BSM&TOP PHYSICS (AFTER LHC)

ROBERTO FRANCESCHINI (CERN)

OLOMOUC, SEP. 22 2016

9th International Workshop on Top Quark Physics TOP 2016

Outline

- status and prospect for new physics at LHC
- examples (mostly SUSY) and ideas
- conclusions

LHC status and ~~perspectives~~ flash

- top quark physics at LHC is entering precision age
- by 2018 LHC will have **0.1/ab**=100/fb
- in sight: new Higgs bosons and new electroweak states

Menu

despite the great prospects, some flies on the ointment:

- squarks in the difficult regions
- light degenerate chargino (Higgsino-like)
- light singlets (*e.g.* $pp \to S \to \gamma\gamma$)

Challenges

* compressed
* diluted
* delayed

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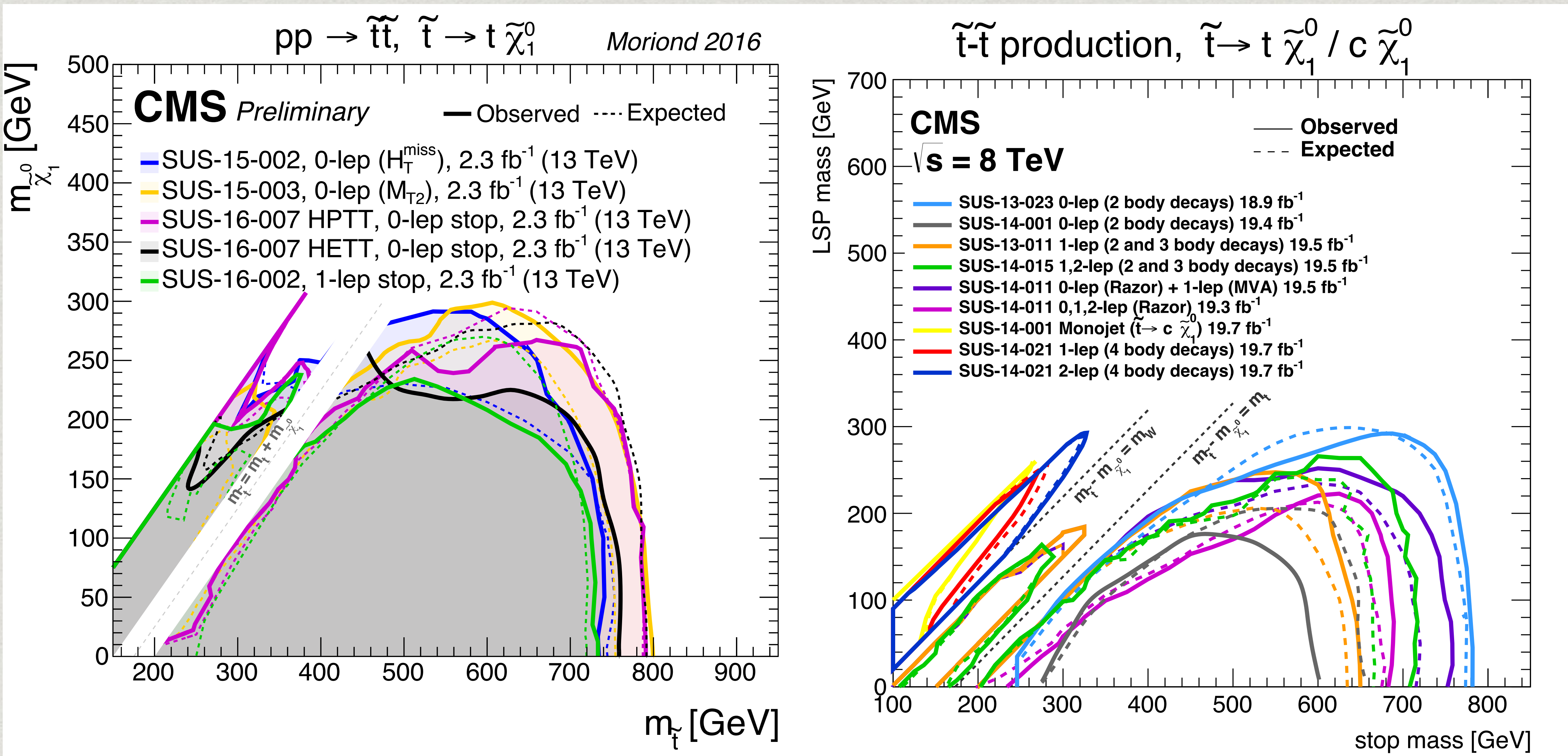
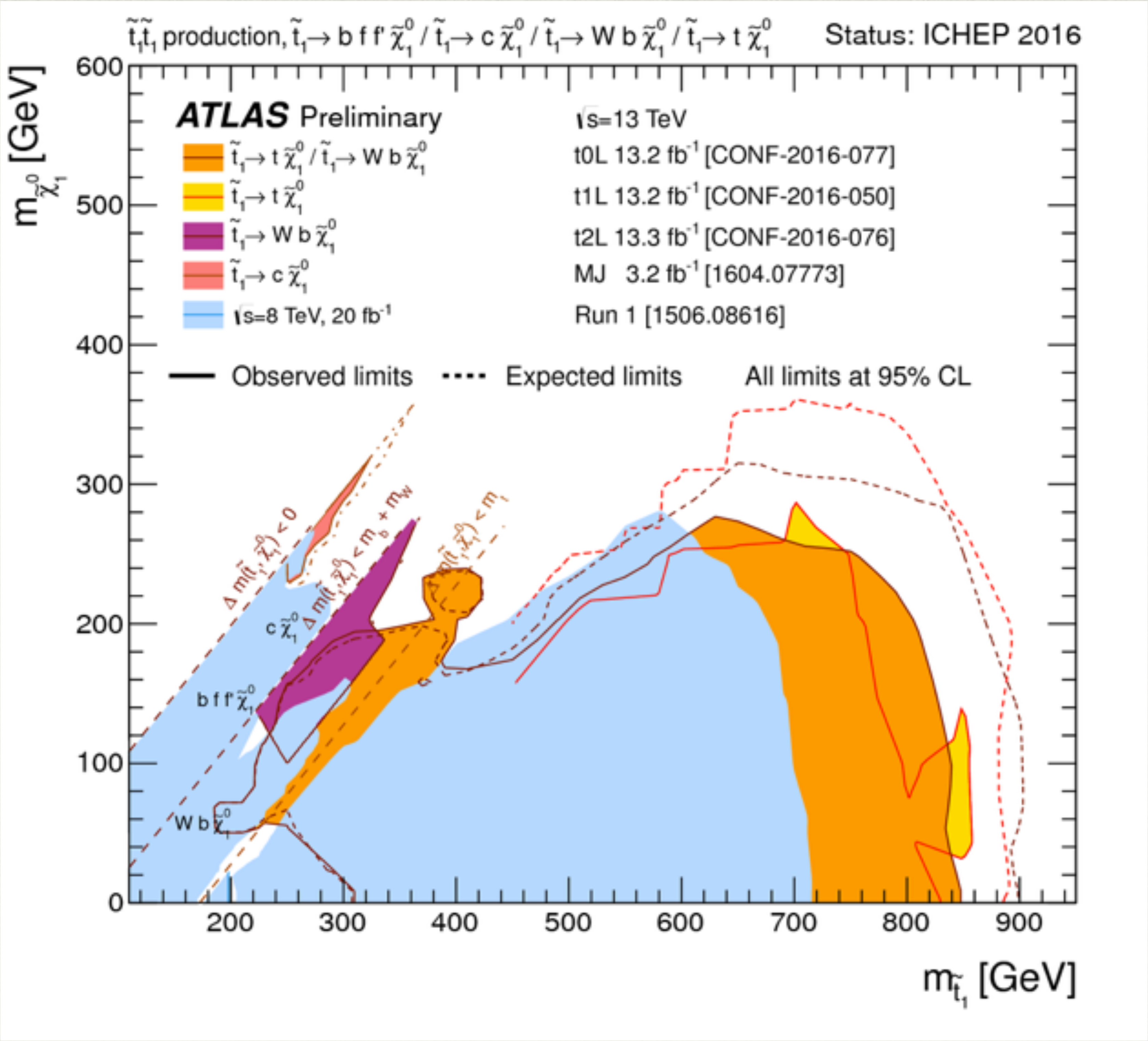


pp → t̃t̃, t̃ → t χ̃⁰₁
Moriond 2016
CMS Preliminary
Observed
Expected
SUS-15-002, 0-lep (H_T^miss), 2.3 fb⁻¹ (13 TeV)
SUS-15-003, 0-lep (M_T2), 2.3 fb⁻¹ (13 TeV)
SUS-16-007 HPTT, 0-lep stop, 2.3 fb⁻¹ (13 TeV)
SUS-16-007 HETT, 0-lep stop, 2.3 fb⁻¹ (13 TeV)
SUS-16-002, 1-lep stop, 2.3 fb⁻¹ (13 TeV)
m_t̃ = m_t + m_χ̃⁰₁
m_χ̃⁰₁ [GeV]
m_t̃ [GeV]
t̃-t̃ production, t̃→ t χ̃⁰₁ / c χ̃⁰₁
CMS
√s = 8 TeV
Observed
Expected
SUS-13-023 0-lep (2 body decays) 18.9 fb⁻¹
SUS-14-001 0-lep (2 body decays) 19.4 fb⁻¹
SUS-13-011 1-lep (2 and 3 body decays) 19.5 fb⁻¹
SUS-14-015 1,2-lep (2 and 3 body decays) 19.5 fb⁻¹
SUS-14-011 0-lep (Razor) + 1-lep (MVA) 19.5 fb⁻¹
SUS-14-011 0,1,2-lep (Razor) 19.3 fb⁻¹
SUS-14-001 Monojet (t̃→ c χ̃⁰₁) 19.7 fb⁻¹
SUS-14-021 1-lep (4 body decays) 19.7 fb⁻¹
SUS-14-021 2-lep (4 body decays) 19.7 fb⁻¹
m_t̃ - m_χ̃⁰₁ = m_W
m_t̃ - m_χ̃⁰₁ = m_t
LSP mass [GeV]
stop mass [GeV]

Do not enter

CMS Preliminary
SUS-15-002, 0-lep
SUS-15-003, 0-lep (M_{T2})
SUS-16-007 HPTT
SUS-16-007 HETT
SUS-16-002, 1-lep stop,
$m_{\tilde{\chi}^0_1}$ [GeV]
STOP
DO NOT
ENTER
$\tilde{t} \rightarrow t\,\tilde{\chi}^0_1$ / c $\tilde{\chi}^0_1$
Observed
Expected
stop mass [GeV]

Do not enter



t̃₁t̃₁ production, t̃₁→ b f f' χ̃⁰₁ / t̃₁→ c χ̃⁰₁ / t̃₁→ W b χ̃⁰₁ / t̃₁→ t χ̃⁰₁
Status: ICHEP 2016
ATLAS Preliminary
√s=13 TeV
t̃₁→ t χ̃⁰₁ / t̃₁→ W b χ̃⁰₁
t0L 13.2 fb⁻¹ [CONF-2016-077]
t̃₁→ t χ̃⁰₁
t1L 13.2 fb⁻¹ [CONF-2016-050]
t̃₁→ W b χ̃⁰₁
t2L 13.3 fb⁻¹ [CONF-2016-076]
t̃₁→ c χ̃⁰₁
MJ 3.2 fb⁻¹ [1604.07773]
√s=8 TeV, 20 fb⁻¹
Run 1 [1506.08616]
Observed limits
Expected limits
All limits at 95% CL
m χ̃⁰₁ [GeV]
m t̃₁ [GeV]

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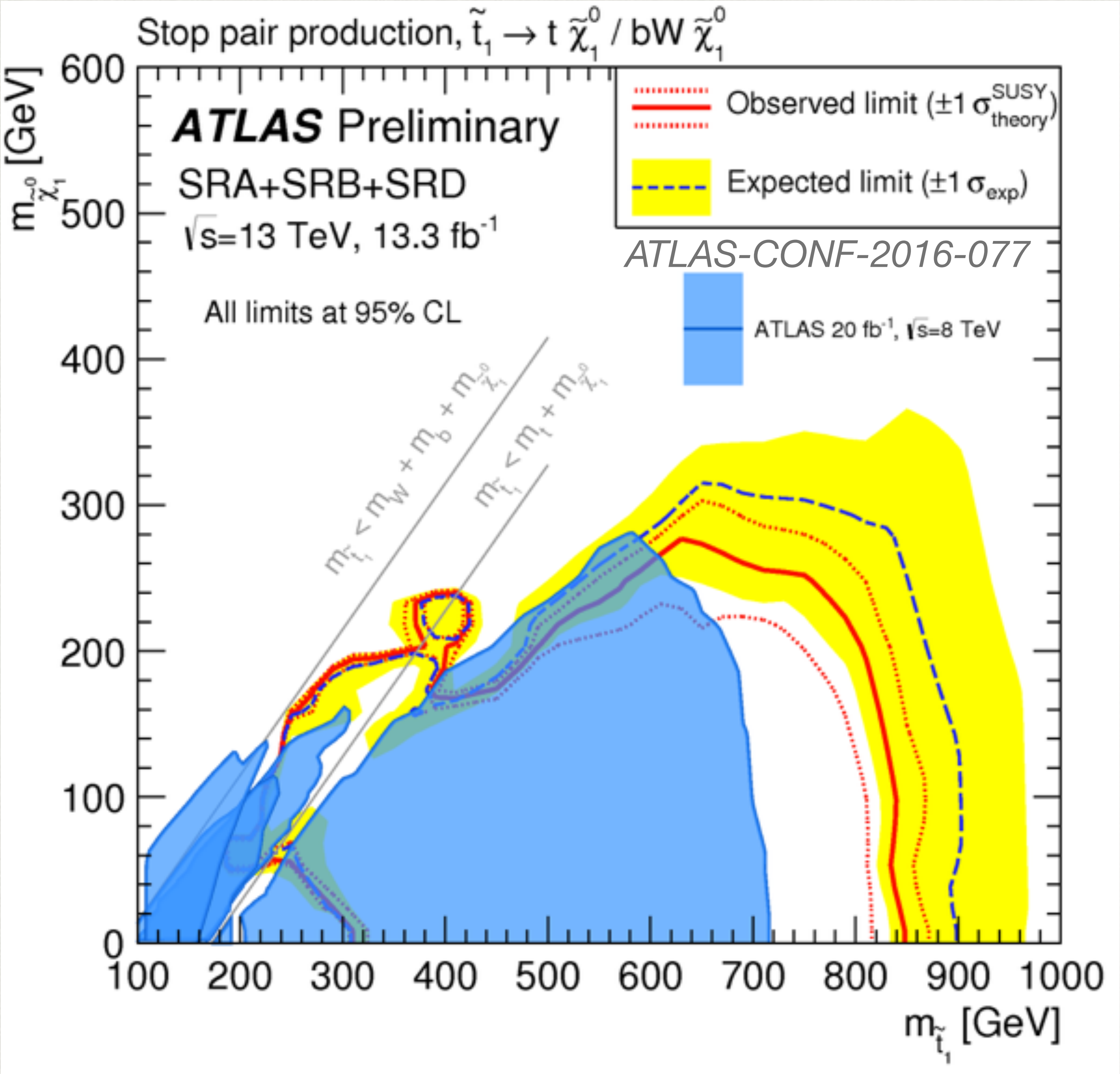
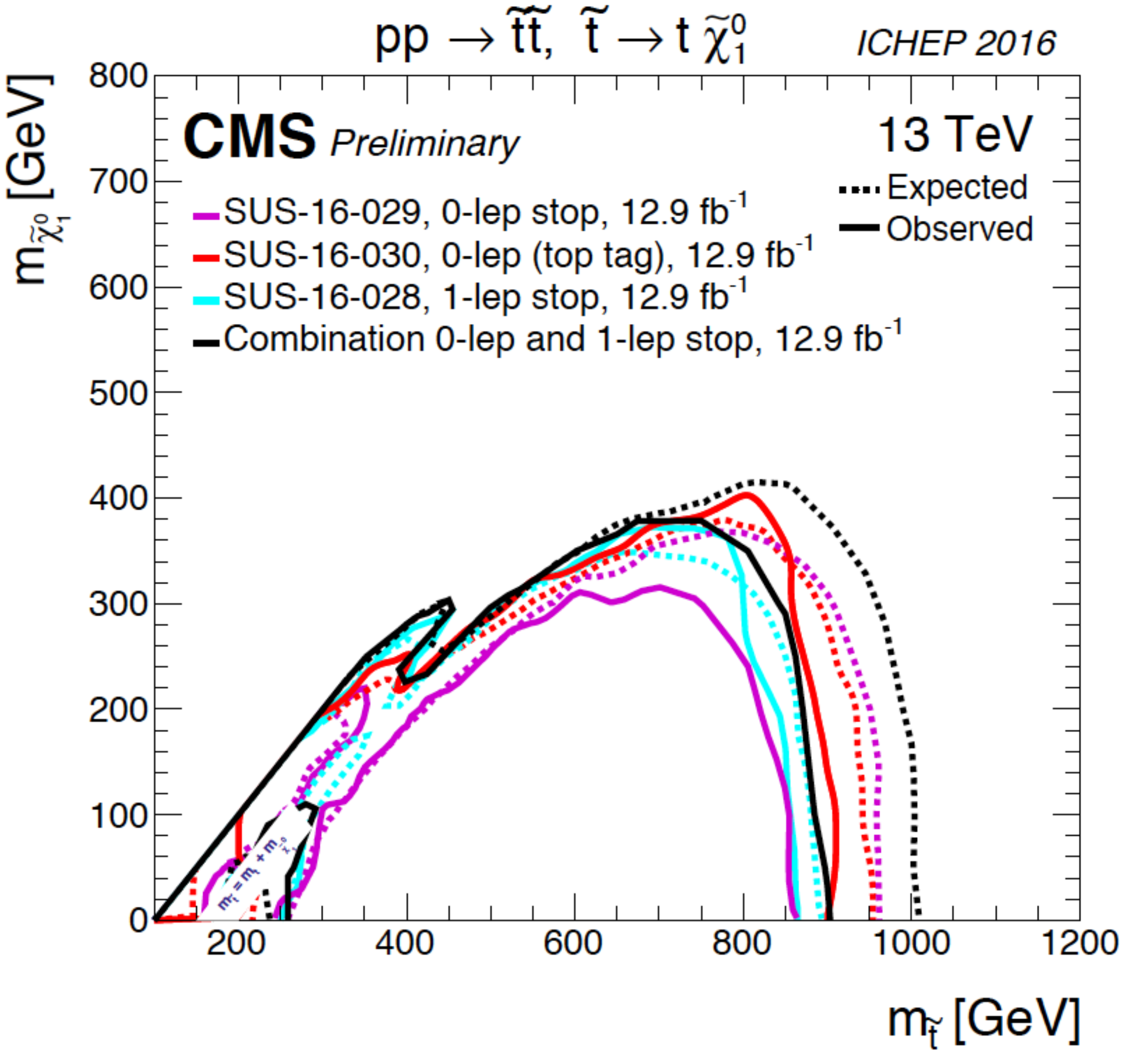
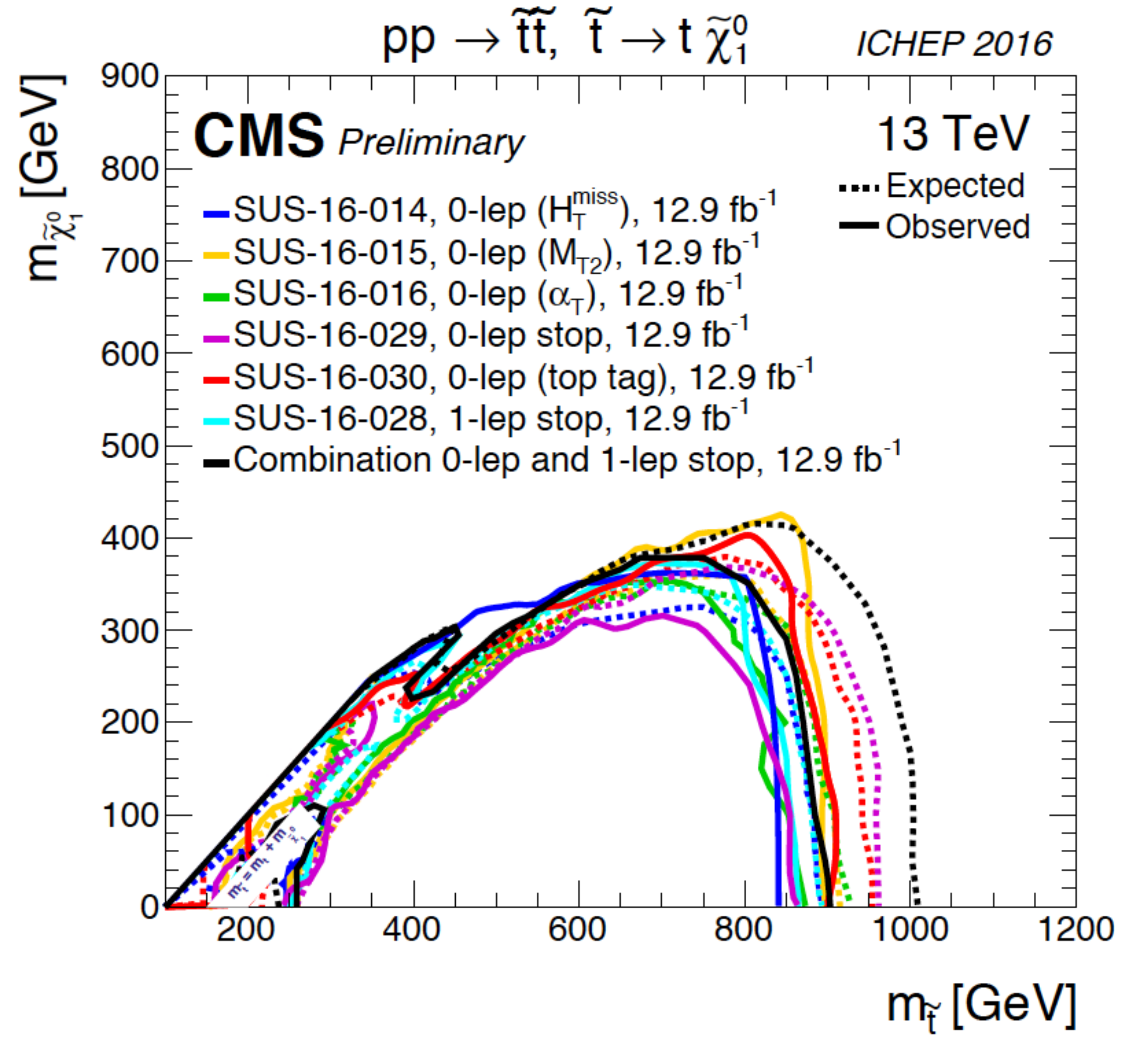


