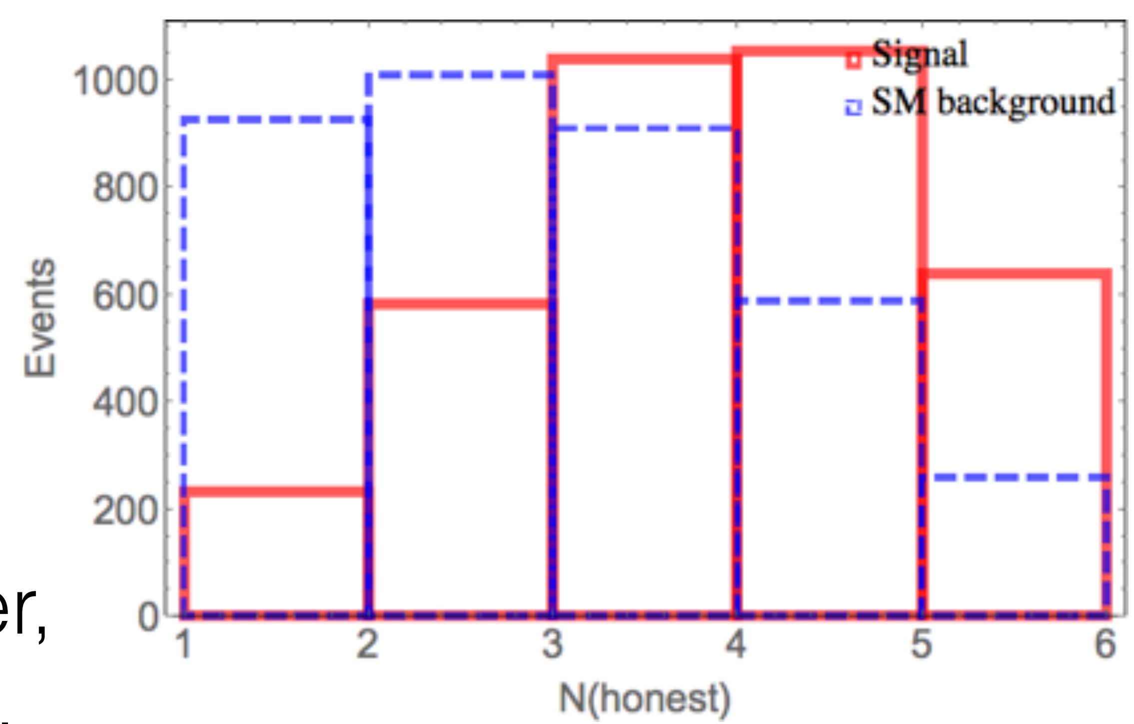
$$\not{E}_{T,8}^{\rm cut} = 60,\ 100,\ 140\ \mathrm{GeV};\qquad \not{E}_{T,13}^{\rm cut} = 90,\ 180\ \mathrm{GeV}$$

Basic cut on jets: ***pT* > 40 GeV**

Cut flow

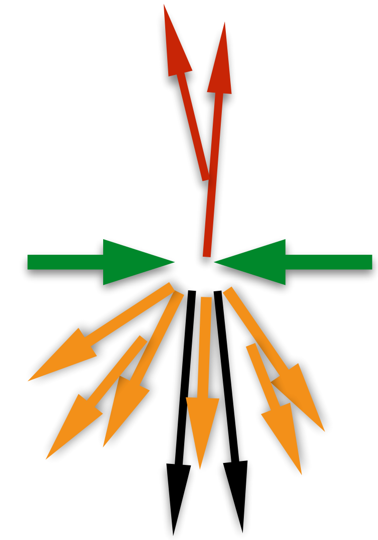


Cut I
$N_{\text{honest}} \geq n$



8 TeV collider,
1 TeV gluino.

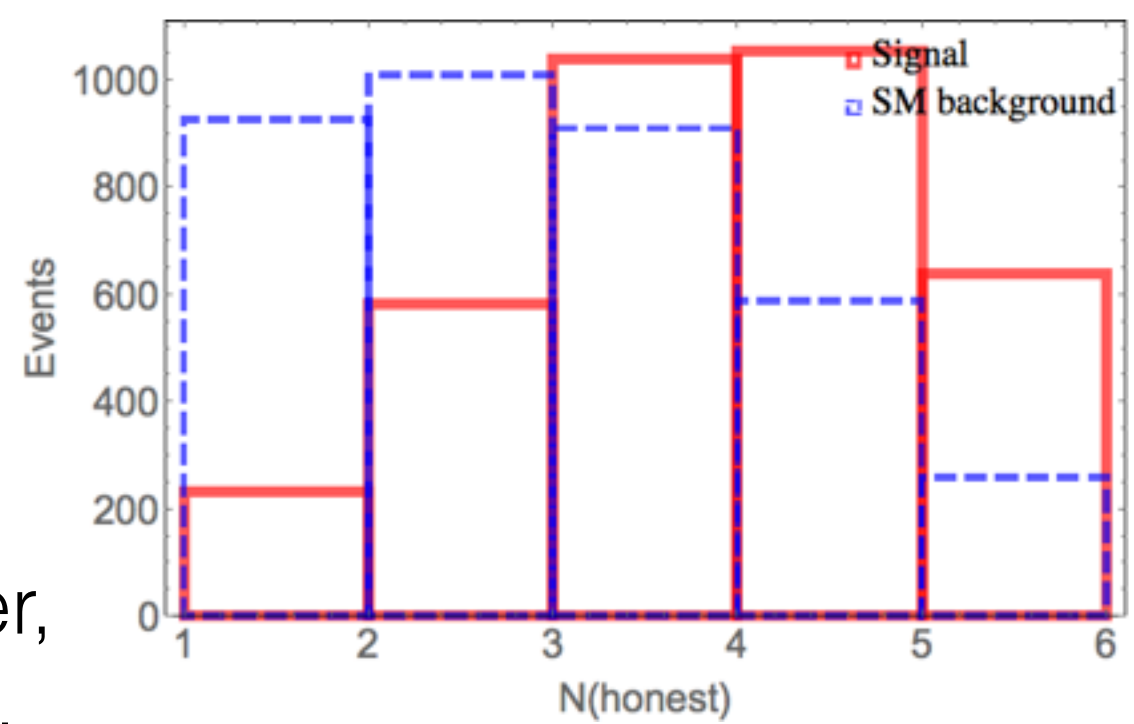
Cut flow



Cut I
$N_{\text{honest}} \geq n$

$m^2_{j_1 j_2} \approx E_1 E_2 \Delta\theta^2_{12}$, so $E^{\text{ISR}}_{\text{tag}} = \Delta M$ => $m_{j_1 j_2} \leq \Delta M$

If n = 4, satisfy: $\boxed{\text{At least two pairs of honest jets bound in invariant mass}}$