Stop pair production, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}^0_1$ / bW $\tilde{\chi}^0_1$
ATLAS Preliminary
SRA+SRB+SRD
$\sqrt{s}$=13 TeV, 13.3 fb^{-1}
All limits at 95% CL
Observed limit ($\pm 1\ \sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\ \sigma_{exp}$)
ATLAS-CONF-2016-077
ATLAS 20 fb^{-1}, $\sqrt{s}$=8 TeV
$m_{\tilde{t}_1} < m_W + m_b + m_{\tilde{\chi}^0_1}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}^0_1}$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
100
200
300
400
500
600
700
800
900
1000

Do not enter



pp → t̃t̃, t̃ → t χ̃⁰₁
ICHEP 2016
CMS Preliminary
13 TeV
Expected
Observed
SUS-16-029, 0-lep stop, 12.9 fb⁻¹
SUS-16-030, 0-lep (top tag), 12.9 fb⁻¹
SUS-16-028, 1-lep stop, 12.9 fb⁻¹
Combination 0-lep and 1-lep stop, 12.9 fb⁻¹
m_χ̃⁰₁ [GeV]
m_t̃ [GeV]
0
100
200
300
400
500
600
700
800
1000
1200

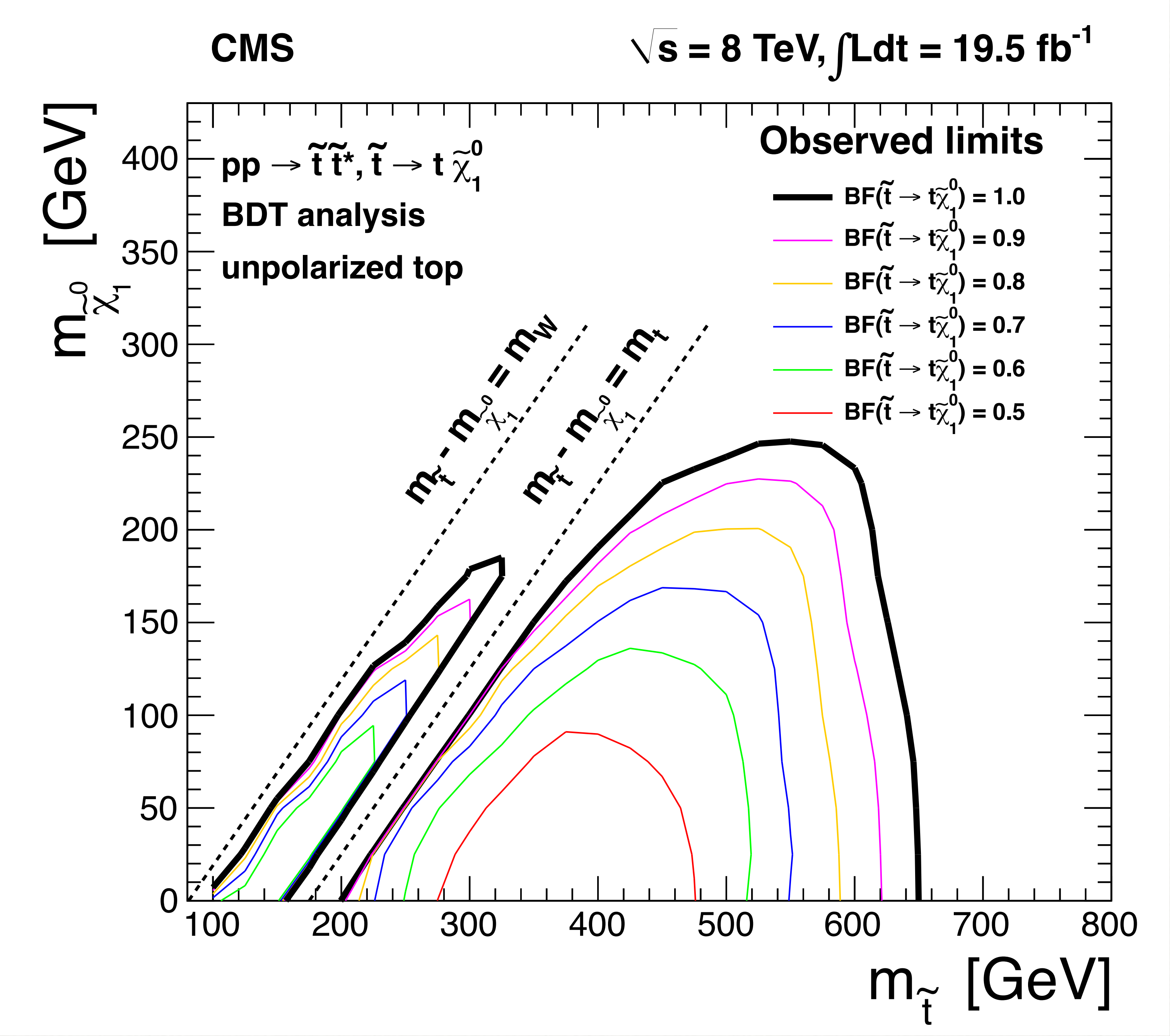


pp → t̃t̃, t̃ → t χ̃⁰₁
ICHEP 2016
CMS Preliminary
13 TeV
Expected
Observed
SUS-16-014, 0-lep (H_T^miss), 12.9 fb⁻¹
SUS-16-015, 0-lep (M_T2), 12.9 fb⁻¹
SUS-16-016, 0-lep (α_T), 12.9 fb⁻¹
SUS-16-029, 0-lep stop, 12.9 fb⁻¹
SUS-16-030, 0-lep (top tag), 12.9 fb⁻¹
SUS-16-028, 1-lep stop, 12.9 fb⁻¹
Combination 0-lep and 1-lep stop, 12.9 fb⁻¹
m_χ̃⁰₁ [GeV]
m_t̃ [GeV]
0
100
200
300
400
500
600
700
800
900
1000
1200

Challenges

- compressed ⇒ little visible energy
- diluted
- delayed

Dilution



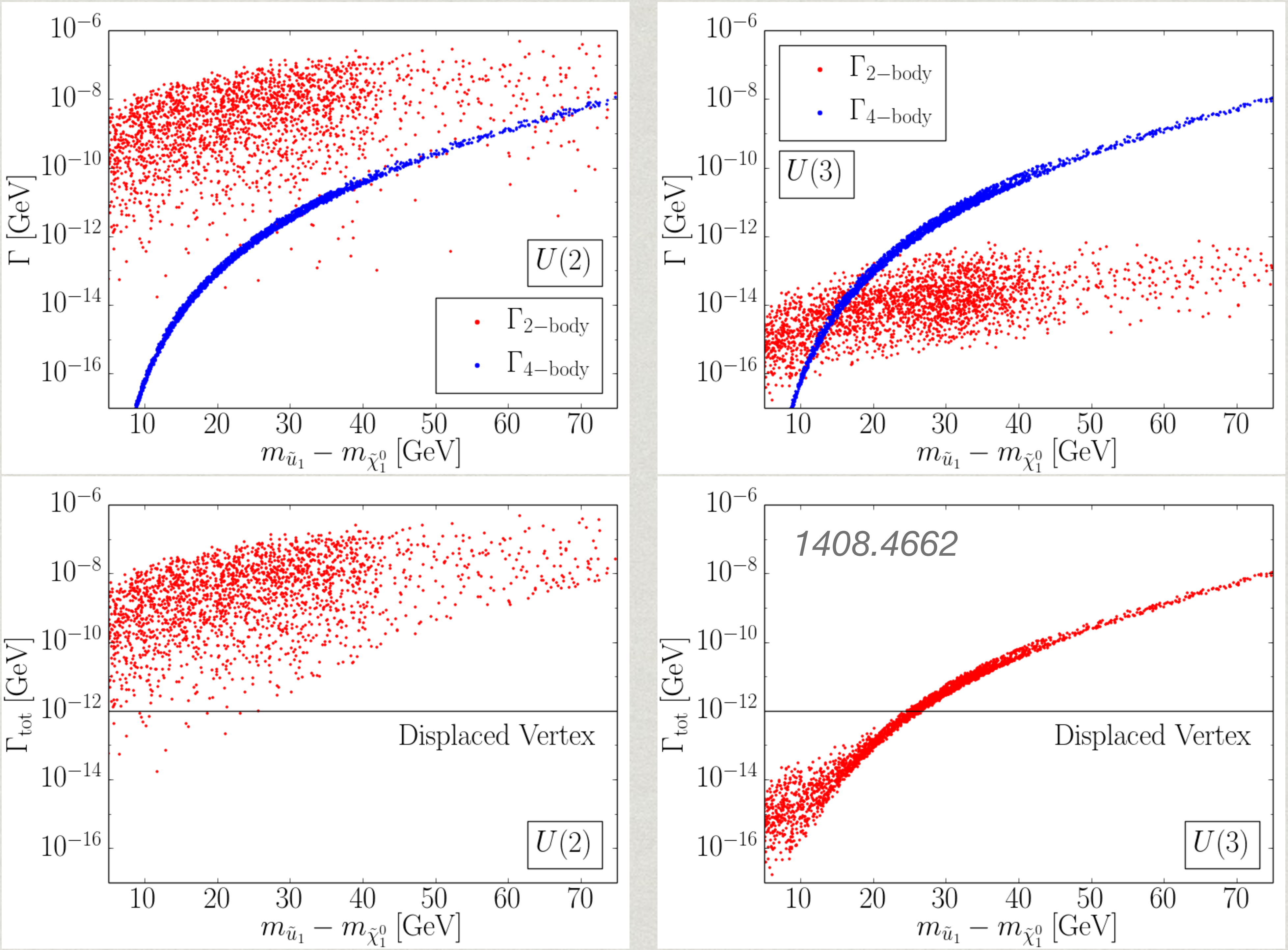
CMS
$\sqrt{s}$ = 8 TeV, $\int$Ldt = 19.5 fb^{-1}
$pp \to \tilde{t}\tilde{t}^{*}, \tilde{t} \to t\,\tilde{\chi}^0_1$
BDT analysis
unpolarized top
Observed limits
BF($\tilde{t} \to t\tilde{\chi}^0_1$) = 1.0
BF($\tilde{t} \to t\tilde{\chi}^0_1$) = 0.9
BF($\tilde{t} \to t\tilde{\chi}^0_1$) = 0.8
BF($\tilde{t} \to t\tilde{\chi}^0_1$) = 0.7
BF($\tilde{t} \to t\tilde{\chi}^0_1$) = 0.6
BF($\tilde{t} \to t\tilde{\chi}^0_1$) = 0.5
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_W$
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_t$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}}$ [GeV]
0
50
100
150
200
250
300
350
400
100
200
300
400
500
600
700
800

Challenges

- compressed ⇒ little visible energy
- diluted ⇒ spread on many channels
- delayed

Wait …

$\tilde{t} \to b\, ff'\chi^0 + c\, \chi^0$

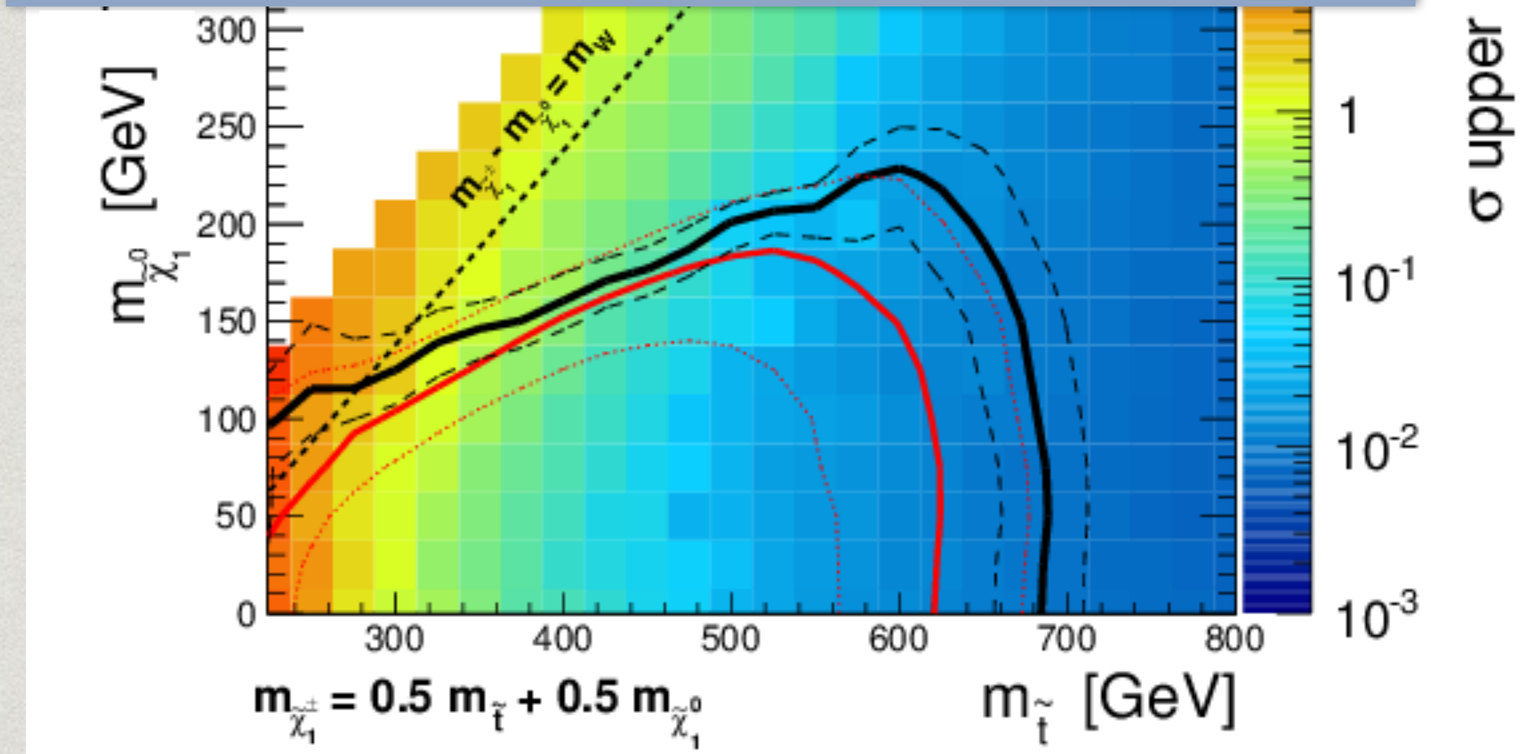


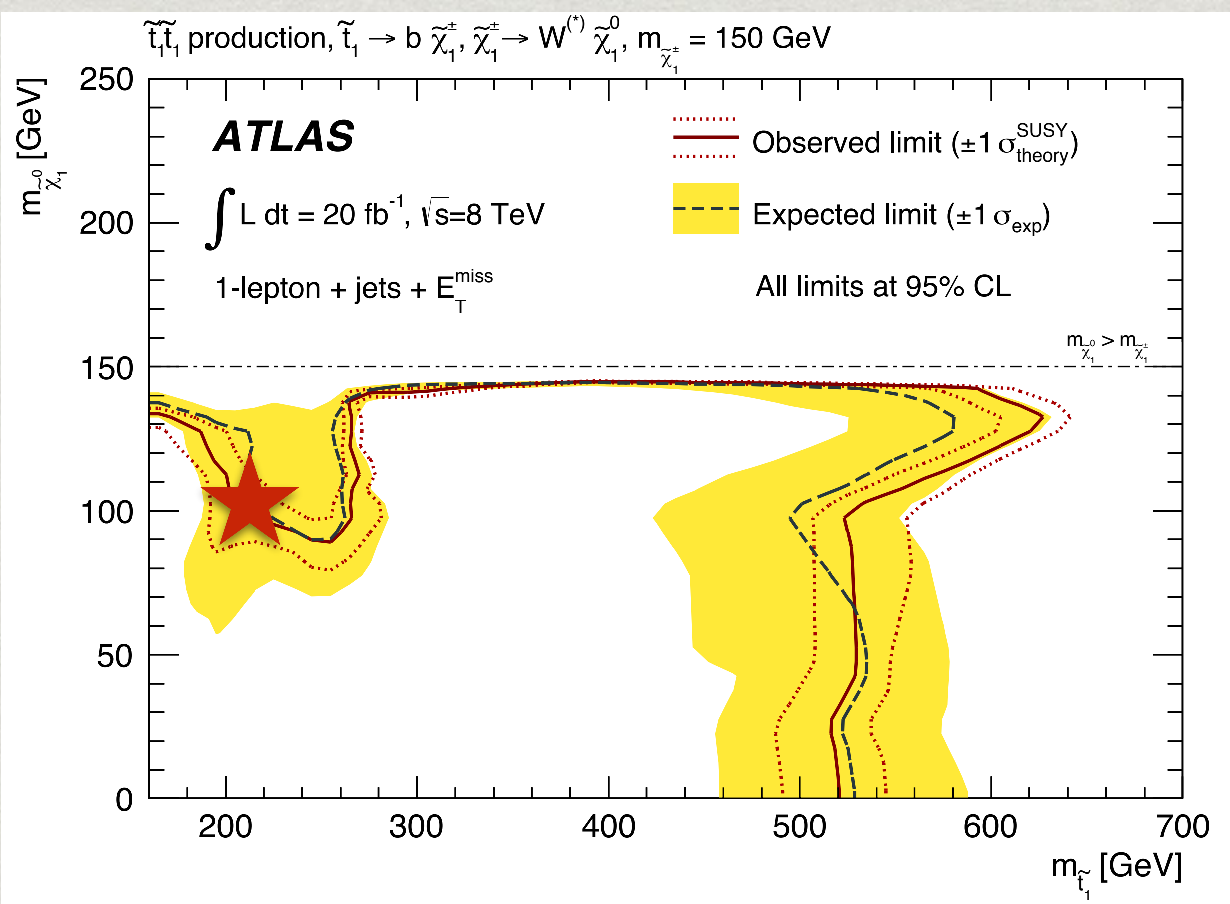
Challenges

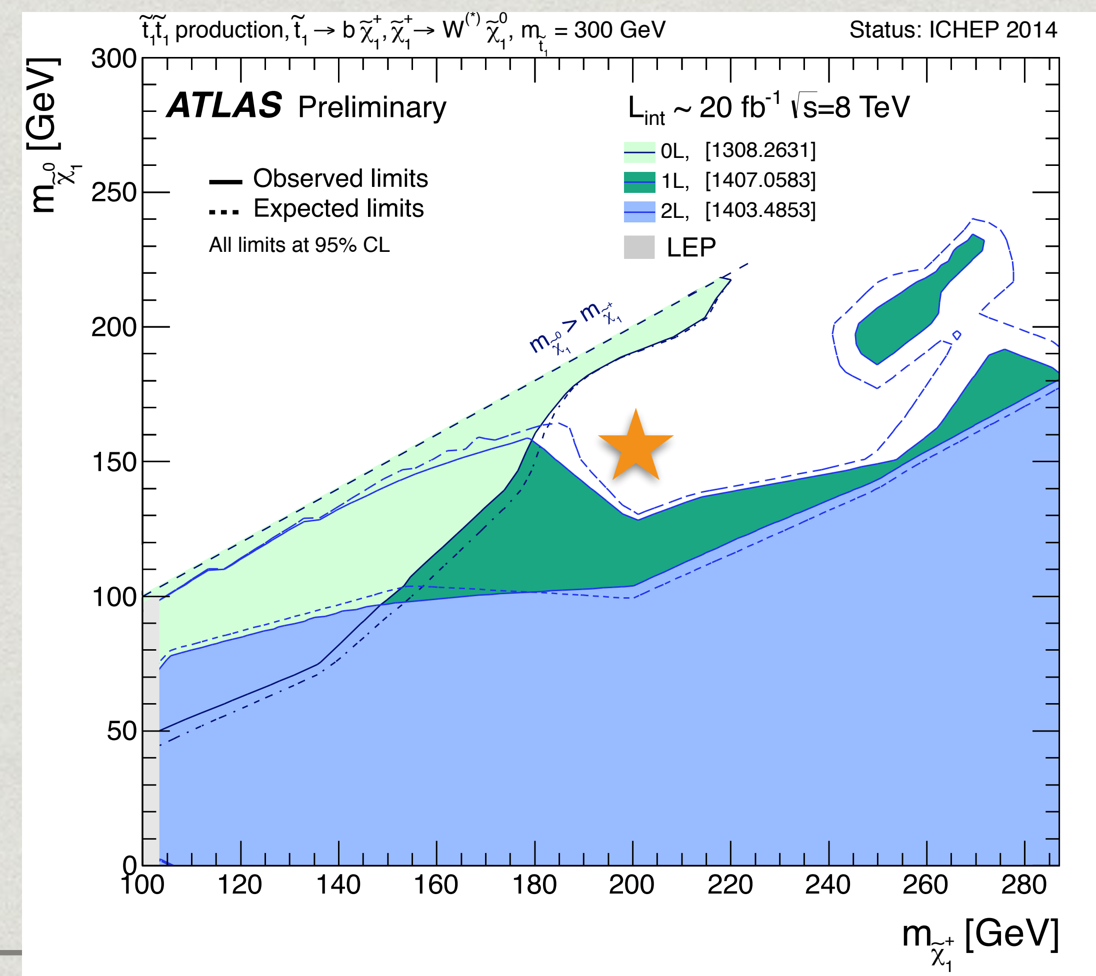
- compressed ⇒ little visible energy
- diluted ⇒ spread on many channels
- delayed ⇒ flavor tags may not work, signal is different than what originally thought

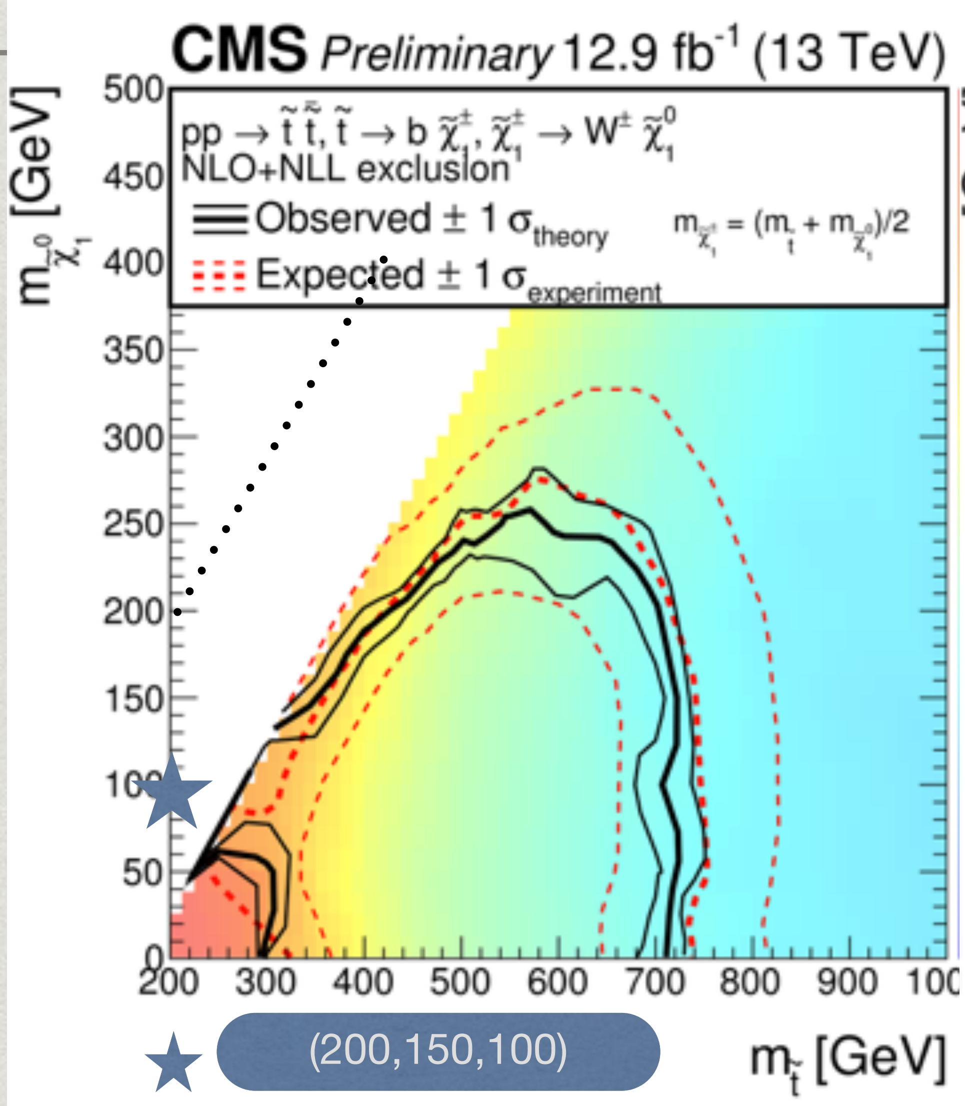
THE MORE THE MERRIER

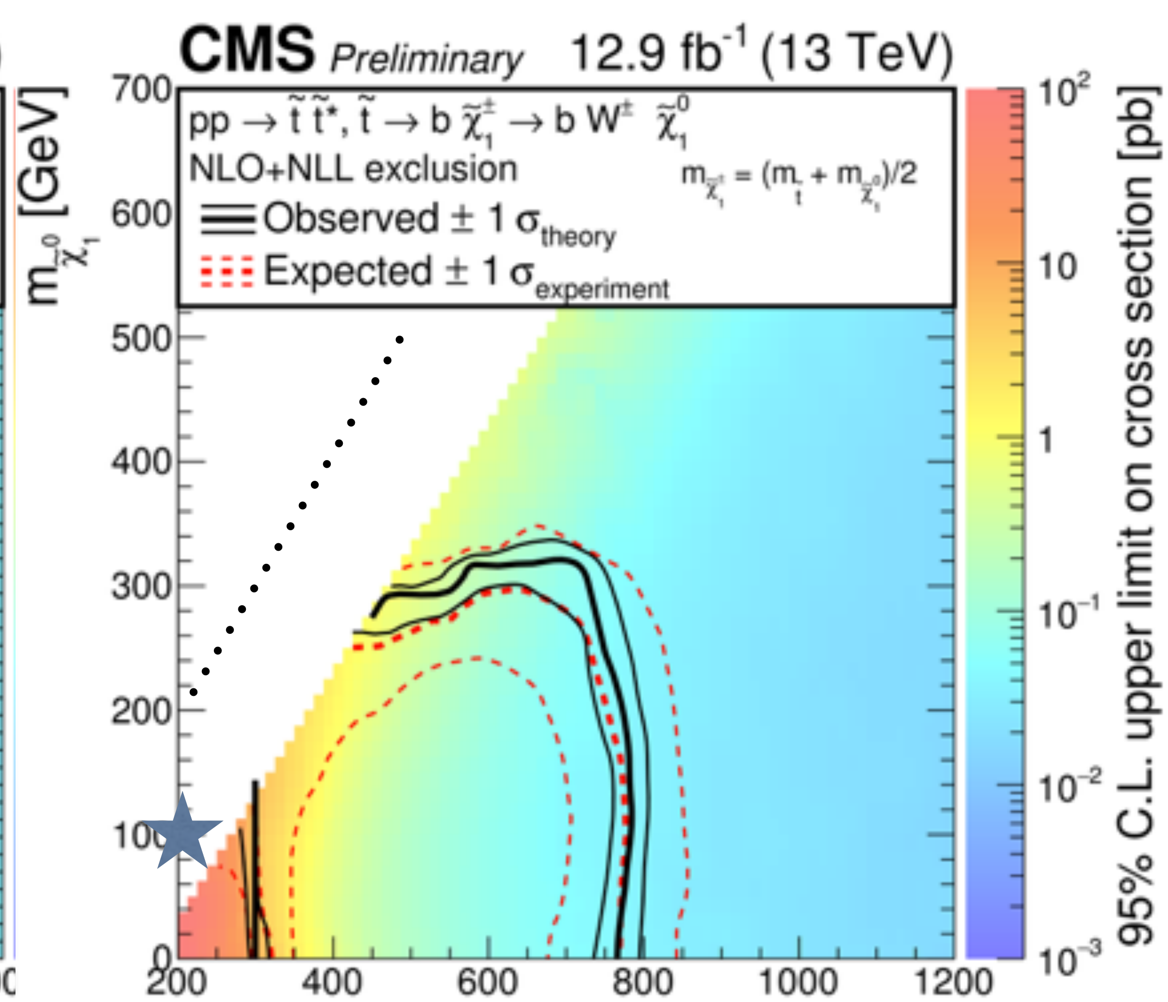
$\tilde{t} \rightarrow b\,\chi^{+} \rightarrow b\ell\nu\chi^{0}$

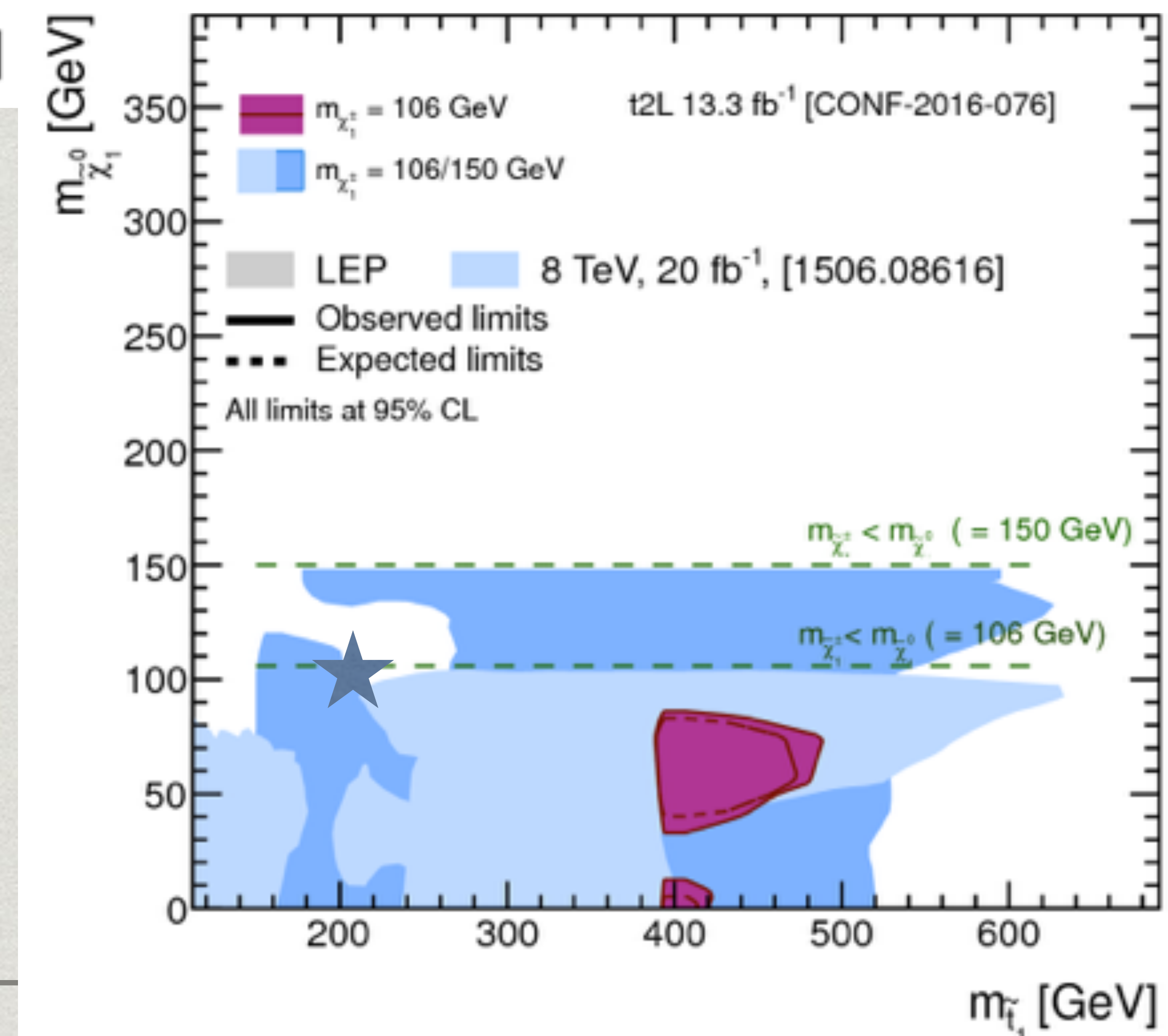







CMS Preliminary 12.9 fb^{-1} (13 TeV)
pp → $\tilde{t}\tilde{\bar{t}}$, $\tilde{t} \to b\,\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$
NLO+NLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
$m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}}$ [GeV]
(200,150,100)


CMS Preliminary 12.9 fb^{-1} (13 TeV)
pp → $\tilde{t}\tilde{t}^*$, $\tilde{t} \to b\,\tilde{\chi}_1^\pm \to b\,W^\pm\,\tilde{\chi}_1^0$
NLO+NLL exclusion
$m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
$m_{\tilde{\chi}_1^0}$ [GeV]
95% C.L. upper limit on cross section [pb]


$m_{\tilde{\chi}_1^\pm}$ = 106 GeV
$m_{\tilde{\chi}_1^\pm}$ = 106/150 GeV
t2L 13.3 fb^{-1} [CONF-2016-076]
LEP
8 TeV, 20 fb^{-1}, [1506.08616]
Observed limits
Expected limits
All limits at 95% CL
$m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_1^0}$ (= 150 GeV)
$m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_1^0}$ (= 106 GeV)
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]