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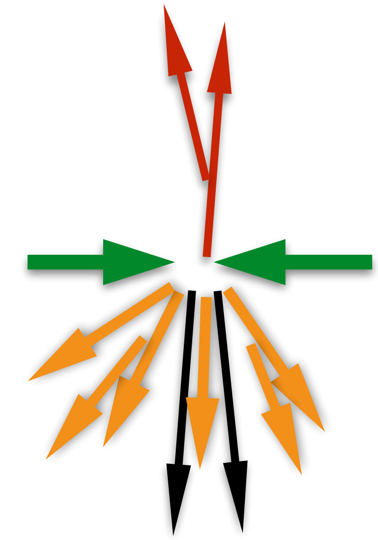
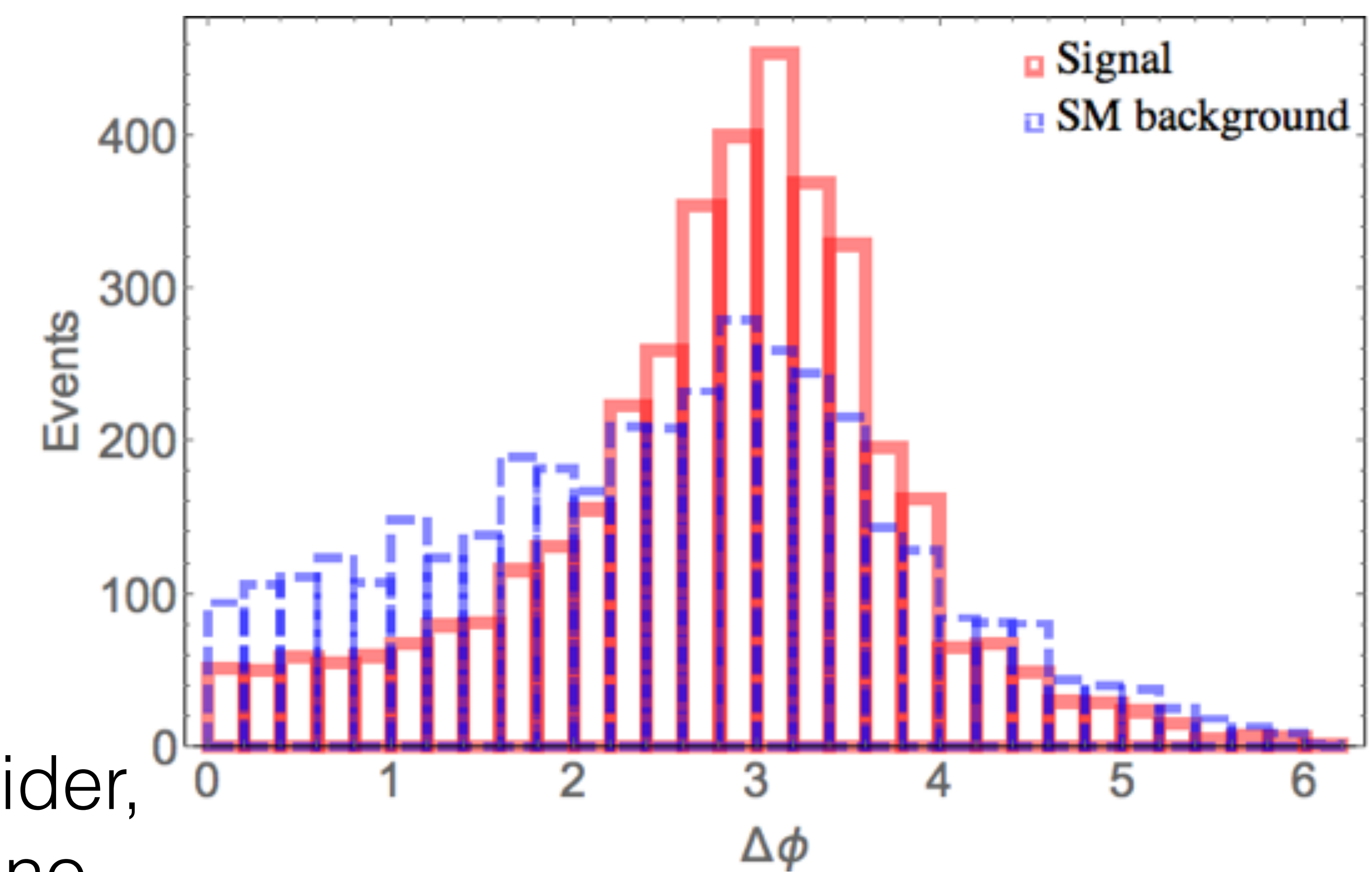


Cut II
$||\Delta\phi(\not{E}_T, j_{\text{ISR,max}})| - \pi| \leq 1.5$

Satisfy: Honest jets and binos recoil vs ISR



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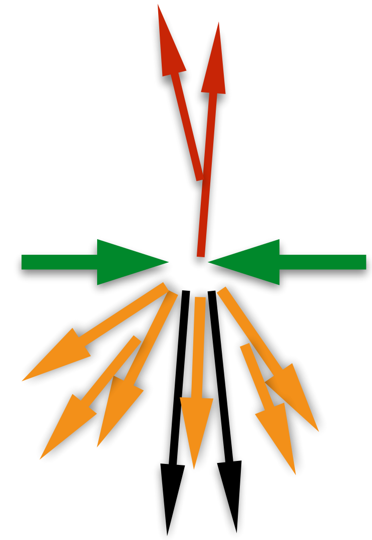
1 TeV gluino.

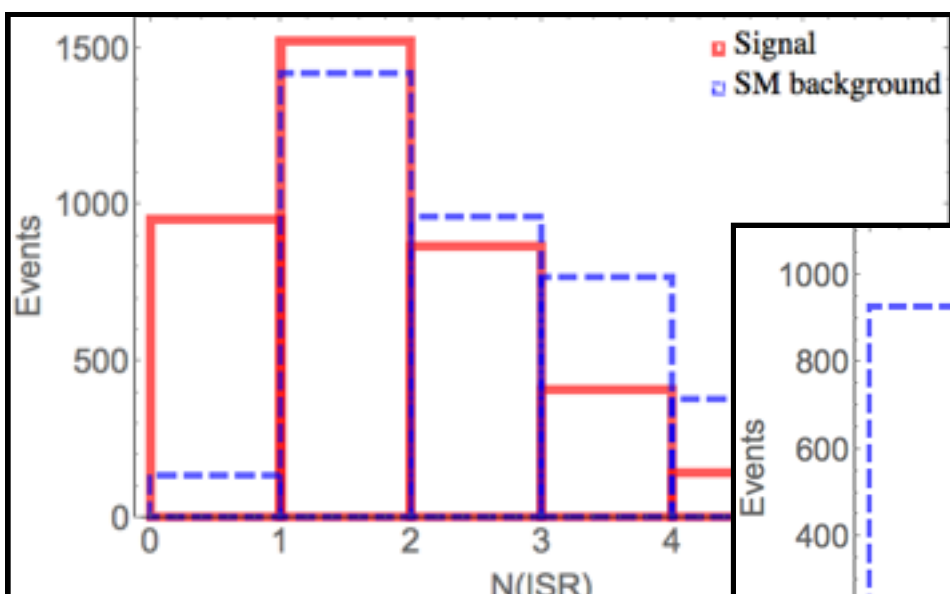
Cut flow



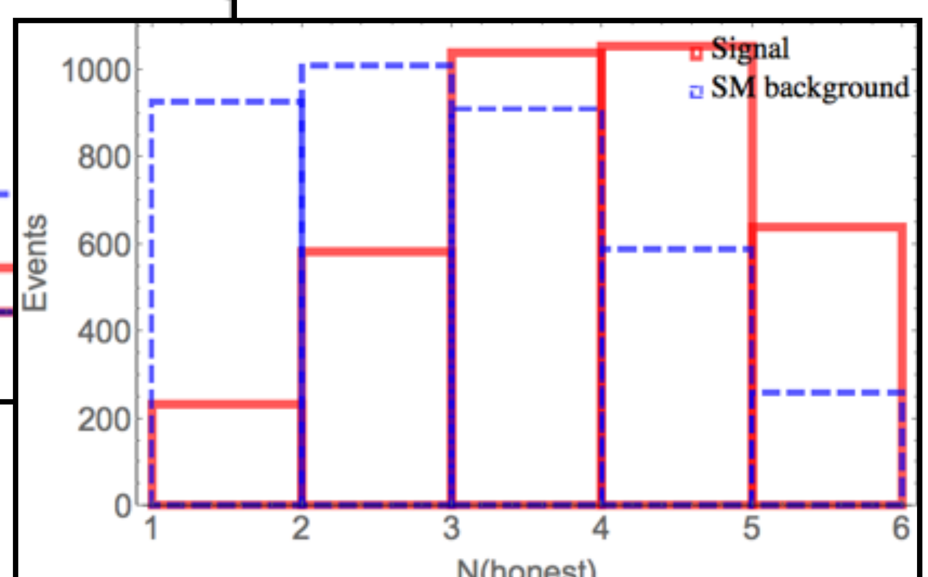
Cut III

$$\rho \equiv \frac{N_{\mathrm{ISR}}}{N_{\mathrm{honest}}}$$

Account for:

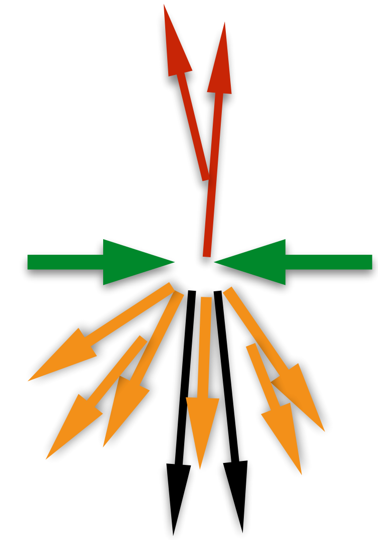


8 TeV collider,
1 TeV gluino.



Honest jets outnumber ISR jets

Cut flow



Cut III

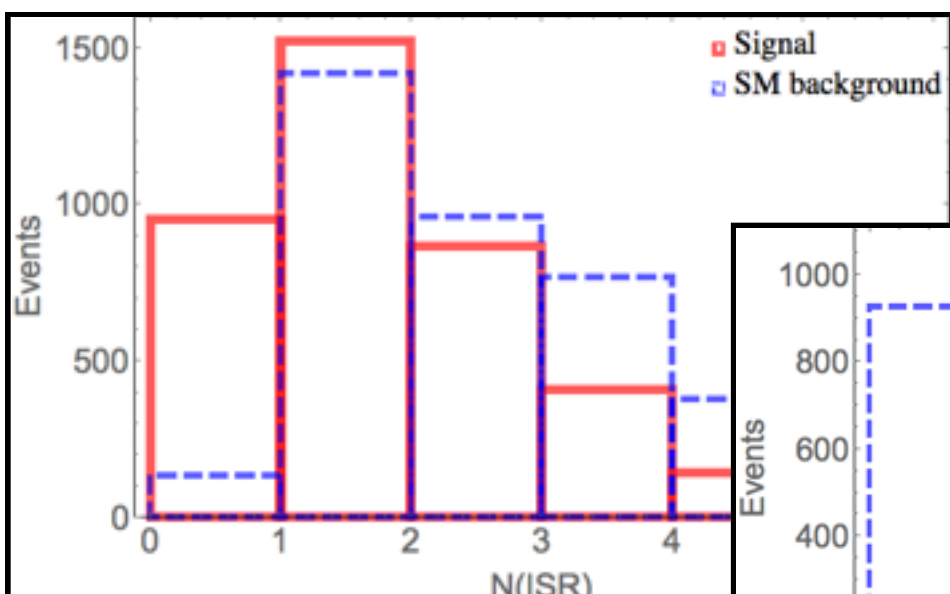
$$\rho \equiv \frac{\sum_{i=0}^{N_{\mathrm{ISR}}} E^{i}_{\mathrm{ISR}}}{\not{E}_T} \frac{N_{\mathrm{ISR}}}{N_{\mathrm{honest}}} \leq k(\sqrt{s}, m_{\tilde{g}})$$

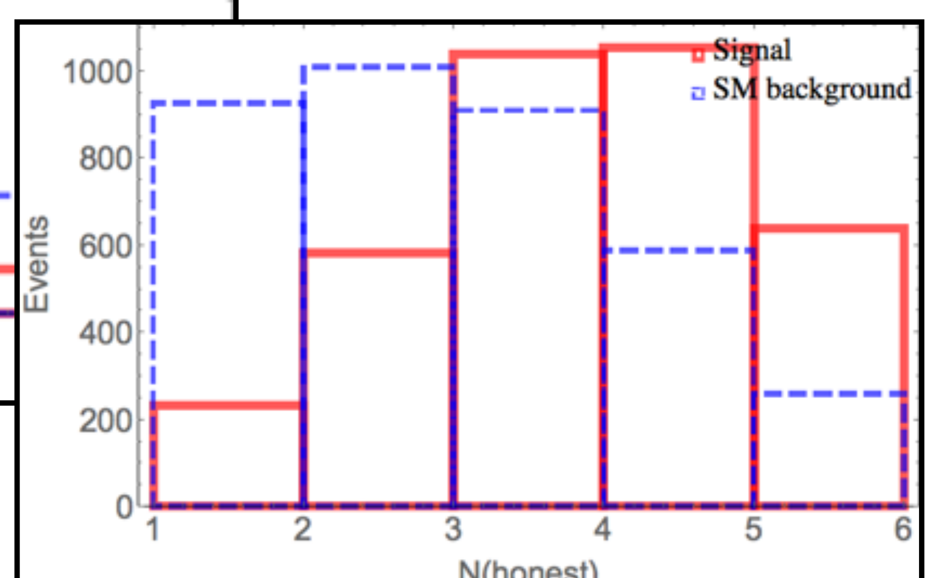
0.9 - 2

Honest jets and binos recoil vs ISR

Account for: $p_{T_{\mathrm{ISR}}}/\not{E}_T$ peaks at $m_{\tilde{g}}/m_{\tilde{\chi}^0} \simeq 1$

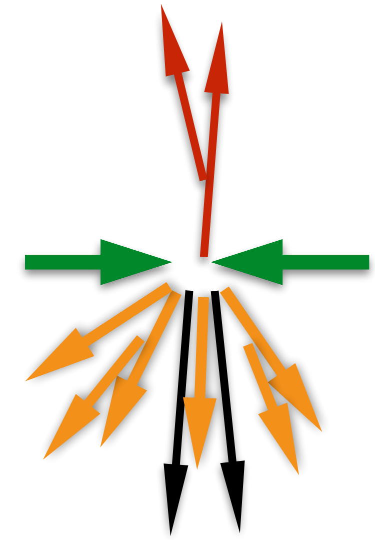
Honest jets outnumber ISR jets





8 TeV collider,
1 TeV gluino.

Cut flow



Cut III

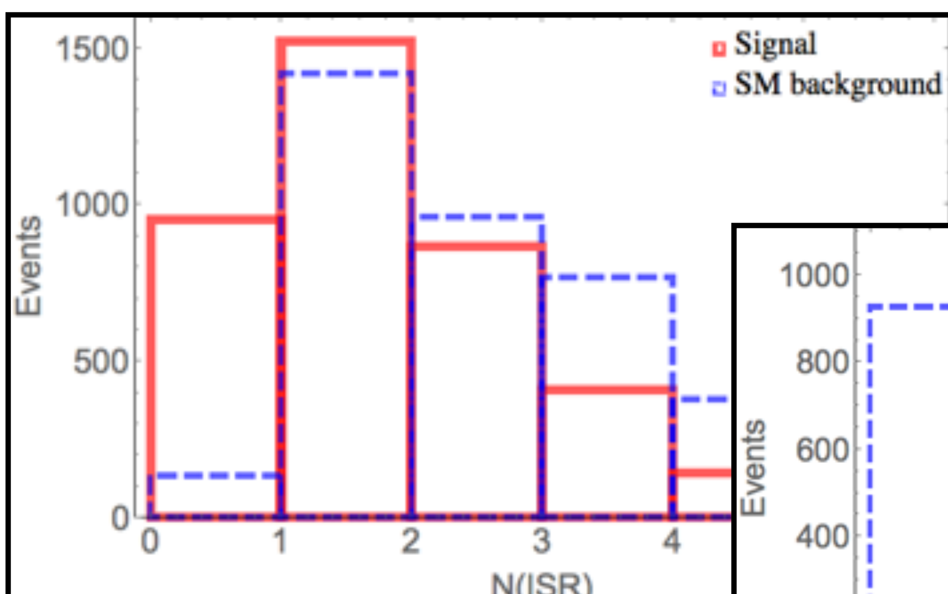
$$\rho \equiv \frac{\sum_{i=0}^{N_{\rm ISR}} E^i_{\rm ISR}}{\not{E}_T} \frac{N_{\rm ISR}}{N_{\rm honest}} \leq k(\sqrt{s}, m_{\tilde{g}})$$

0.9 - 2

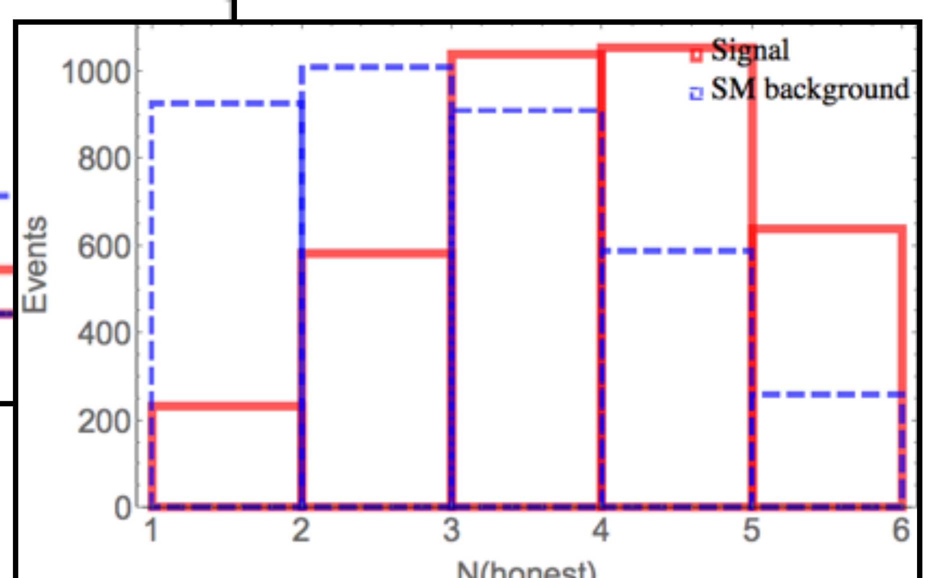
Honest jets and binos recoil vs ISR

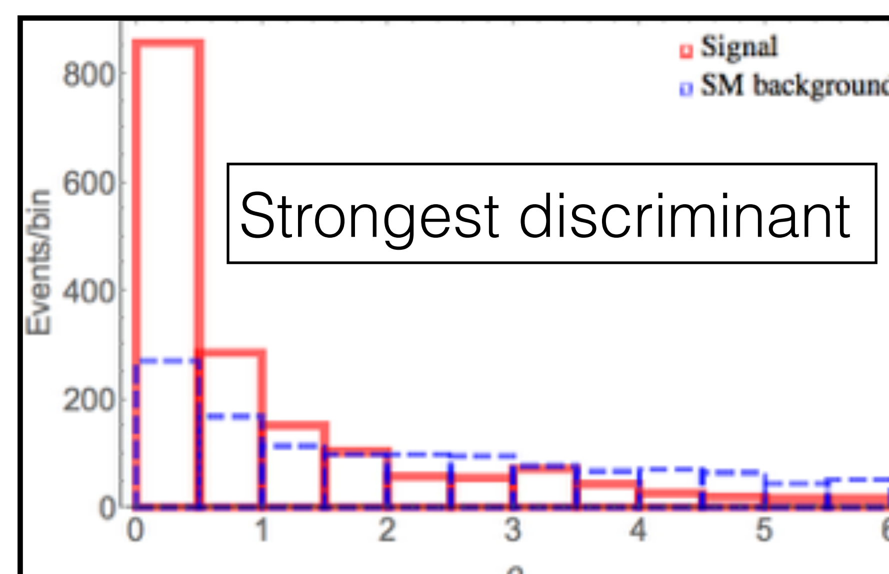
Account for: $\boxed{p_{T_{\rm ISR}}/\not{E}_T \text{ peaks at } m_{\tilde{g}}/m_{\tilde{\chi}^0} \simeq 1}$