THE MORE THE MERRIER

INCLUDING CHARGINO IS EVEN MORE CHALLENGING

AFTER SEVERAL YEARS OF LHC

BLINDSPOTS ARE STILL THERE

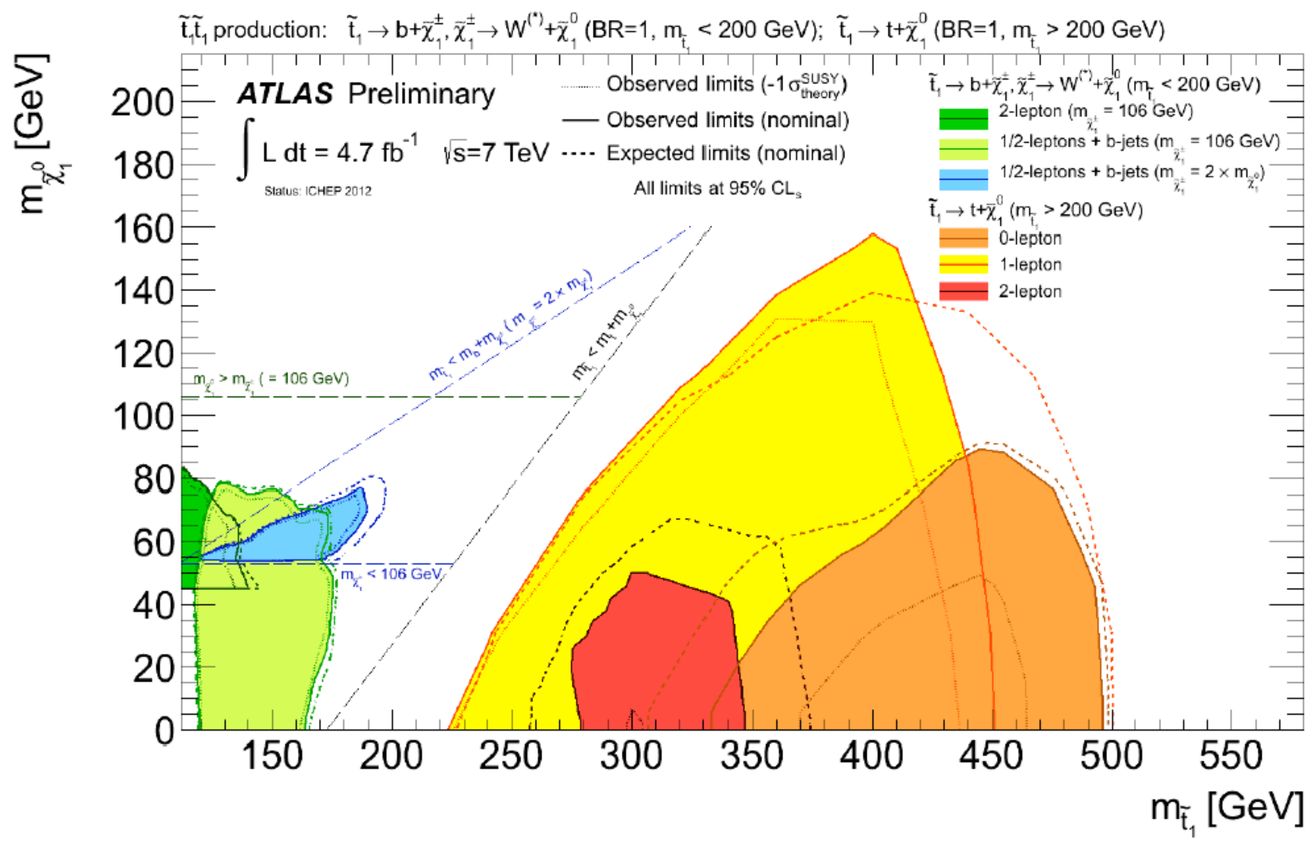
- light stop searches seem very challenging
- situation is even more complex for $\tilde{t} \to \chi^+ b$

3. Light stop

There has been much discussion at this workshop along the lines:

Light stop is highly motivated by naturalness of SUSY.

Light stop is difficult to observe at the LHC. Current limits are weak. Cases such as $m(\widetilde{t}) \approx m_t$, $m(\widetilde{\chi}) \sim 200\ \mathrm{GeV}$, competing decay channels subvert these limits.



So, why not

$$m(\widetilde{t}) < 250\ \mathrm{GeV}$$

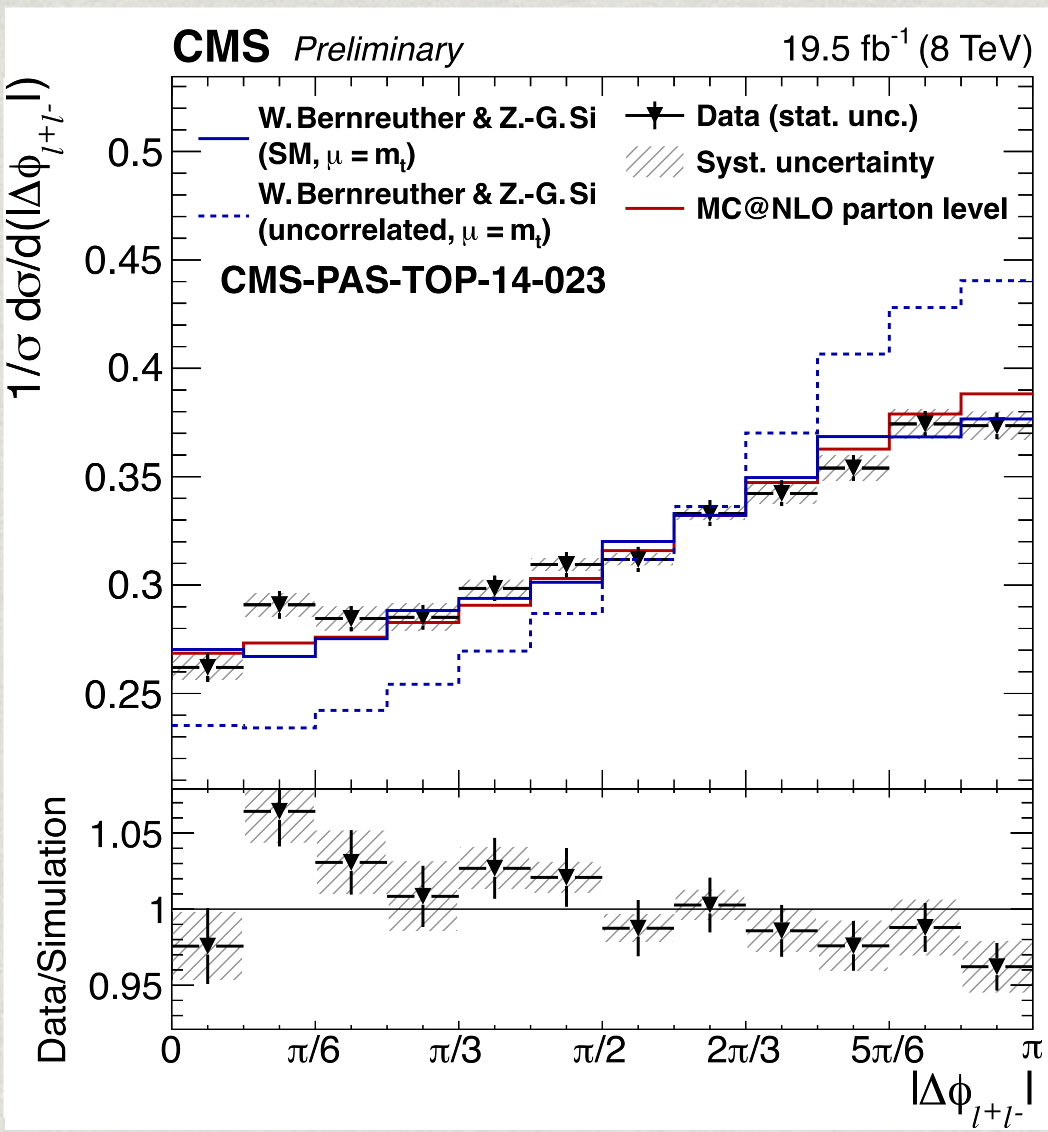
?

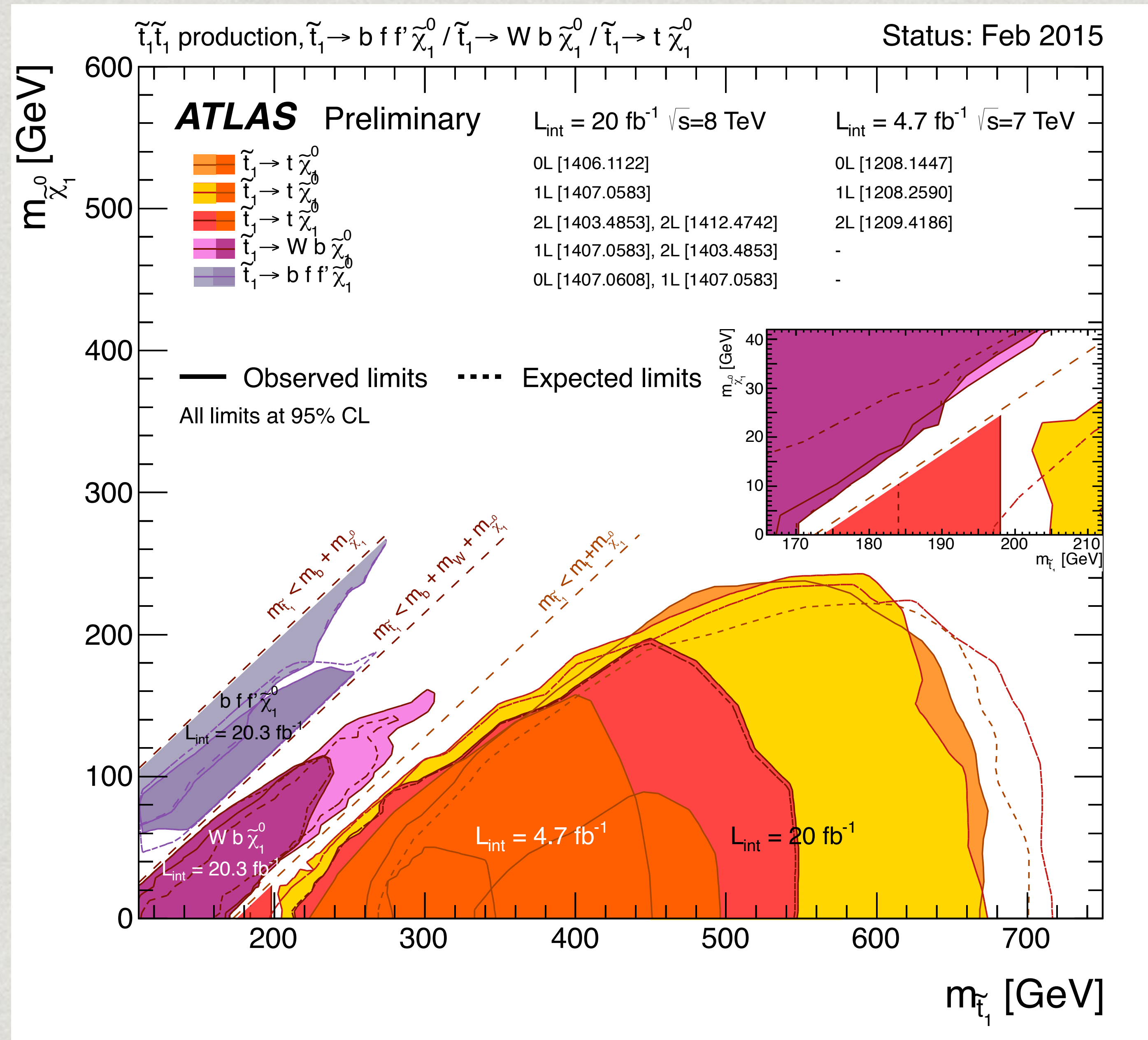
M. Peskin July 2012

$\Delta\phi(\ell\ell)$

1205.5808 1412.4742+ATLAS-CONF-2014-056

$$\mathcal{L}_{eff} = -\frac{\widetilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\widetilde{d}_t}{2} i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu},$$