Honest jets outnumber ISR jets

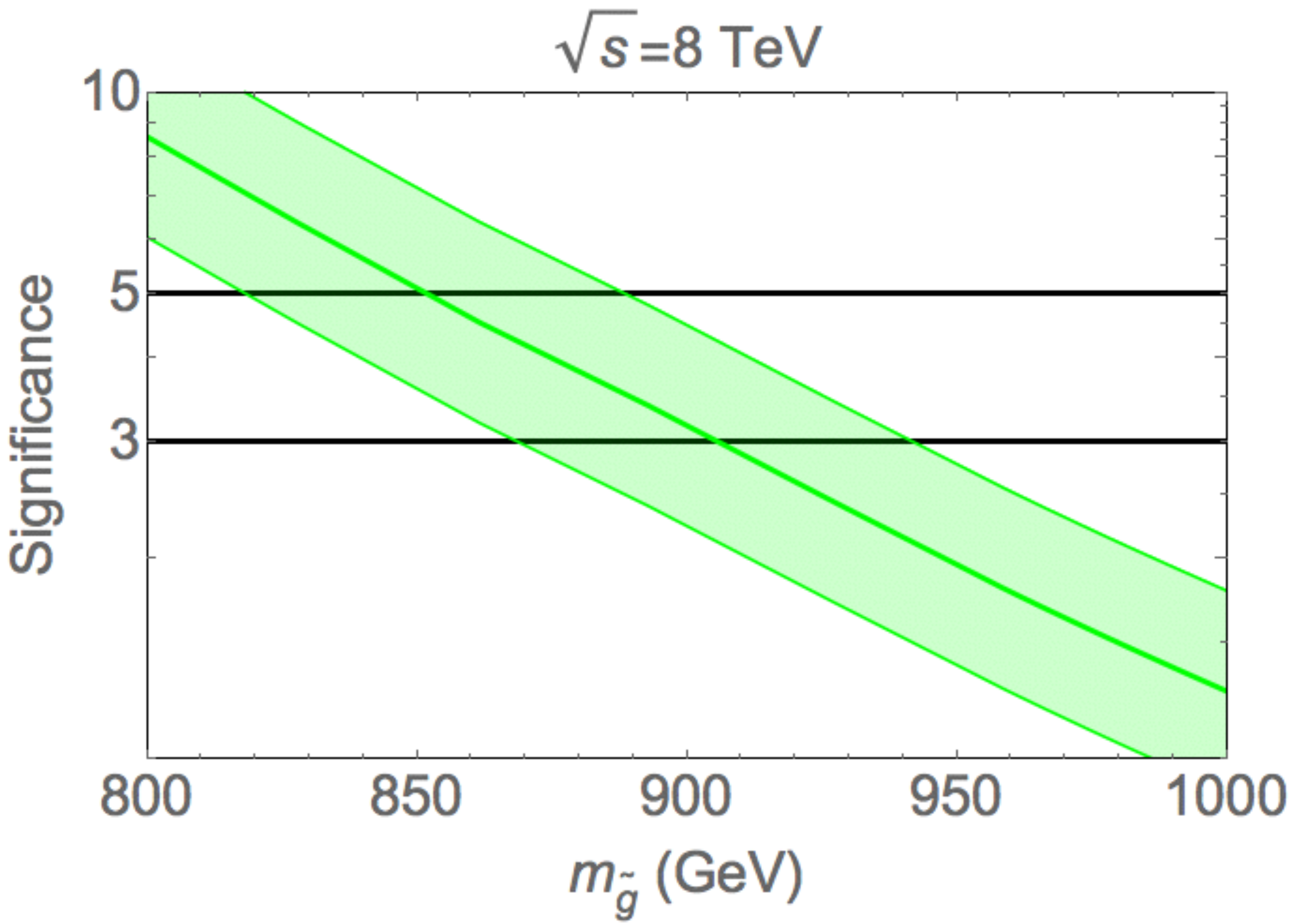


8 TeV collider,
1 TeV gluino.





Limits

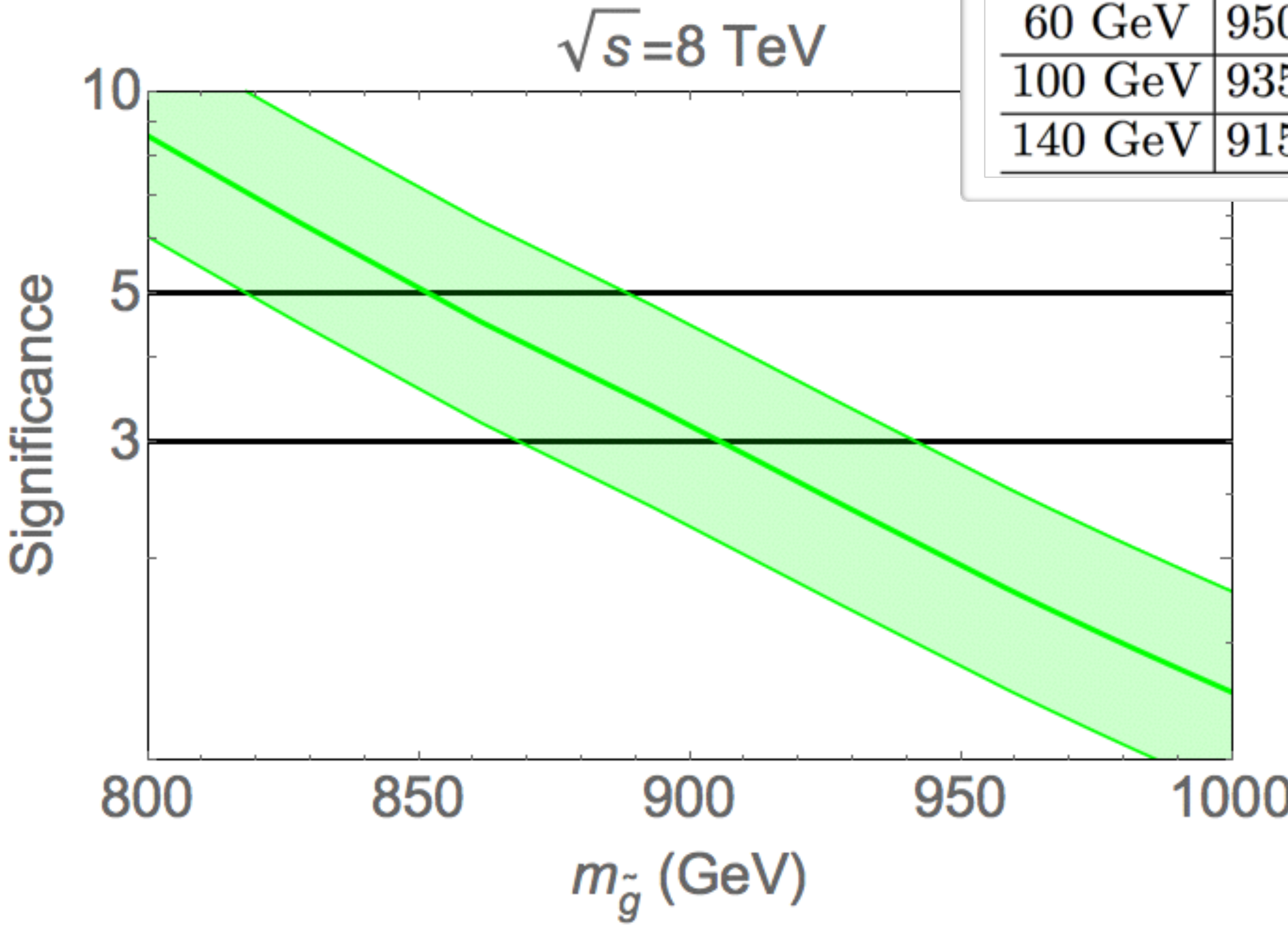


Bands: BG floated up and down by 2, subsuming uncertainty from matching, choice of factorization scale and PDF, etc.

Limits

$\not{E}_{T,8}^{\text{cut}}$	2σ	3σ	5σ
60 GeV	950 GeV	905 GeV	850 GeV
100 GeV	935 GeV	875 GeV	835 GeV
140 GeV	915 GeV	860 GeV	815 GeV

$\sqrt{s} = 8$ TeV, $\mathcal{L} = 20$ fb^{-1}



Recall: current 8 TeV bound is m(gluino) < 600 GeV.