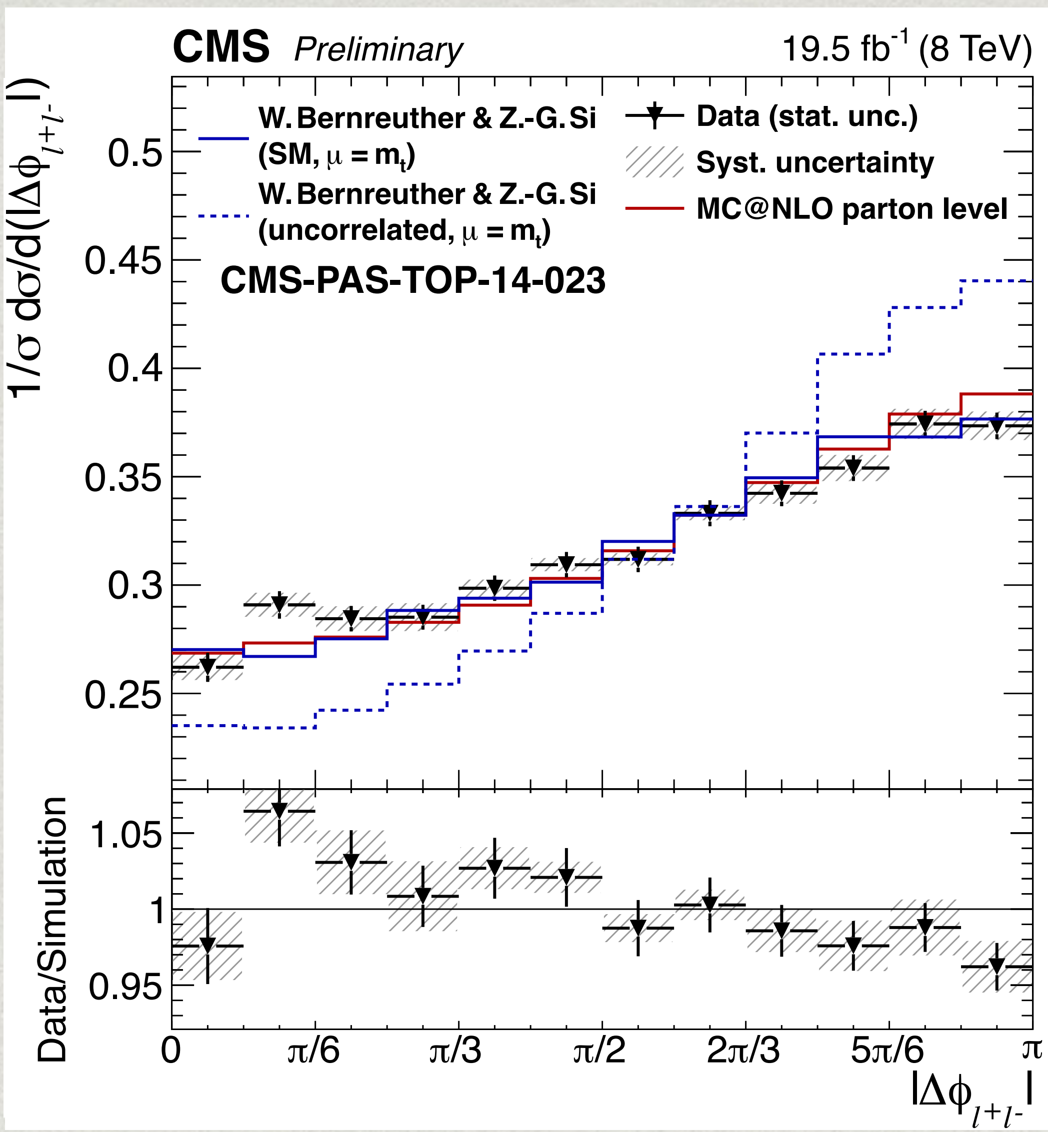


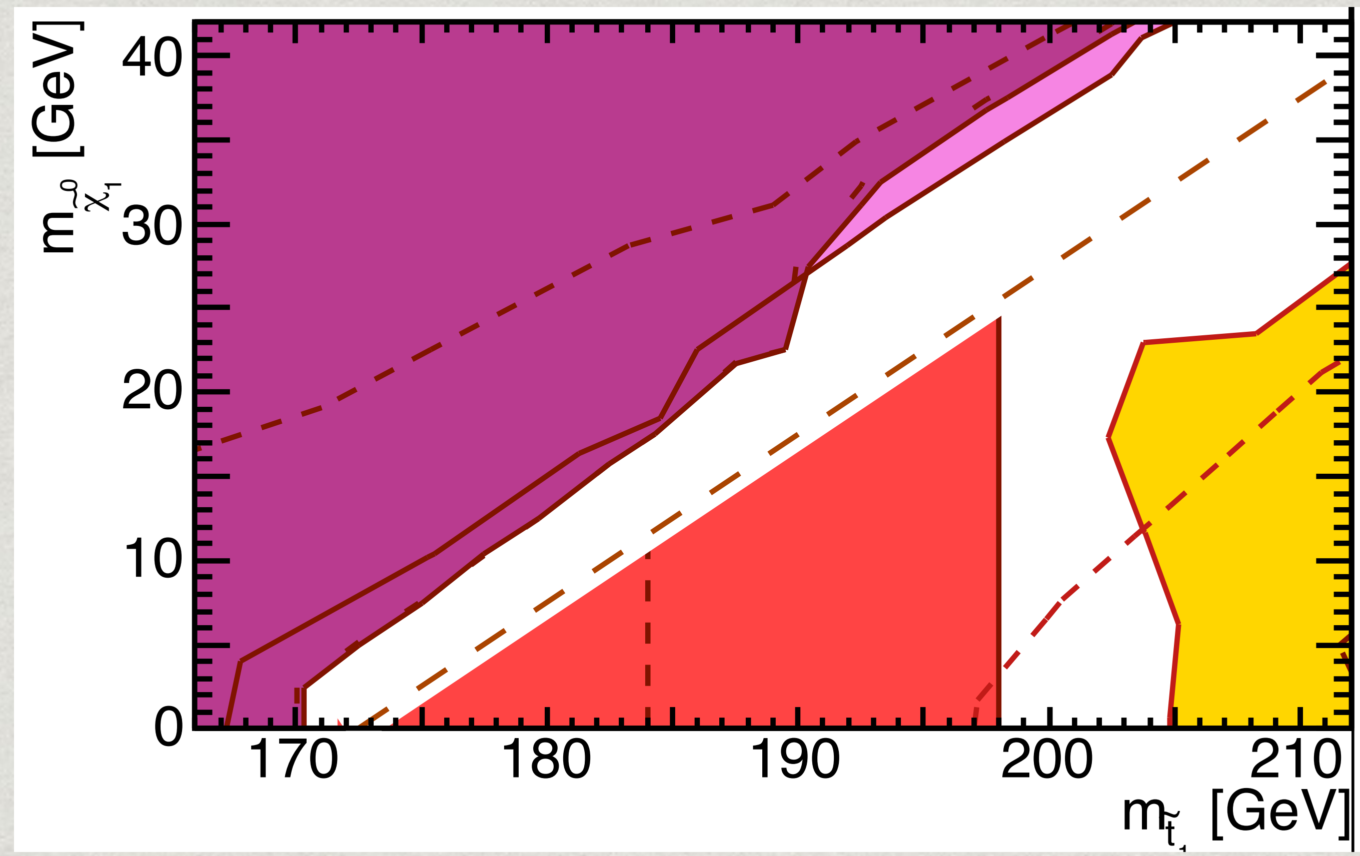


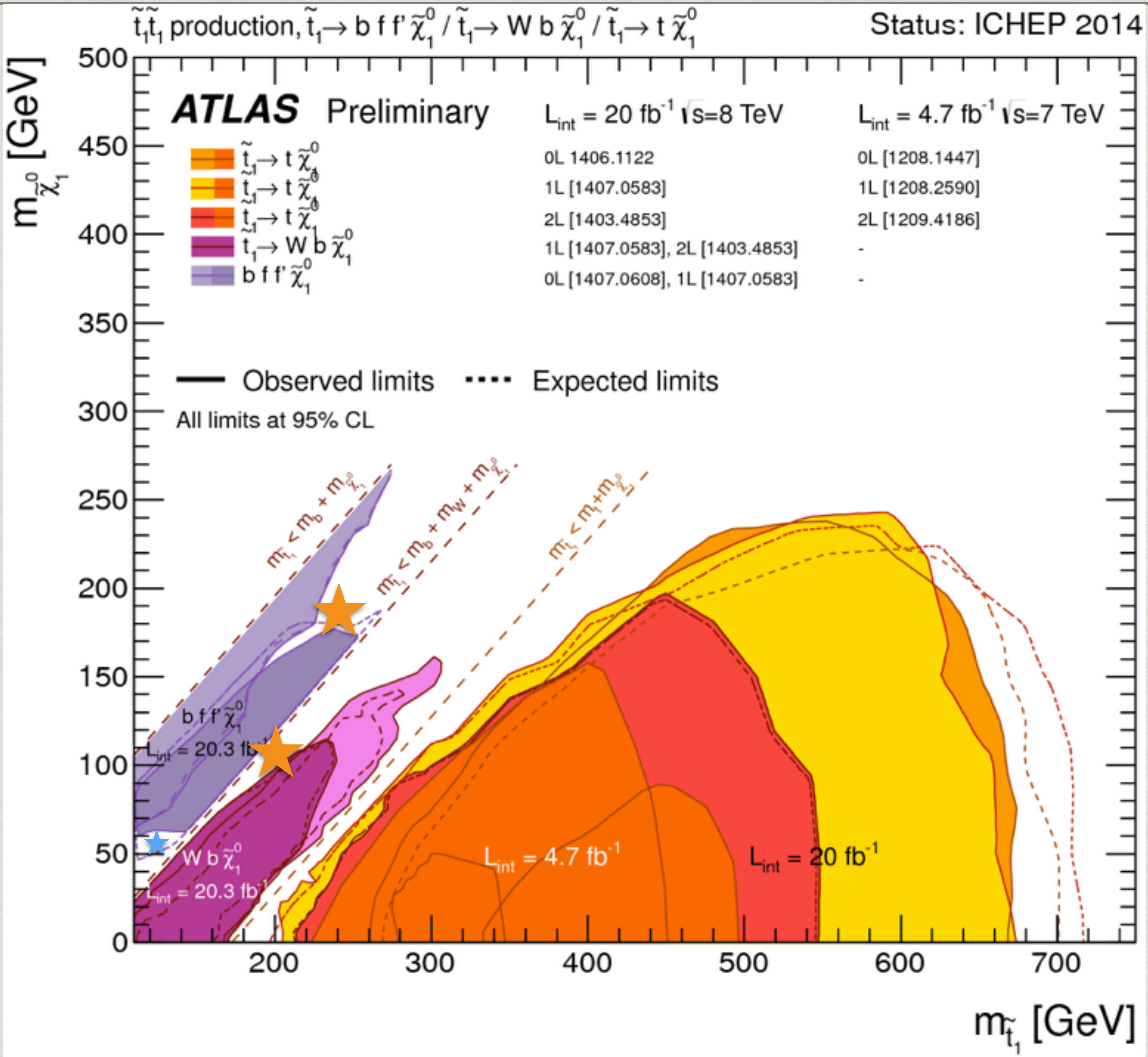
$\Delta\phi(\ell\ell)$

1205.5808 1412.4742+ATLAS-CONF-2014-056

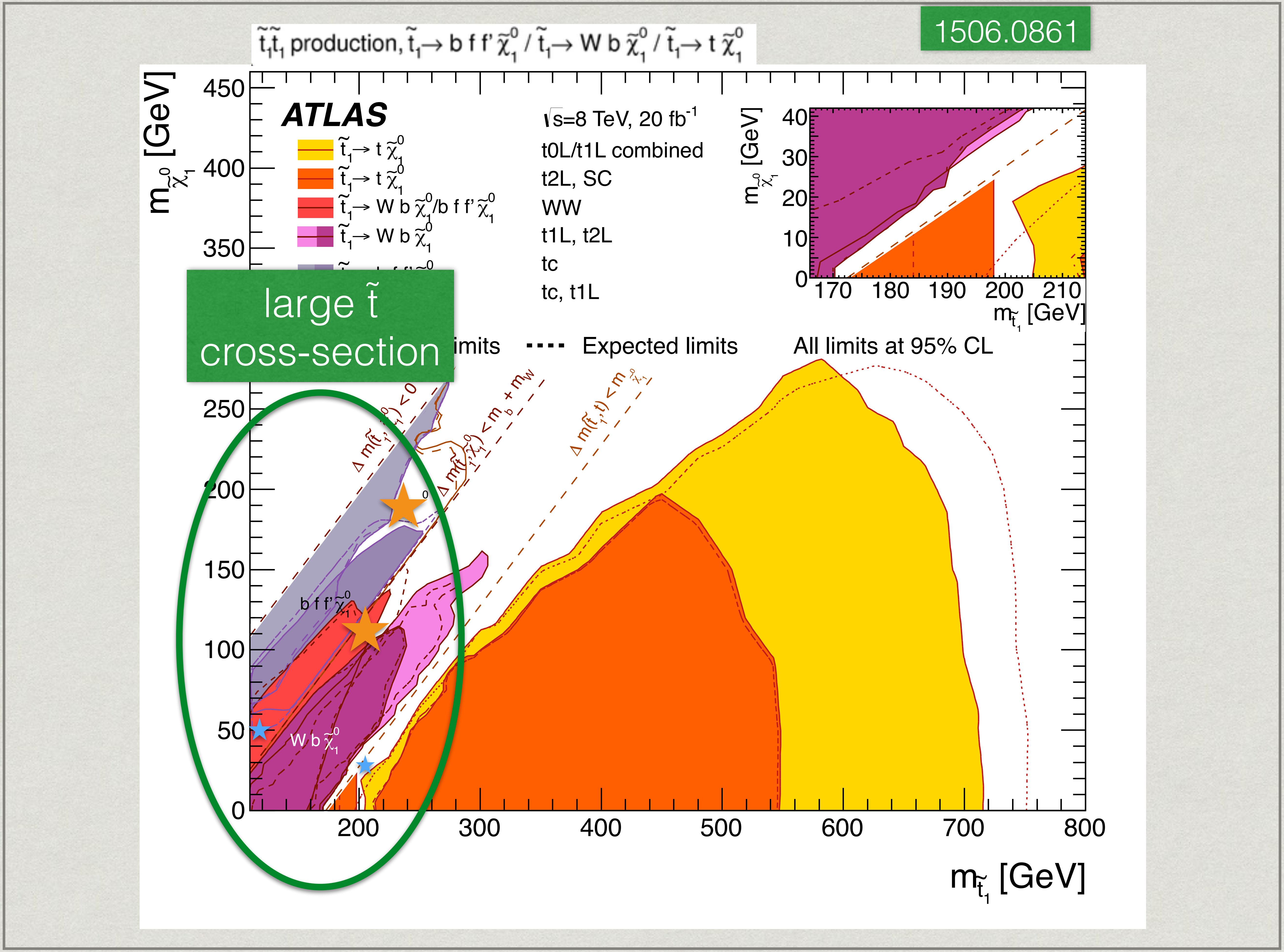
$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2} i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu},$$







$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
Status: ICHEP 2014
ATLAS Preliminary
L_{int} = 20 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ 0L 1406.1122 0L [1208.1447]
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ 1L [1407.0583] 1L [1208.2590]
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ 2L [1403.4853] 2L [1209.4186]
$\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ 1L [1407.0583], 2L [1403.4853] -
$b f f' \tilde{\chi}_1^0$ 0L [1407.0608], 1L [1407.0583] -
Observed limits
Expected limits
All limits at 95% CL
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$b f f' \tilde{\chi}_1^0$
L_{int} = 20.3 fb^{-1}
$W b \tilde{\chi}_1^0$
L_{int} = 20.3 fb^{-1}
L_{int} = 4.7 fb^{-1}
L_{int} = 20 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
50
100
150
200
250
300
350
400
450
500
200
300
400
500
600
700



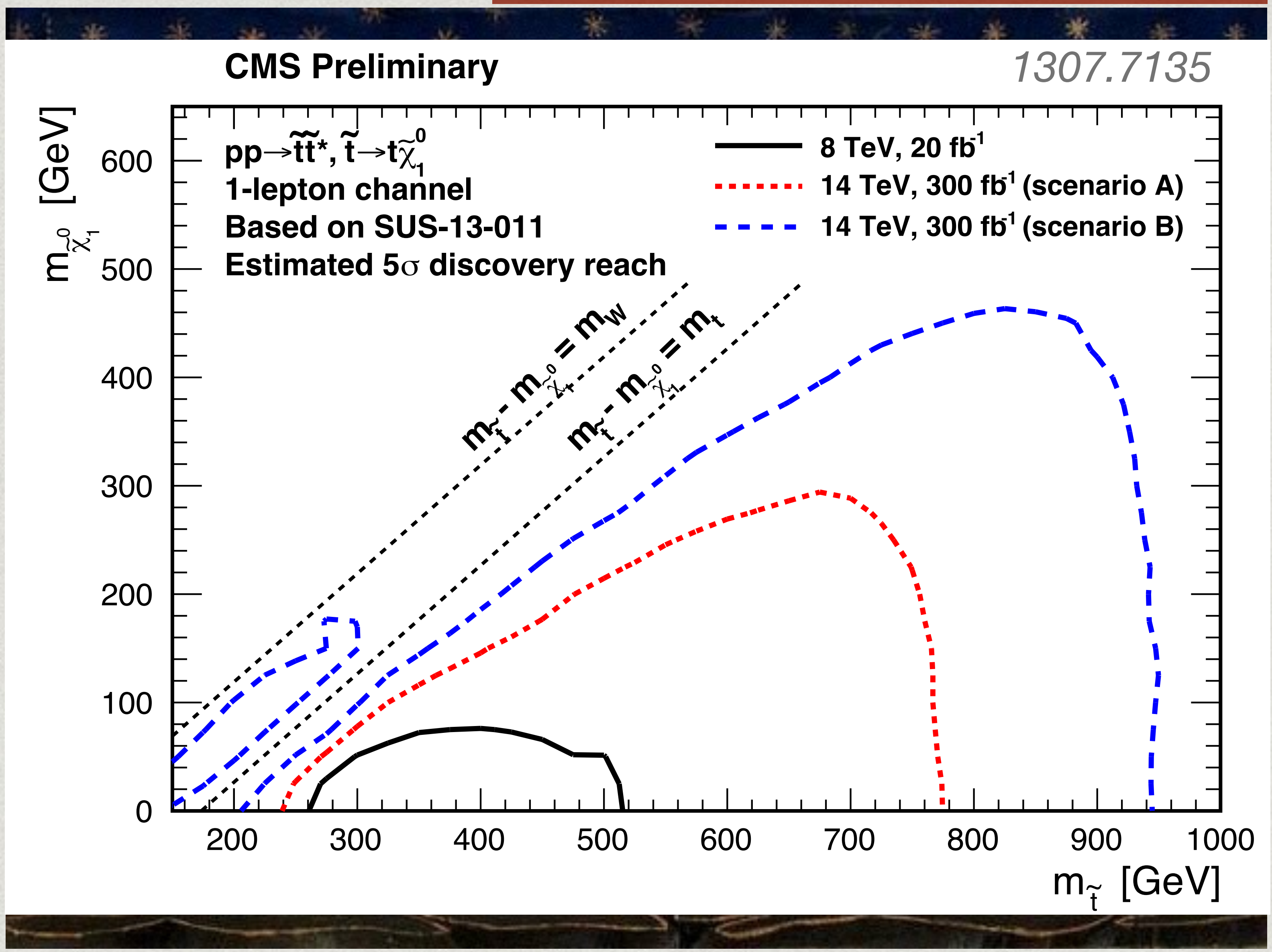
1506.0861
t̃₁t̃₁ production, t̃₁→ b f f' χ̃₁⁰ / t̃₁→ W b χ̃₁⁰ / t̃₁→ t χ̃₁⁰
ATLAS
√s=8 TeV, 20 fb⁻¹
t̃₁→ t χ̃₁⁰ t0L/t1L combined
t̃₁→ t χ̃₁⁰ t2L, SC
t̃₁→ W b χ̃₁⁰/b f f' χ̃₁⁰ WW
t̃₁→ W b χ̃₁⁰ t1L, t2L
tc
tc, t1L
large t̃ cross-section
imits
Expected limits
All limits at 95% CL
Δ m(t̃₁, χ̃₁⁰) < 0
Δ m(t̃₁, χ̃₁⁰) < m_b + m_W
Δ m(t̃₁, t) < m_χ̃₁⁰
b f f' χ̃₁⁰
W b χ̃₁⁰
m_χ̃₁⁰ [GeV]
m_t̃₁ [GeV]

New physics after the end of LHC

Cristoforo de Predis (o Preda) (Milano 1440/1445 - 1486)

New physics after the end of LHC

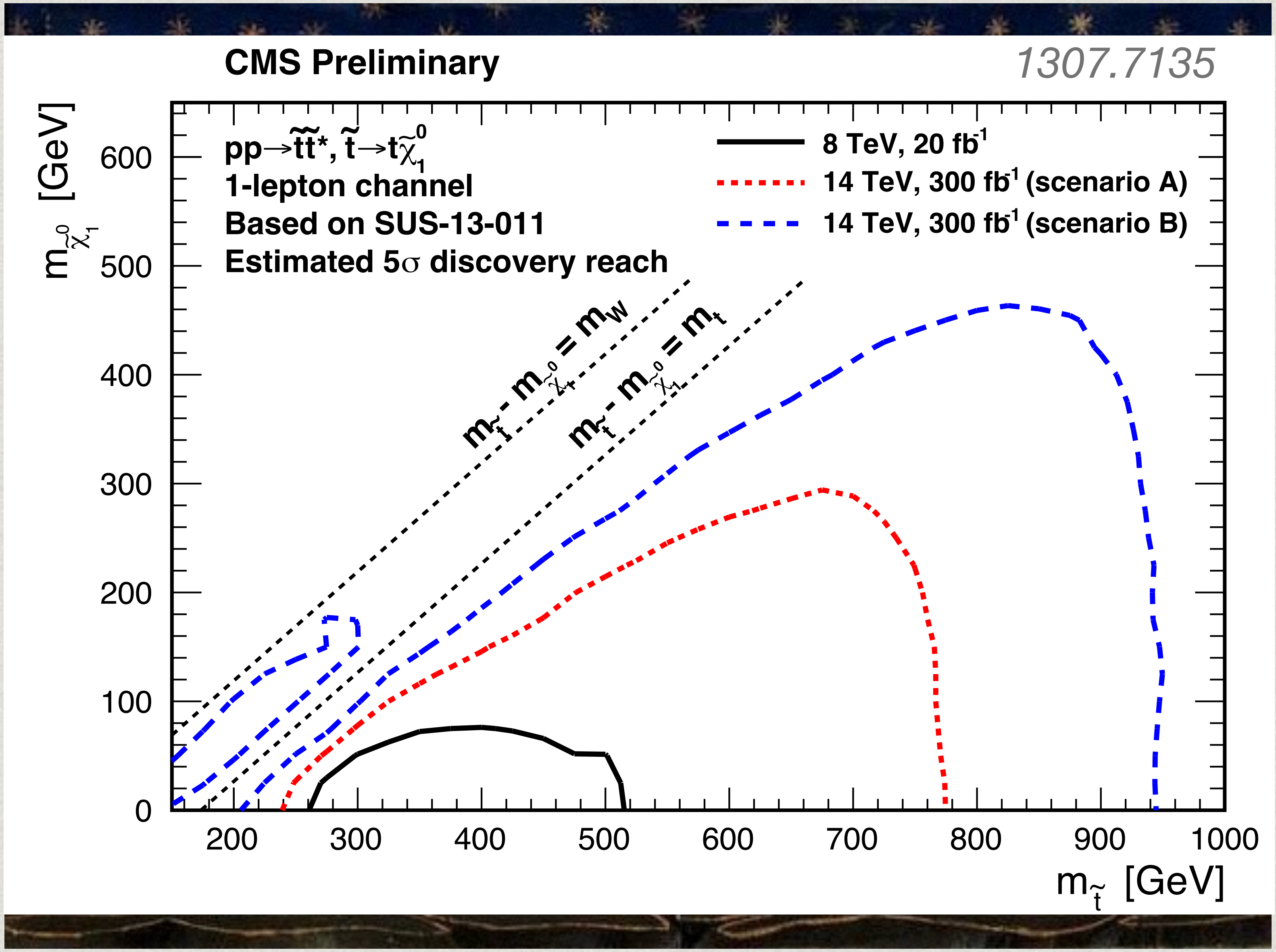
Cristoforo de Predis (o Preda) (Milano 1440/1445 - 1486)



most of the 5σ discovery region is excluded at 95% C.L.