Prospects: Monojets

Matt Low, L. T. Wang:1404.0682

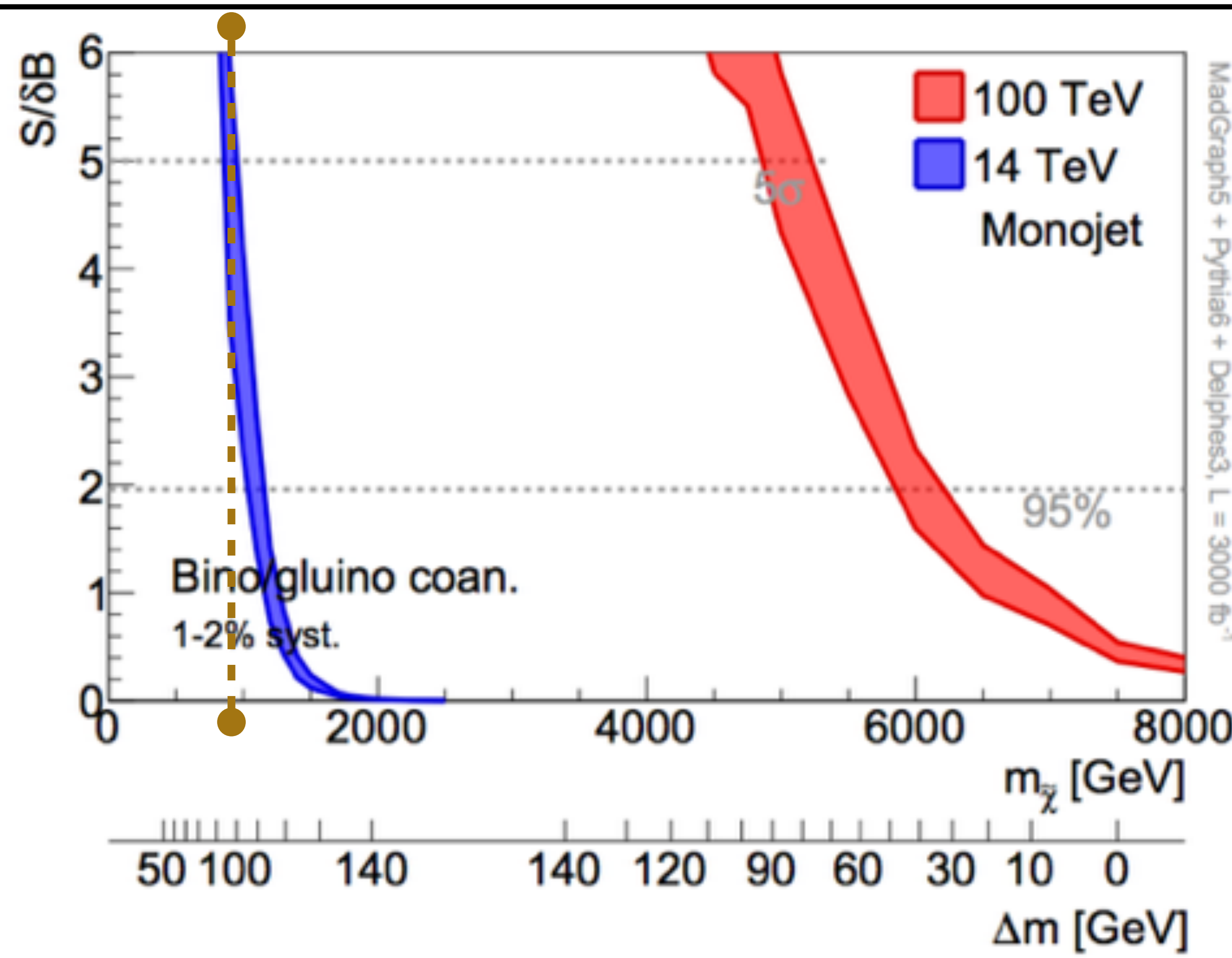
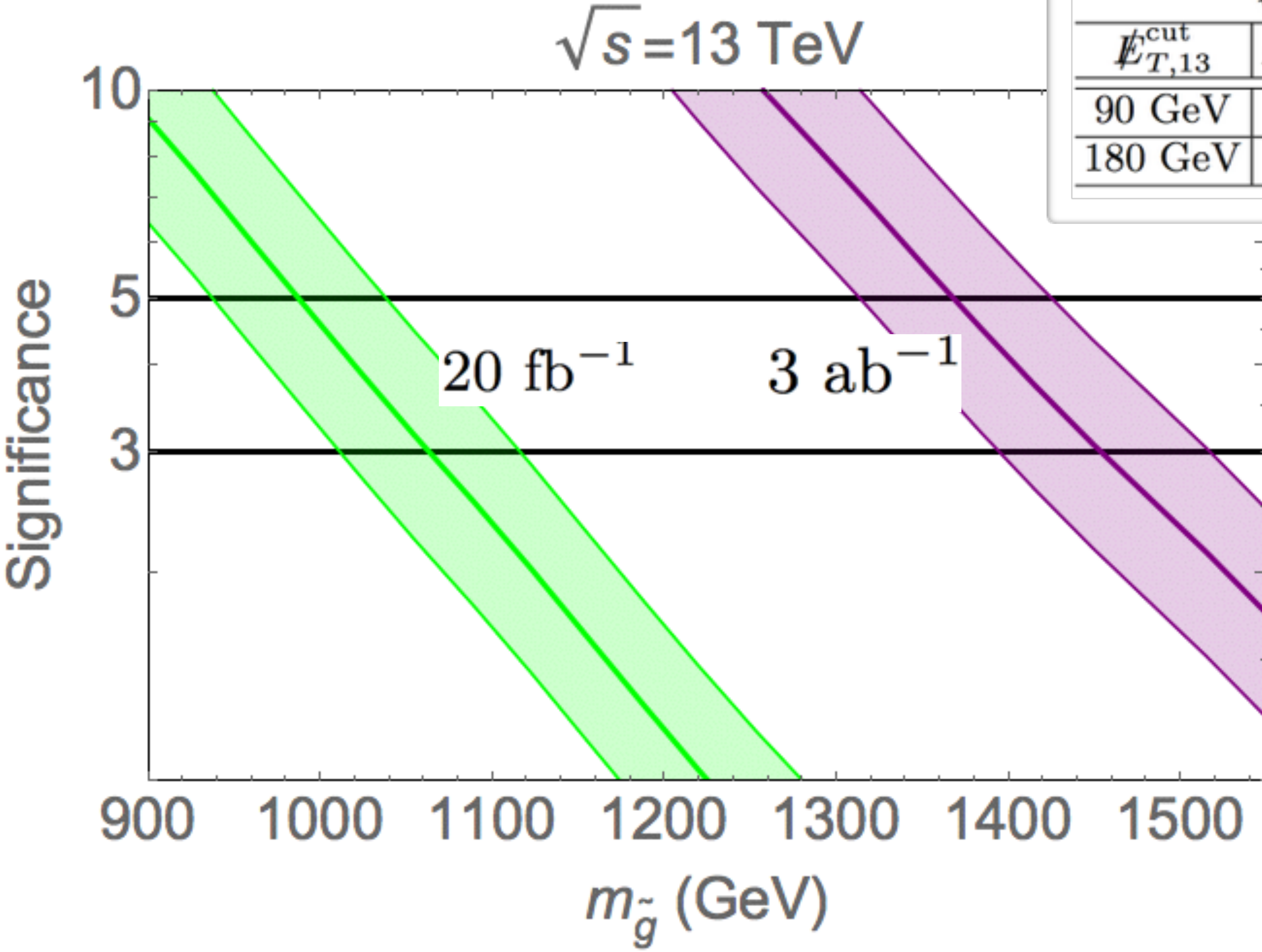


Figure 11: The mass reach in the gluino coannihilation scenario in the monojet channel with $\mathcal{L} = 3000$ fb^{-1} for the 14 TeV LHC (blue) and a 100 TeV proton-proton collider (red). The bands are generated by varying the background systematics between $1-2\%$ and the signal systematic uncertainty is set to 10%. The lower x-axis displays the gluino-bino mass splitting Δm for a given bino mass which is required to saturate the relic density [99, 100]. A tick is placed every 10 GeV with the exception of the consecutive $\Delta m = 140$ GeV ticks.

Prospects

$\sqrt{s} = 13$ TeV, 5σ reach			
$\not{E}_{T,13}^{\mathrm{cut}}$	$\mathcal{L} = 3\ \mathrm{fb}^{-1}$	$\mathcal{L} = 20\ \mathrm{fb}^{-1}$	$\mathcal{L} = 3\ \mathrm{ab}^{-1}$
90 GeV	815 GeV	990 GeV	1370 GeV
180 GeV	790 GeV	965 GeV	1340 GeV

$\sqrt{s} = 13$ TeV, 2σ exclusion			
$\not{E}_{T,13}^{\mathrm{cut}}$	$\mathcal{L} = 3\ \mathrm{fb}^{-1}$	$\mathcal{L} = 20\ \mathrm{fb}^{-1}$	$\mathcal{L} = 3\ \mathrm{ab}^{-1}$
90 GeV	950 GeV	1125 GeV	1530 GeV
180 GeV	925 GeV	1100 GeV	1510 GeV



Recall: best 13 TeV bound is m(gluino) < 950 GeV.

End Remarks

Idea can be generalized to

- **squarks,**
- **Dirac masses,**
- **non-SUSY scenarios: color triplet/octet scalar/fermion,**
- **…**

<u>Every compressed scenario may need a custom-built strategy.</u>

Backgrounds like QCD multijets best removed by experimenters.