New physics after the end of LHC

Cristoforo de Predis (o Preda) (Milano 1440/1445 - 1486)



FOCUS ON SUBTLE NEW PHYSICS

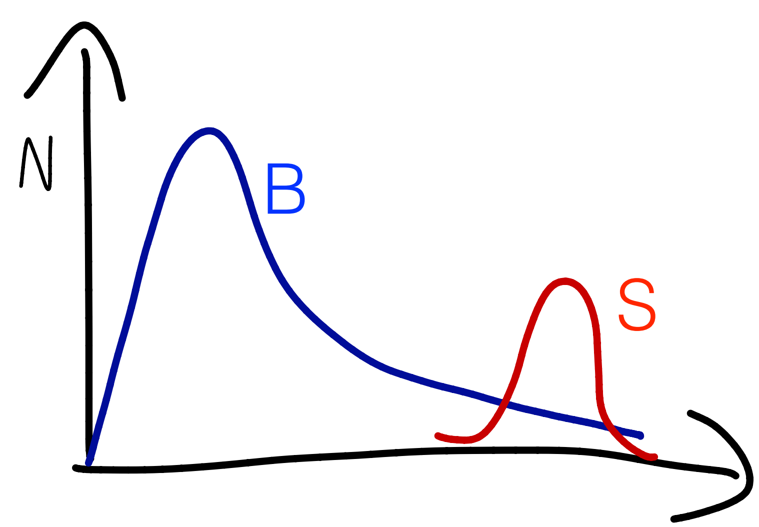
We can search well, “hard new physics” (high-pT)
We struggle with the other half of the possibilities (SM-like)

FROM THE KEYNOTE

signal v. background

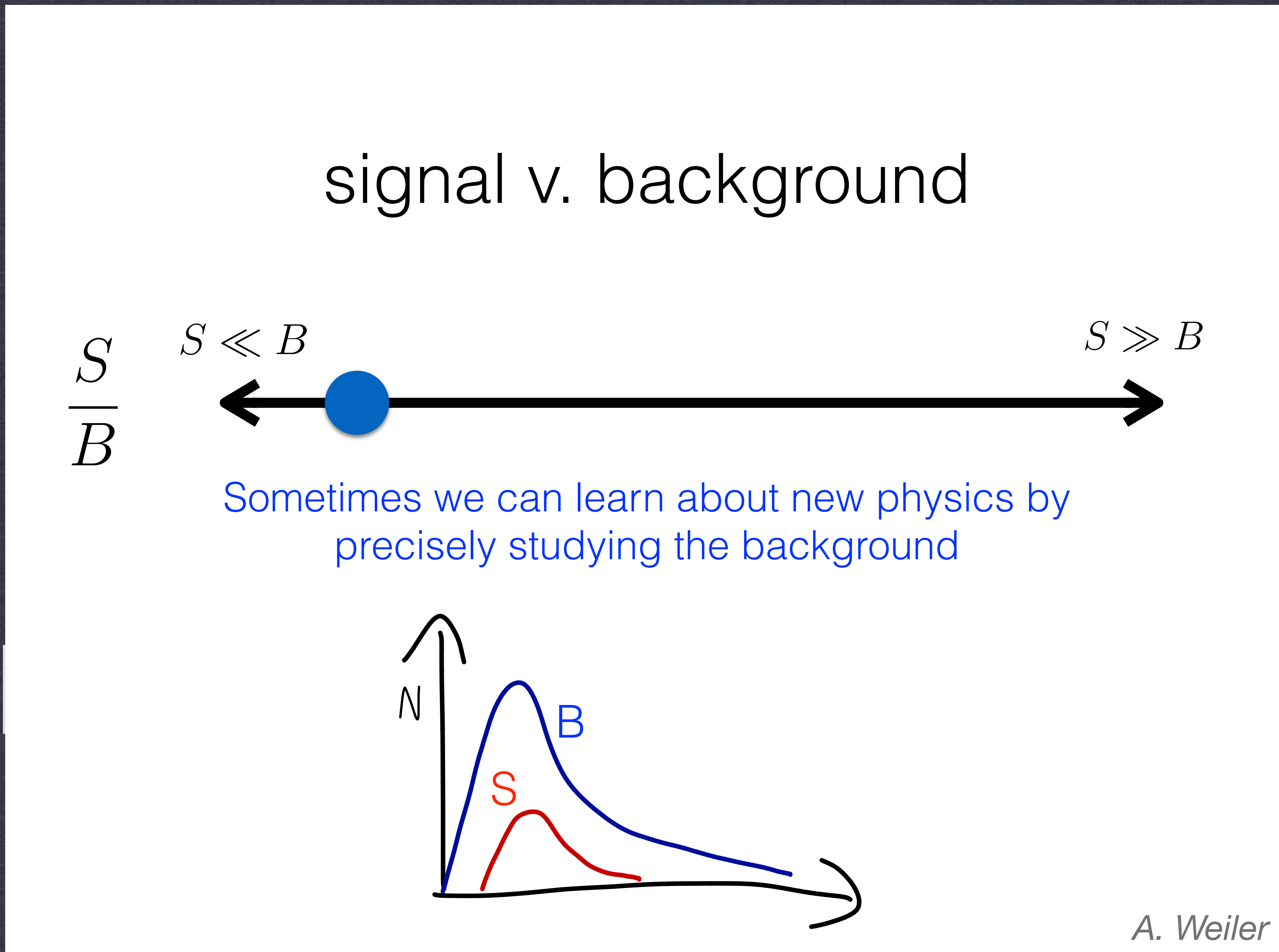
$\frac{S}{B}$ $S \ll B$ $S \gg B$

usually we try to separate new physics from the background



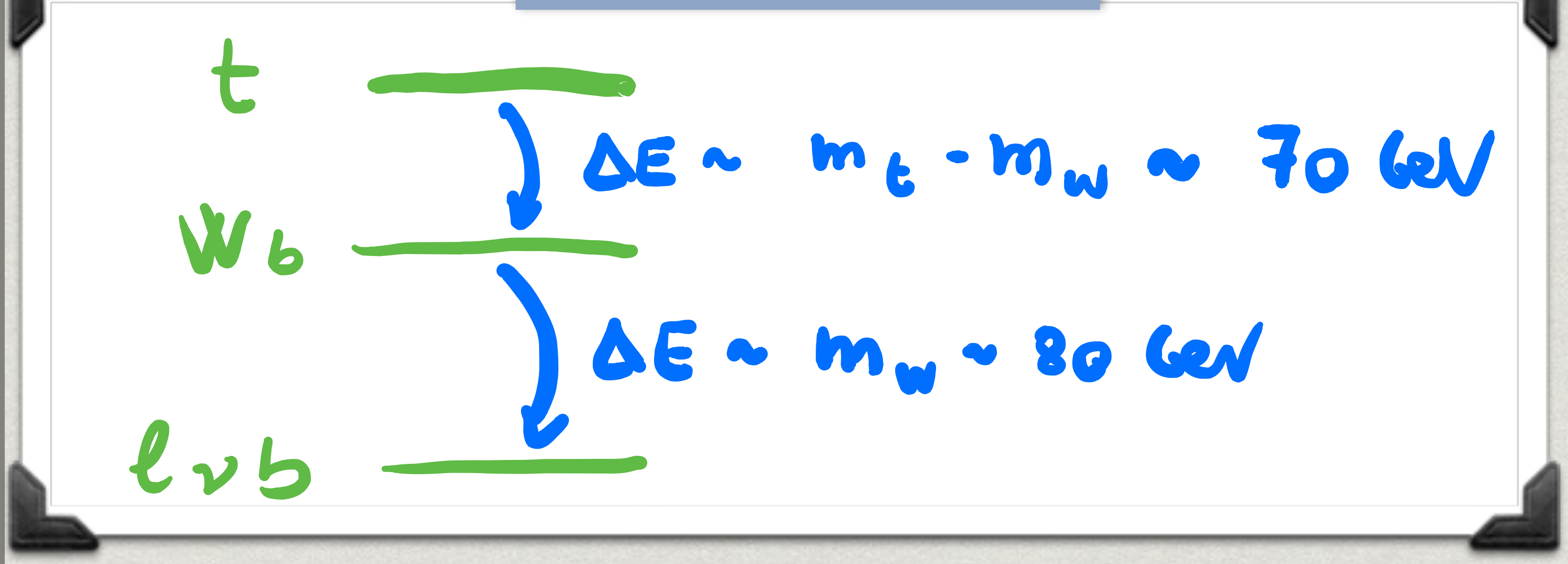
A. Weiler

FROM THE KEYNOTE

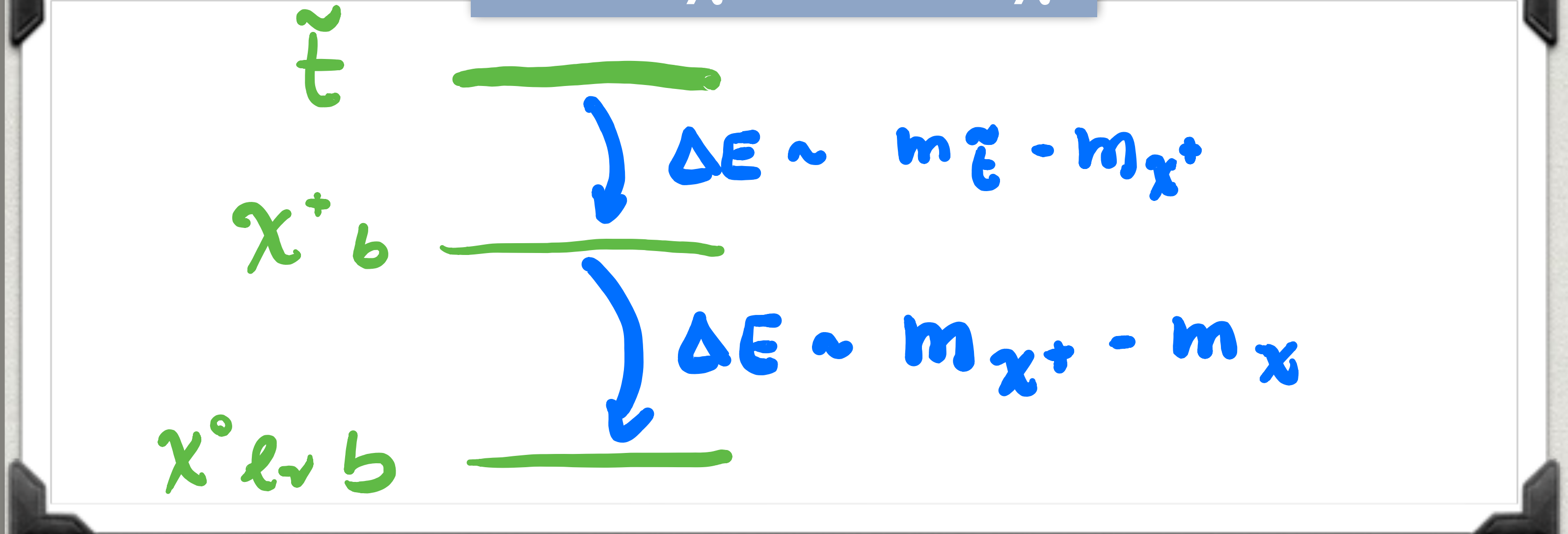


Soft is hard

$t \to bW \to b\ell\nu$

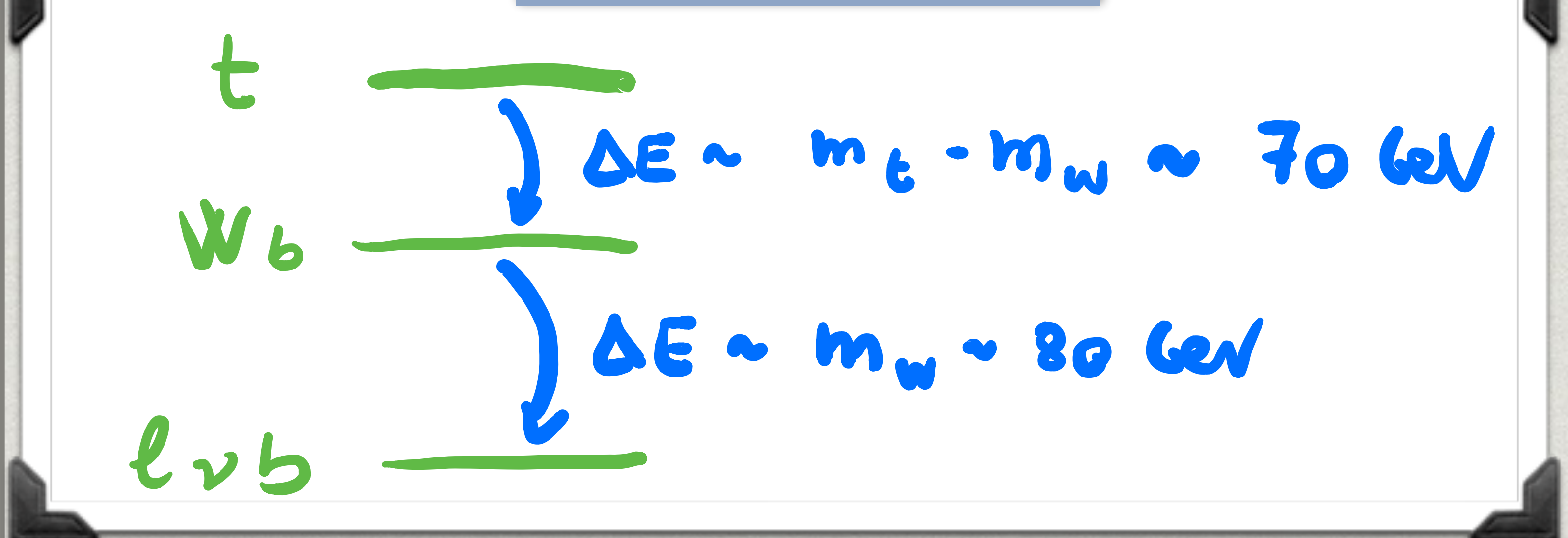


$\tilde{t} \to b\, \chi^+ \to b\ell\nu\chi^0$

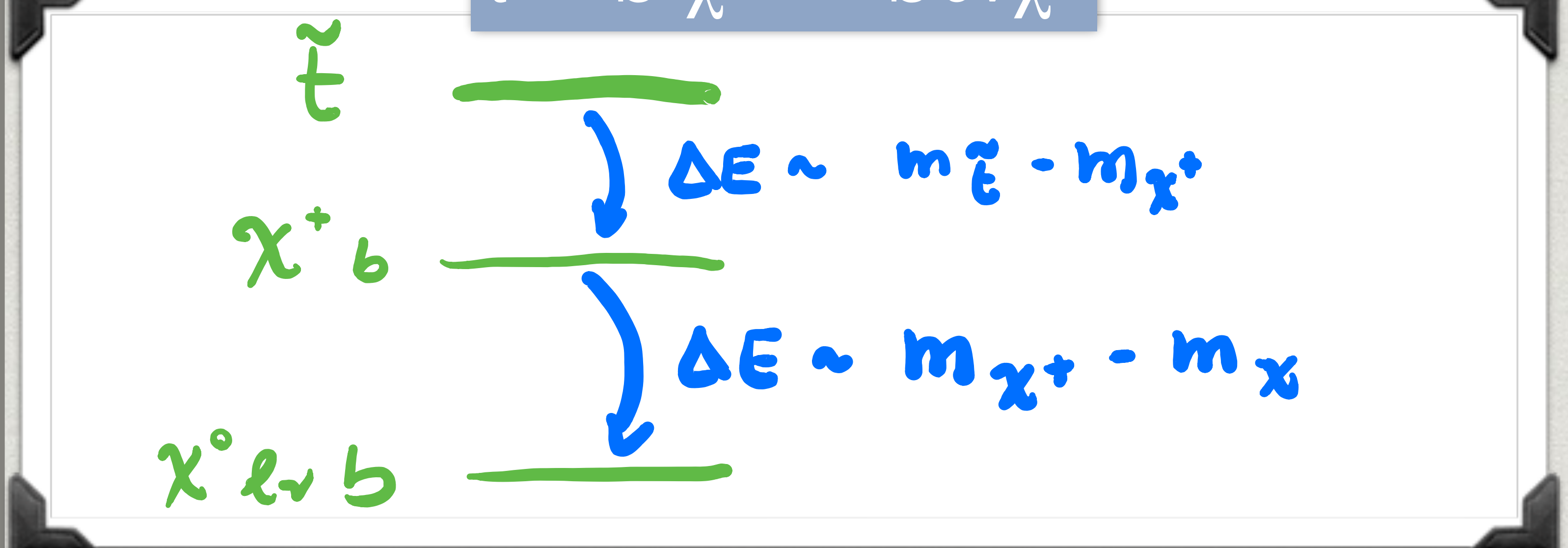


Soft is hard

$t \to bW \to b\ell\nu$



$\tilde{t} \to b\,\chi^+ \to b\ell\nu\chi^0$



New physics is SM-like

Better precision

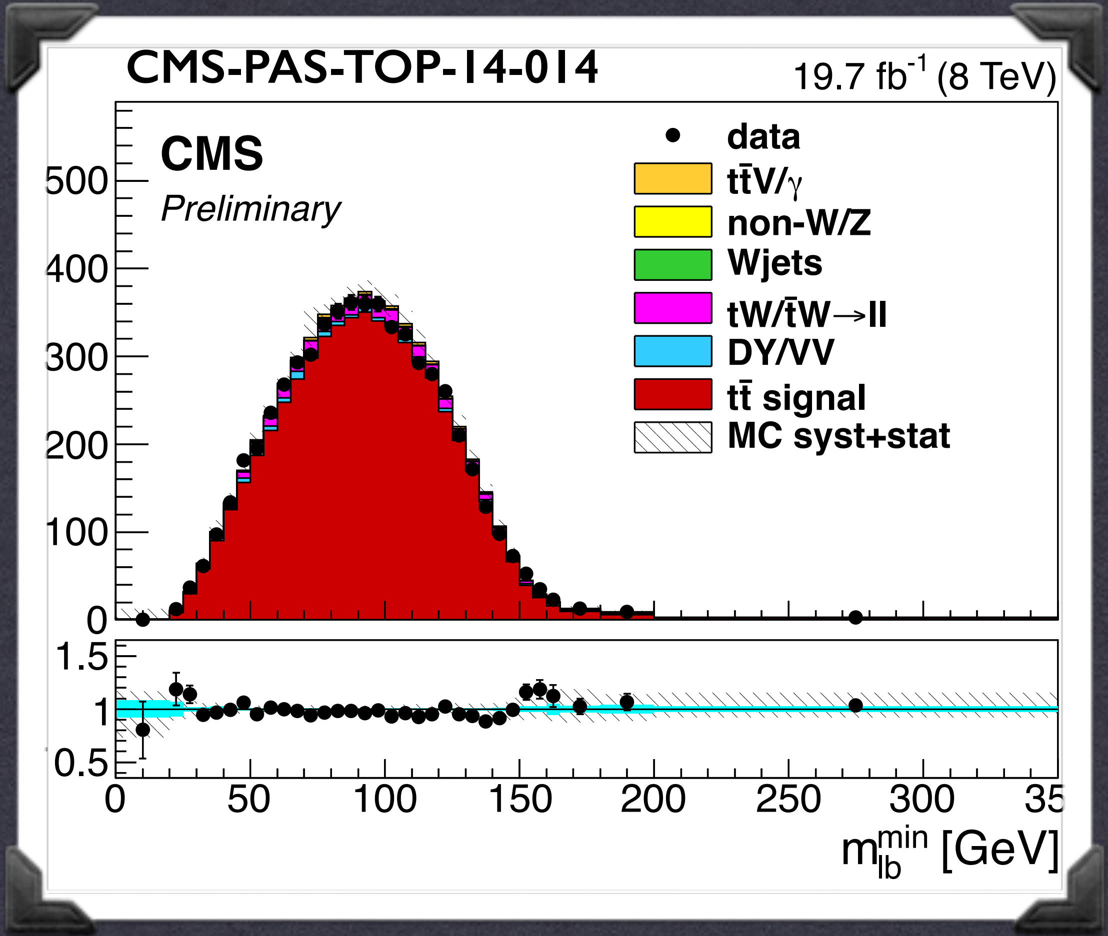
RESOLUTION

RESOLUTION

CLEAN ENVIRONMENT

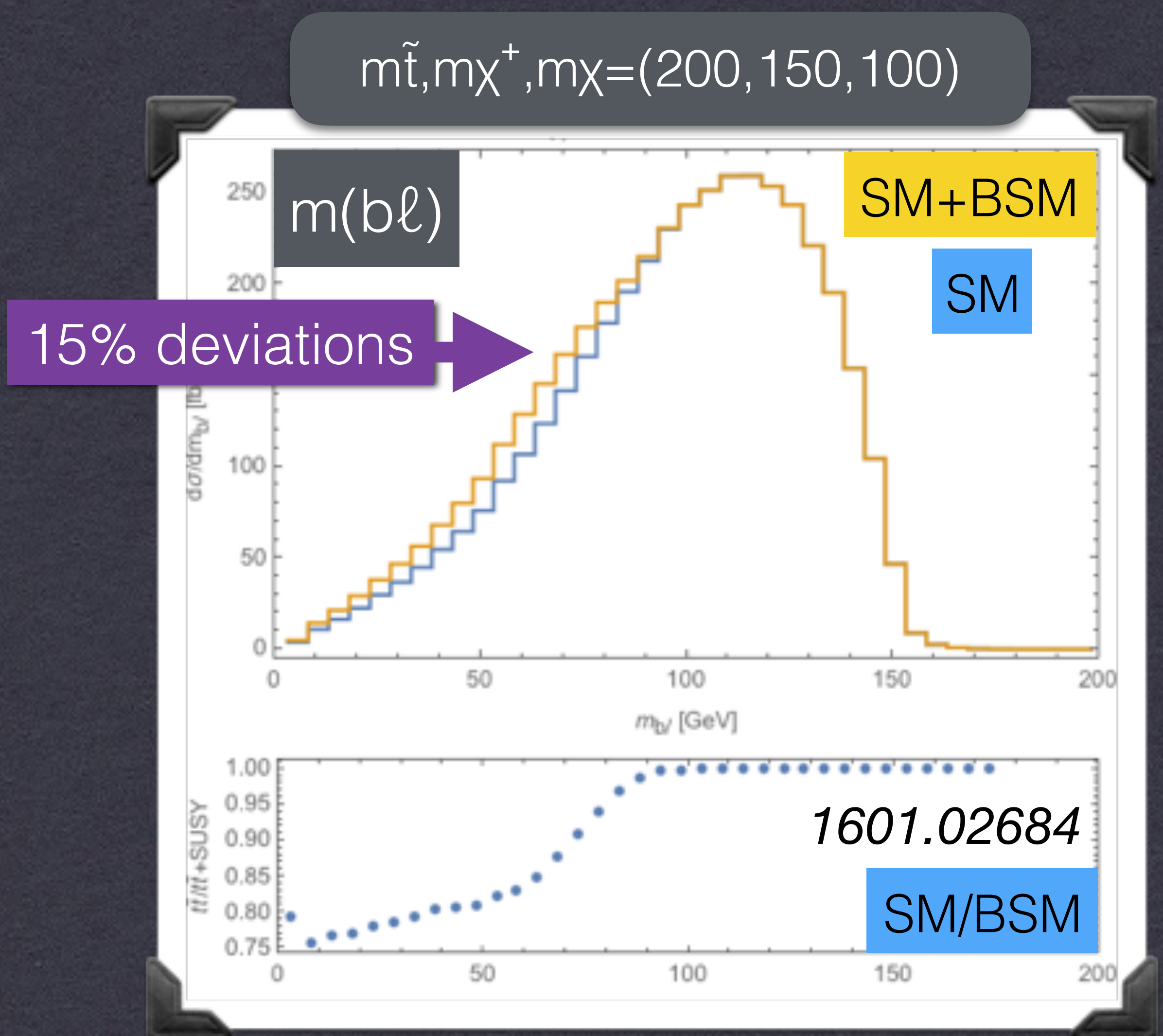
RESOLUTION

PRECISION AT LHC



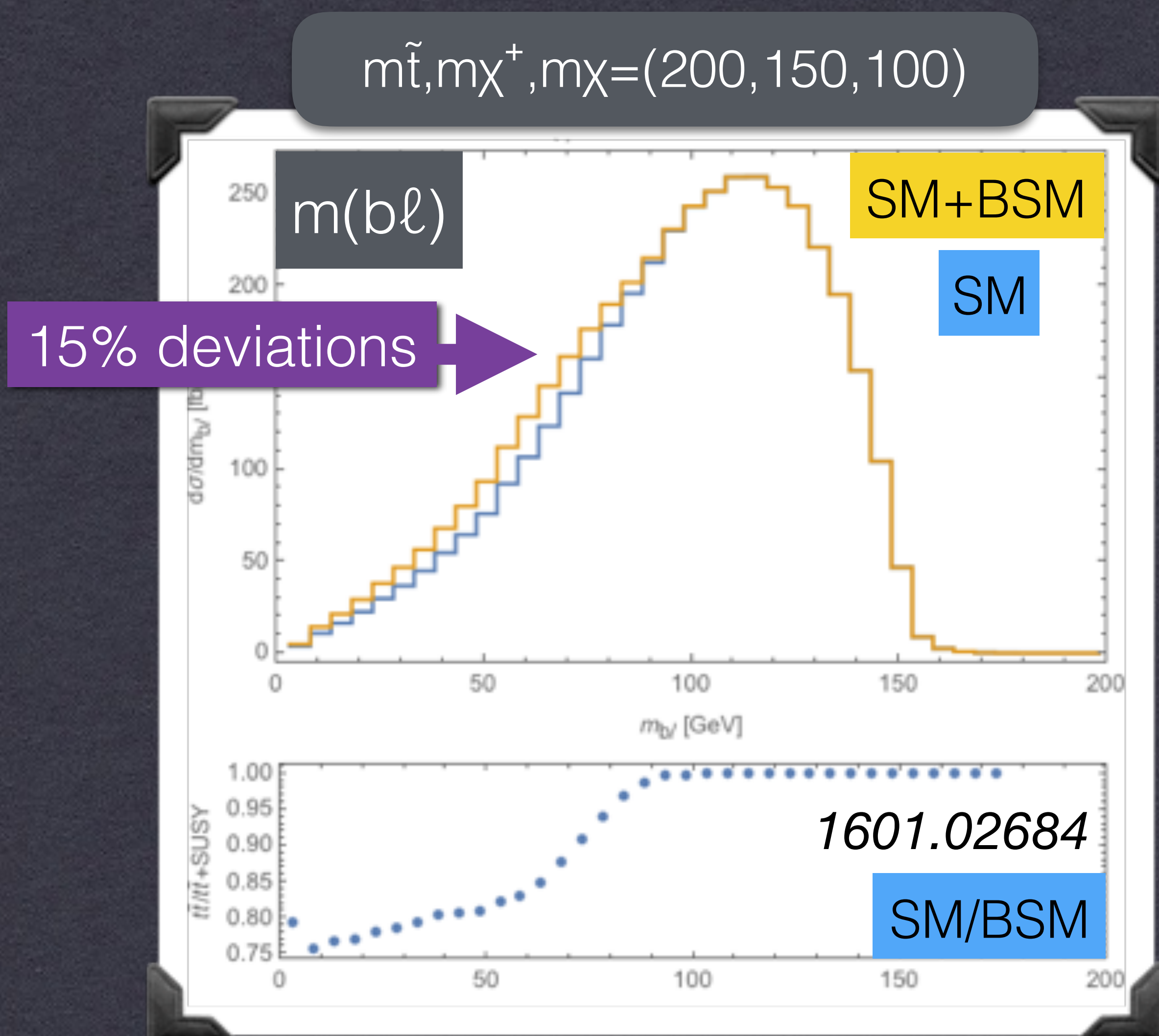
RESOLUTION

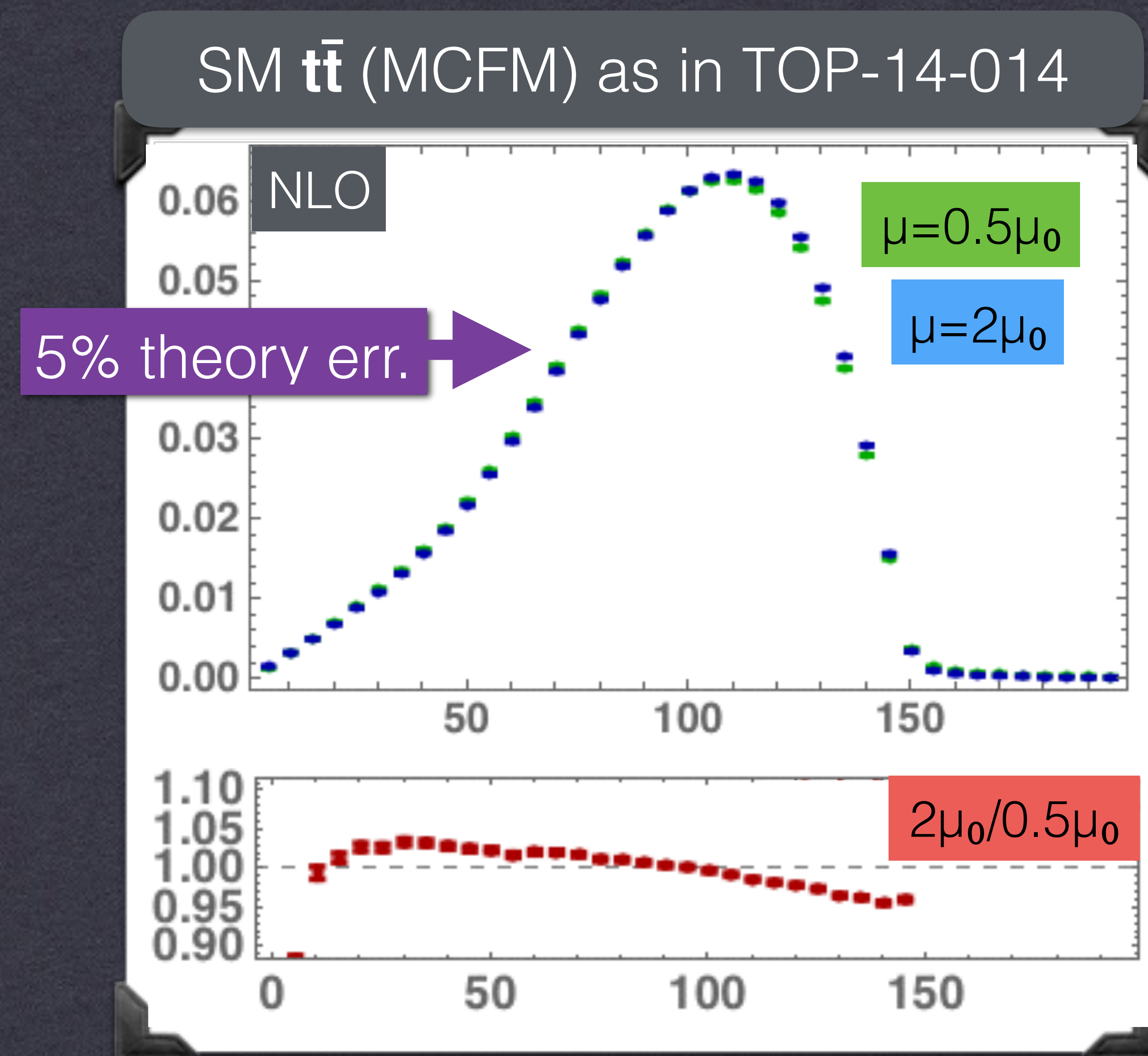
PRECISION AT LHC



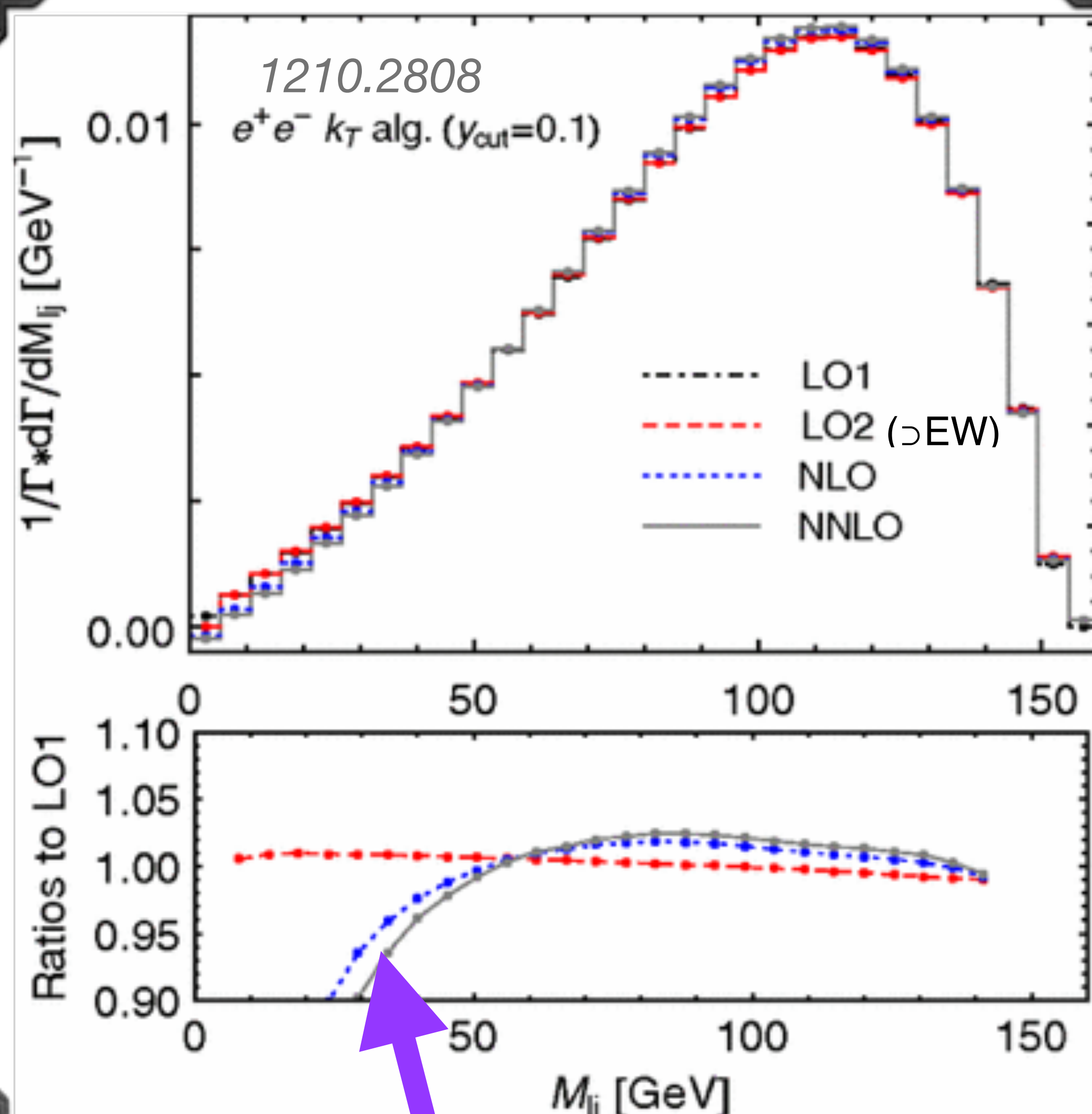
RESOLUTION

PRECISION AT LHC





NNLO top decay



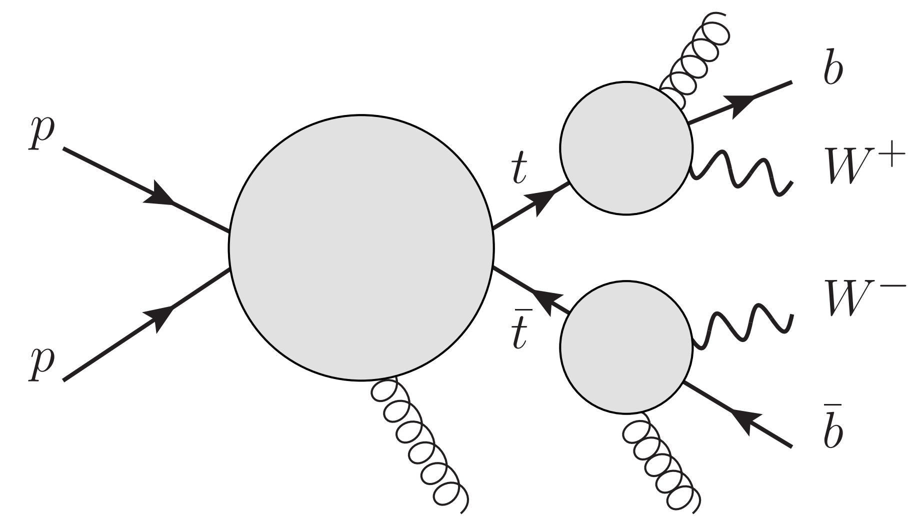
2% NNLO correction

also 1301.7133 NNLO top decay

NLO+PS w/top decay

1607.04538 "bb4ℓ" POWHEG-RES

1412.1828 "tt_dec" POWHEG



S. Pozzorini

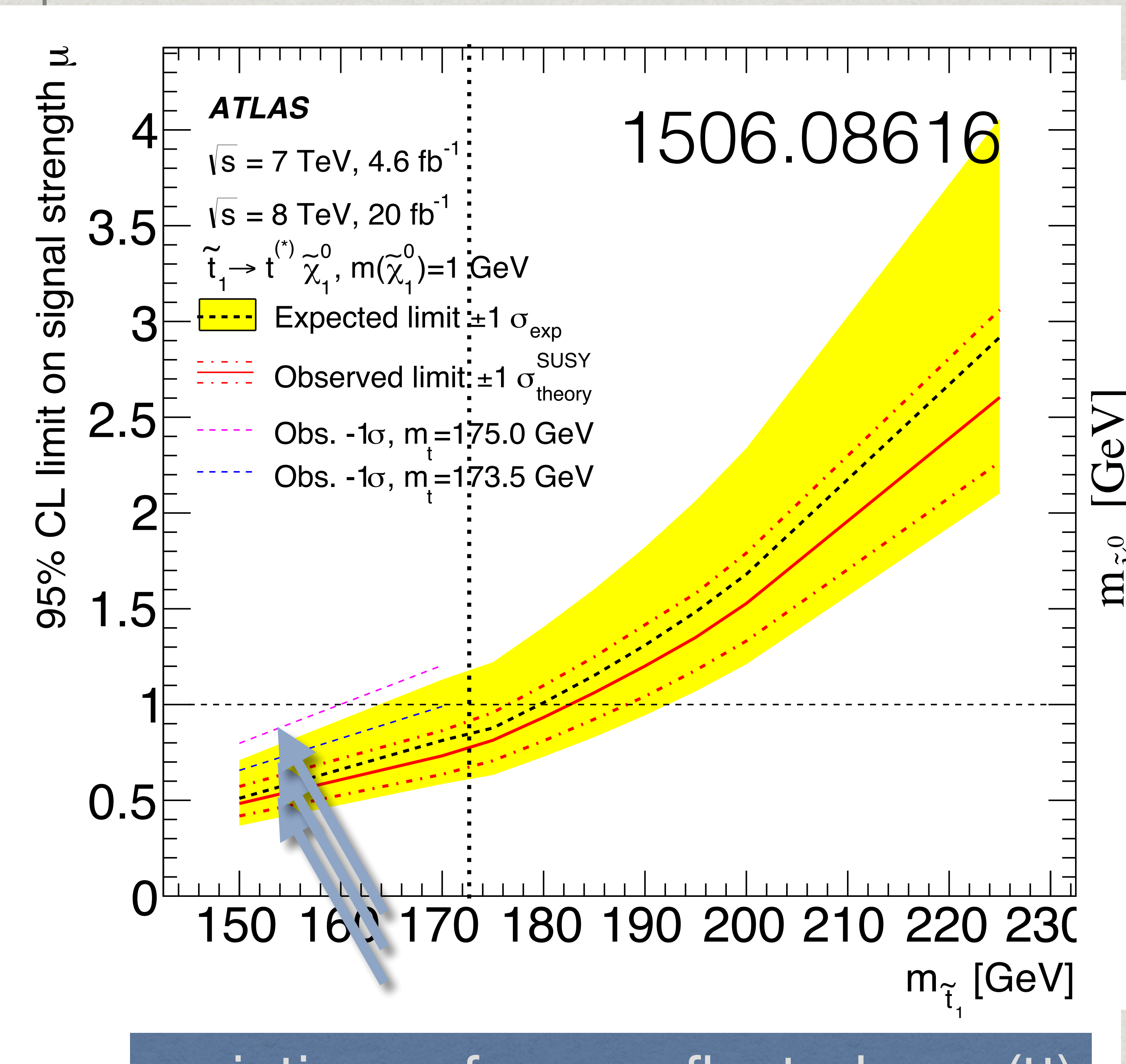
encouraging results form "*tt_dec*"