Trigger information made accessible will be helpful for theorists to perform realistic analysis.

Need new techniques to squeeze SUSY out if and as we run out of it

Thanks for your attention!

Backup

Compressed Hounds

* Compressed gauginos in VBF, plus soft leptons — 1004.4902, G. F. Giudice, T. Han, K. Wang, L. T. Wang
* Disappearing tracks — 1310.3675, ATLAS
* Counting un-reconstructed tracks — 1606.07826, A. Chakraborty, S. Chakraborty, T. S. Roy.

Compressed Stop Hounds

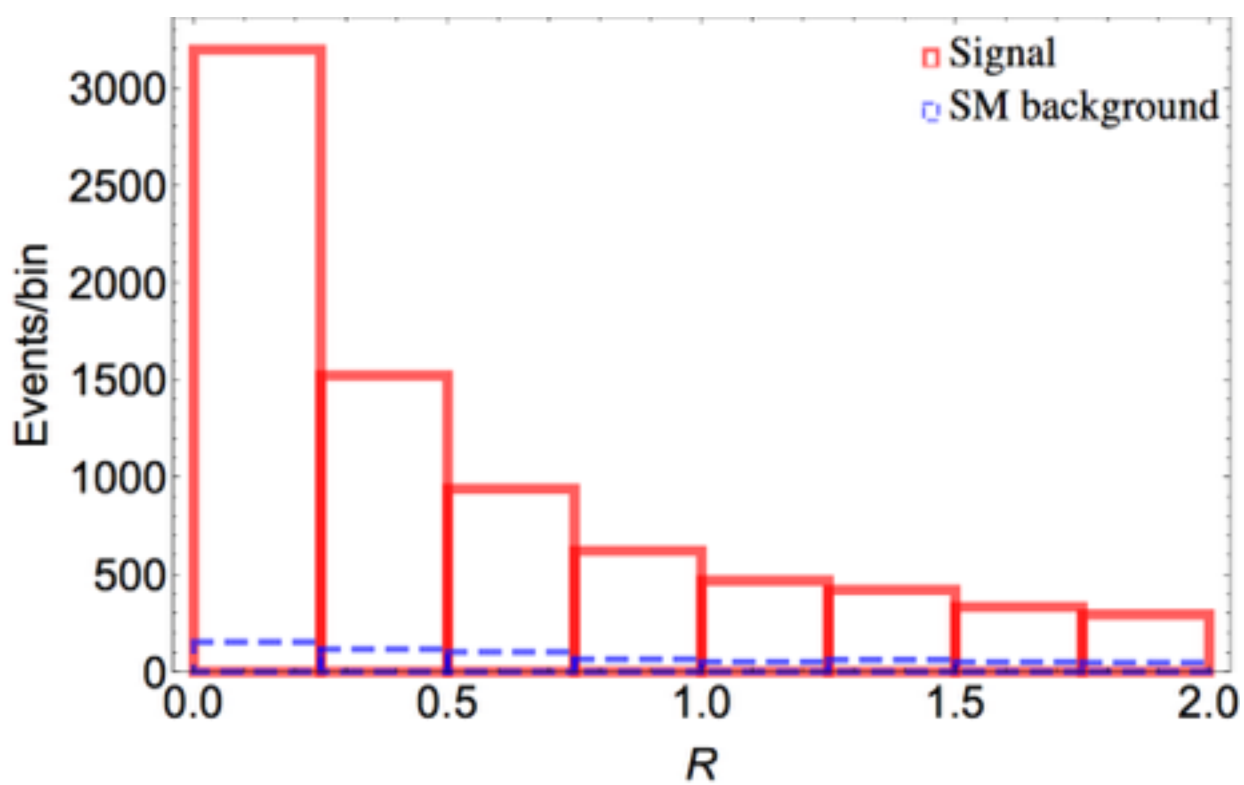
* Spin correlations [m(stop) ~ m(top)] — 9406411, 0205023, 1205.5808
* VBF tagging — 1312.1348
* Stoponium [lifetime(stop) = long] — 9310209, 0801.0237

Cut efficiencies

8 TeV, m(gluino) = 1 TeV

Cut	Signal cross-section (fb)	$Z + 4j$ cross-section (fb)	"Lost leptons" cross-section (fb)
Basic cut + trigger	5.77 ± 0.06	1390 ± 13	2282 ± 46
Cut I $N_{\text{honest}} \geq n$	3.05 ± 0.04 (53%)	393 ± 7 (28%)	544 ± 22 (24%)
Cut II $\left\| \Delta\phi(\not{E}_T, j_{\text{ISR,max}}) \right\| - \pi \| \leq 1.5$	2.72 ± 0.04 (47%)	288 ± 6 (21%)	393 ± 18 (17%)
Cut III $\rho \equiv \frac{\sum_{i=0}^{N_{\text{ISR}}} E^i_{\text{ISR}}}{\not{E}_T} \frac{N_{\text{ISR}}}{N_{\text{honest}}} \leq k(\sqrt{s}, m_{\tilde{g}})$	2.24 ± 0.04 (39%)	145 ± 4 (10%)	242 ± 15 (10%)

<u>Cut III is the real deal.</u>



Matching

- Effect of higher order W/Z + 5 (or more) jets: *k* factors to leading order W/Z + 4 jets.

- More ISR jets selected => Less efficient than W/Z + 4 jets thanks to Cut III.

$$\rho \equiv \frac{\sum_{i=0}^{N_{\rm ISR}} E^i_{\rm ISR}}{\not{E}_T} \frac{N_{\rm ISR}}{N_{\rm honest}} \leq k(\sqrt{s}, m_{\tilde{g}})$$

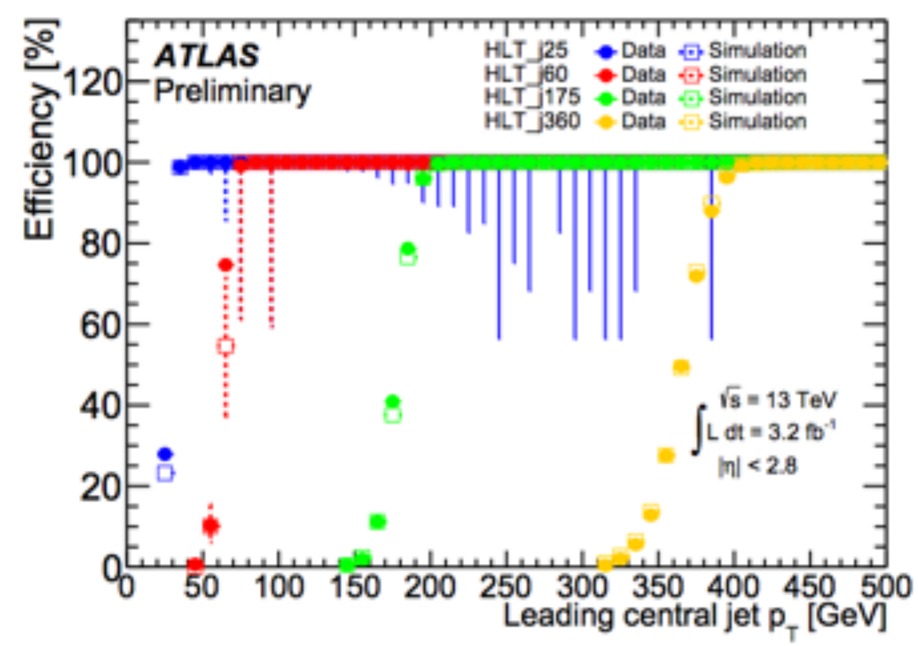
— verified with SHERPA by matching Z+4j with higher multiplicity,

— flat *k* factor justified.

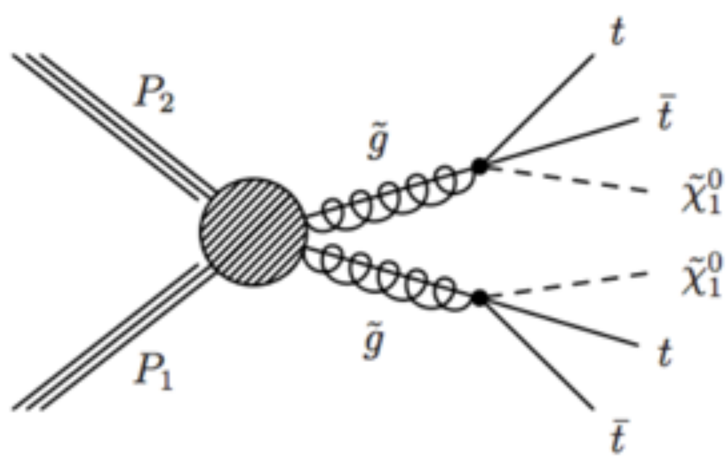
- Smaller than PDF and scale uncertainties, thus subsumed into our systematic uncertainty (-50% to 100%).

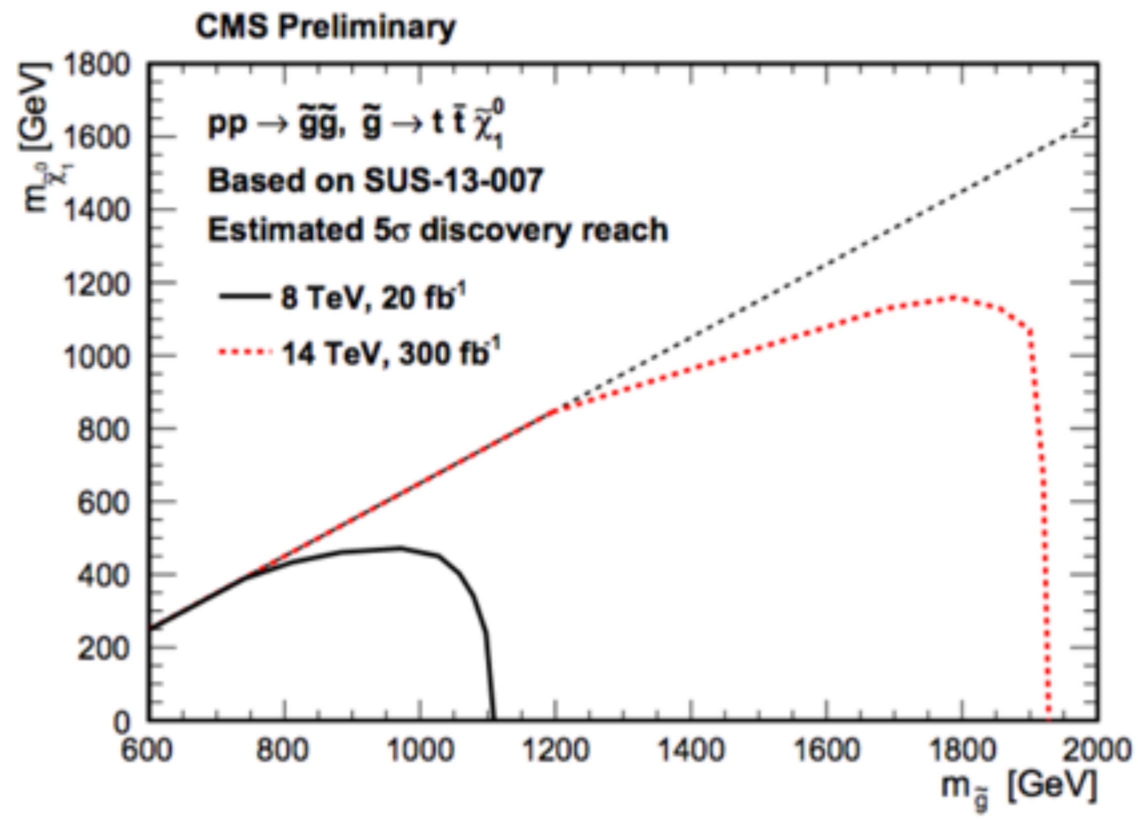
Trigger Menu

Trigger	Typical offline selection	Trigger Selection		Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
		Level-1 (GeV)	HLT (GeV)	$L = 5 \times 10^{33}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	
Single leptons	Single iso μ, $p_T > 21$ GeV	15	20	7	130
	Single e, $p_T > 25$ GeV	20	24	18	139
	Single μ, $p_T > 42$ GeV	20	40	5	33
	Single τ, $p_T > 90$ GeV	60	80	2	41
Two leptons	Two μ's, each $p_T > 11$ GeV	2×10	2×10	0.8	19
	Two μ's, $p_T > 19, 10$ GeV	15	18, 8	7	18
	Two loose e's, each $p_T > 15$ GeV	2×10	2×12	10	5
	One e & one μ, $p_T > 10, 26$ GeV	20 (μ)	7, 24	5	1
	One loose e & one μ, $p_T > 19, 15$ GeV	15, 10	17, 14	0.4	2
	Two τ's, $p_T > 40, 30$ GeV	20, 12	35, 25	2	22
	One τ, one μ, $p_T > 30, 15$ GeV	12, 10 (+jets)	25, 14	0.5	10
	One τ, one e, $p_T > 30, 19$ GeV	12, 15 (+jets)	25, 17	1	3.9
Three leptons	Three loose e's, $p_T > 19, 11, 11$ GeV	15, 2×7	17, 2×9	3	< 0.1
	Three μ's, each $p_T > 8$ GeV	3×6	3×6	< 0.1	4
	Three μ's, $p_T > 19, 2 \times 6$ GeV	15	18, 2×4	7	2
	Two μ's & one e, $p_T > 2 \times 11, 14$ GeV	2×10 (μ's)	2×10, 12	0.8	0.2
	Two loose e's & one μ, $p_T > 2 \times 11, 11$ GeV	2×8, 10	2×12, 10	0.3	< 0.1
One photon	one γ, $p_T > 125$ GeV	22	120	8	20
Two photons	Two loose γ's, $p_T > 40, 30$ GeV	2×15	35, 25	1.5	12
	Two tight γ's, $p_T > 25, 25$ GeV	2×15	2×20	1.5	7
Single jet	Jet ($R = 0.4$), $p_T > 400$ GeV	100	360	0.9	18
	Jet ($R = 1.0$), $p_T > 400$ GeV	100	360	0.9	23
E_T^{miss}	$E_T^{\mathrm{miss}} > 180$ GeV	50	70	0.7	55
Multi-jets	Four jets, each $p_T > 95$ GeV	3×40	4×85	0.3	20
	Five jets, each $p_T > 70$ GeV	4×20	5×60	0.4	15
	Six jets, each $p_T > 55$ GeV	4×15	6×45	1.0	12
b-jets	One loose b, $p_T > 235$ GeV	100	225	0.9	35
	Two medium b's, $p_T > 160, 60$ GeV	100	150, 50	0.9	9
	One b & three jets, each $p_T > 75$ GeV	3×25	4×65	0.9	11
	Two b & two jets, each $p_T > 45$ GeV	3×25	4×35	0.9	9
b-physics	Two μ's, $p_T > 6, 4$ GeV plus dedicated b-physics selections	6, 4	6, 4	8	52
Total				70	1400



CMS Projections





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