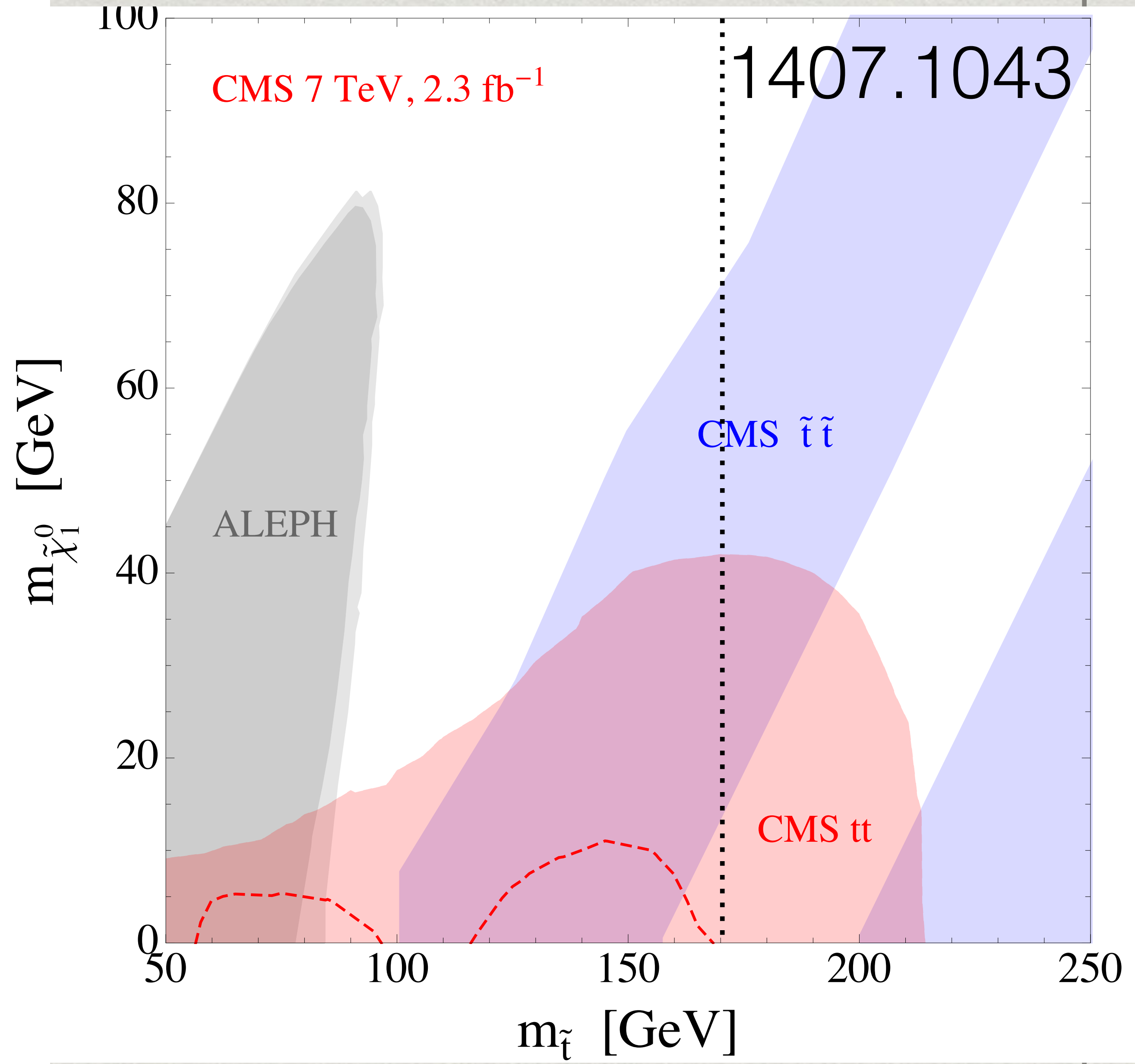
σ(tt̄)

1407.1043 + 1406.5375 + 1506.08616

light stop effects on top cross-section

mχ ≠ 1 GeV



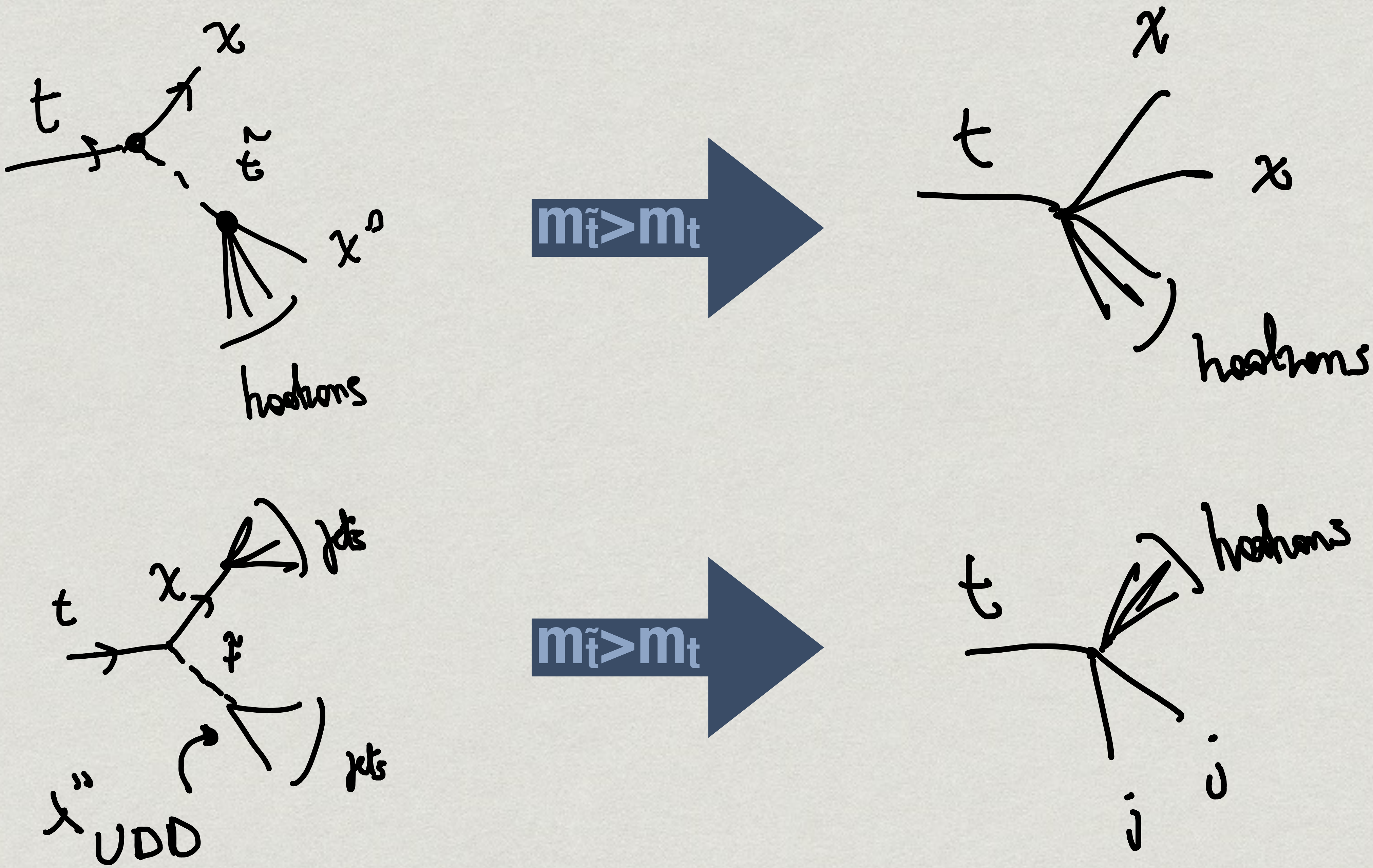


variations of mtop reflected on σ(tt)

A window on heavier new physics

RPC SUSY

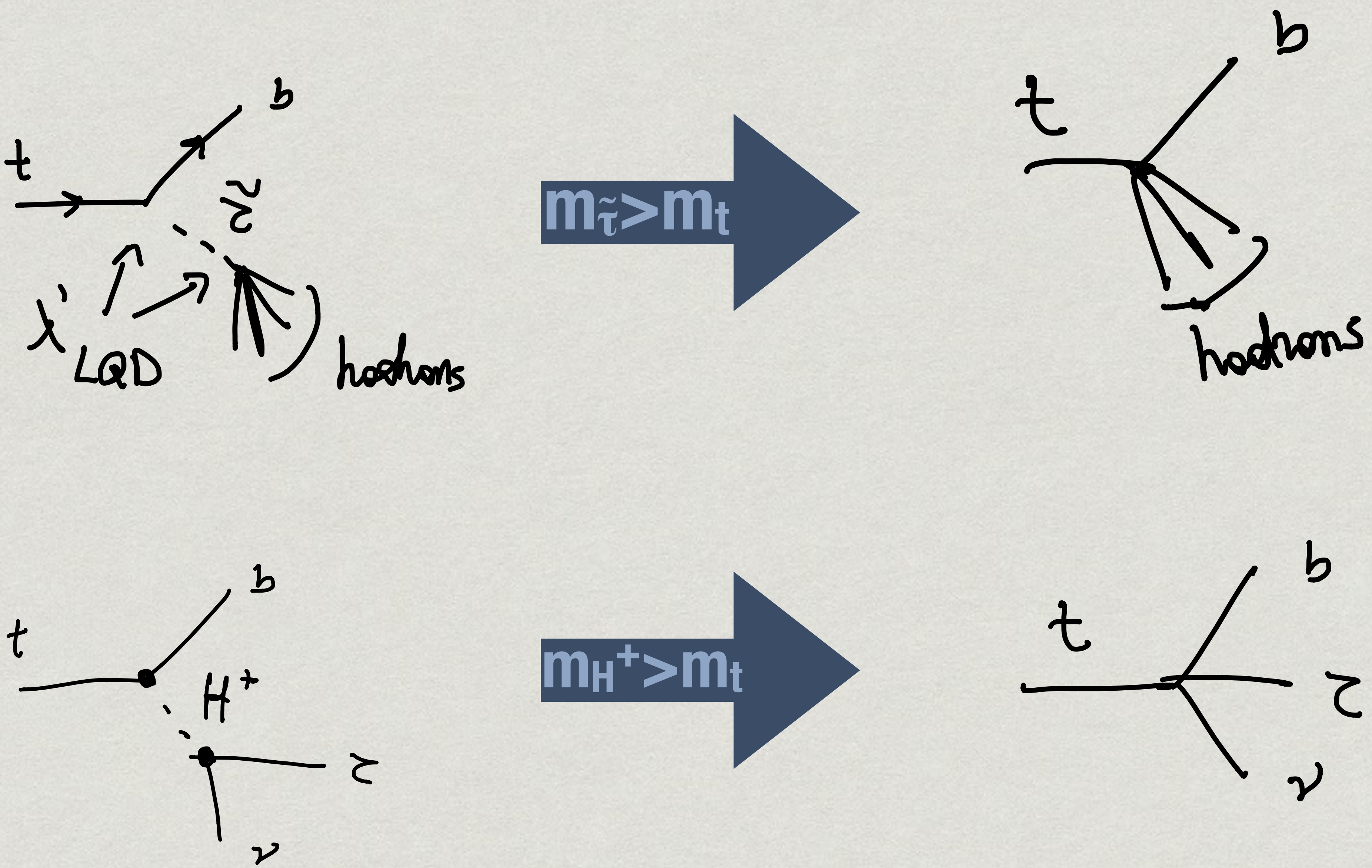
RPV SUSY



displaced χ^0 decay

A window on heavier new physics

RPV SUSY



of course these are just "templates" for thinking, lots of possible signals

top decays to BSM

top as a "portal"

Direct production of light new physics:

- $t \to \tilde{t}\,\chi$ (few % BR in the MSSM, t-$\tilde{t}$-χ coupling)
- $t \to \tilde{\tau}\, b \to b\, b\, c$ (RPV λ', AFAIK not fully covered at LEP)
- $t \to bH^{+} \to b\tau\nu$ (CMS-PAS-HIG-12-052)

Indirect test through higher dimensional operators:

- $t \to cZ, cH$ (and $c \to q$, 1508.05796, 1312.4194, PAS-TOP-14-020)
- $t \to bc\ell$ (BNV 1107.3805, 1310.1618)
- $t \to qe\mu$ (1507.07163)
- $t \to qW$ (1404.2292)
- $t \to bbc$ (1407.1724,1407.1725)
- global BR measurement (1506.05074)

Summary and outlook

- Accumulating evidence indicates that gaps in searches are difficult to fill at the LHC
- Projections are difficult, but a breakthrough seems needed to do better with standard searches strategies
- **Precision in top quark physics has already proven it can be useful for BSM ($\Delta\varphi_{\ell\ell}$, total cross-section, …)**
- **more precision studies interpreted for BSM are needed**

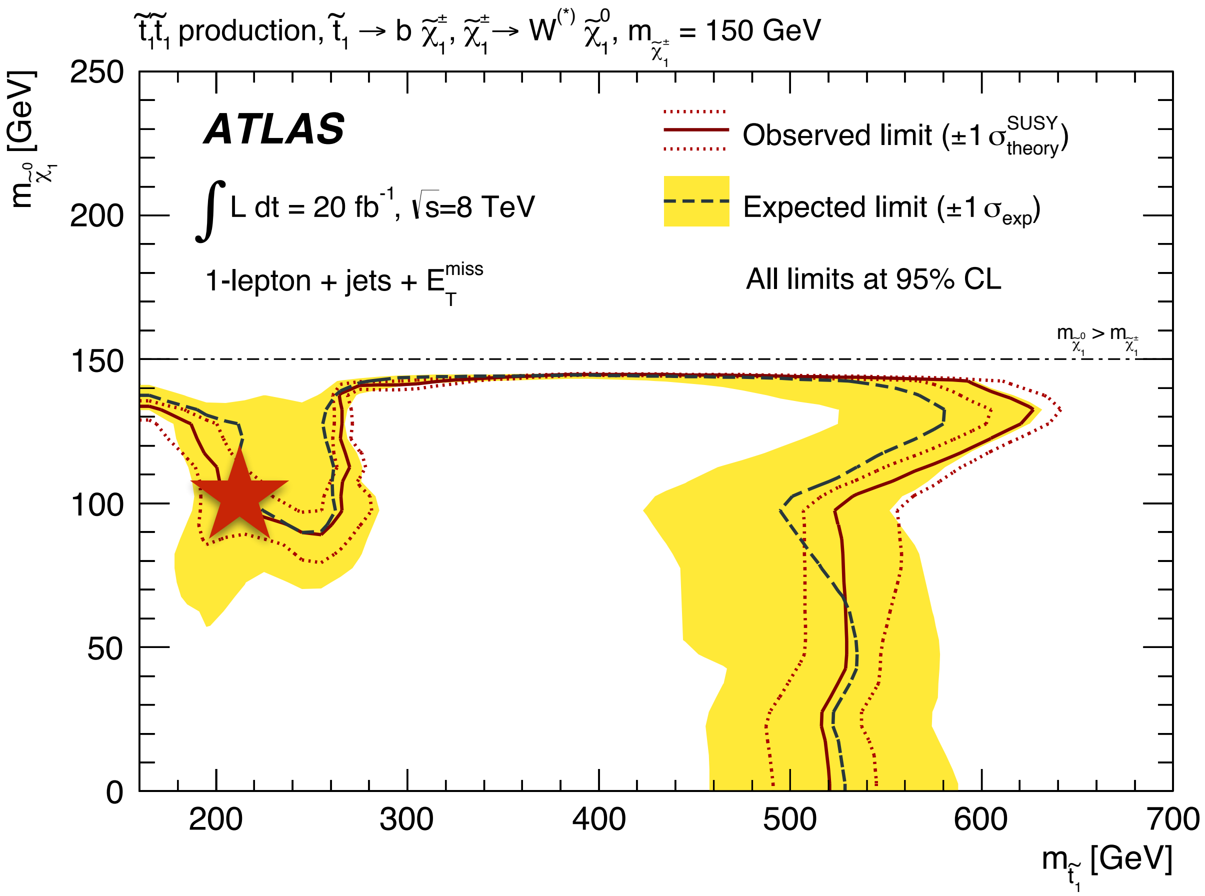
Summary and outlook

- BSM needs top quark precision physics!
- two examples discussed:
    - $\tilde{t}$ production
    - $t \to$ BSM (e.g. $t \to \tilde{t}\chi^0$) and $t \to$ SM via HDO
- new colored states in blindspots

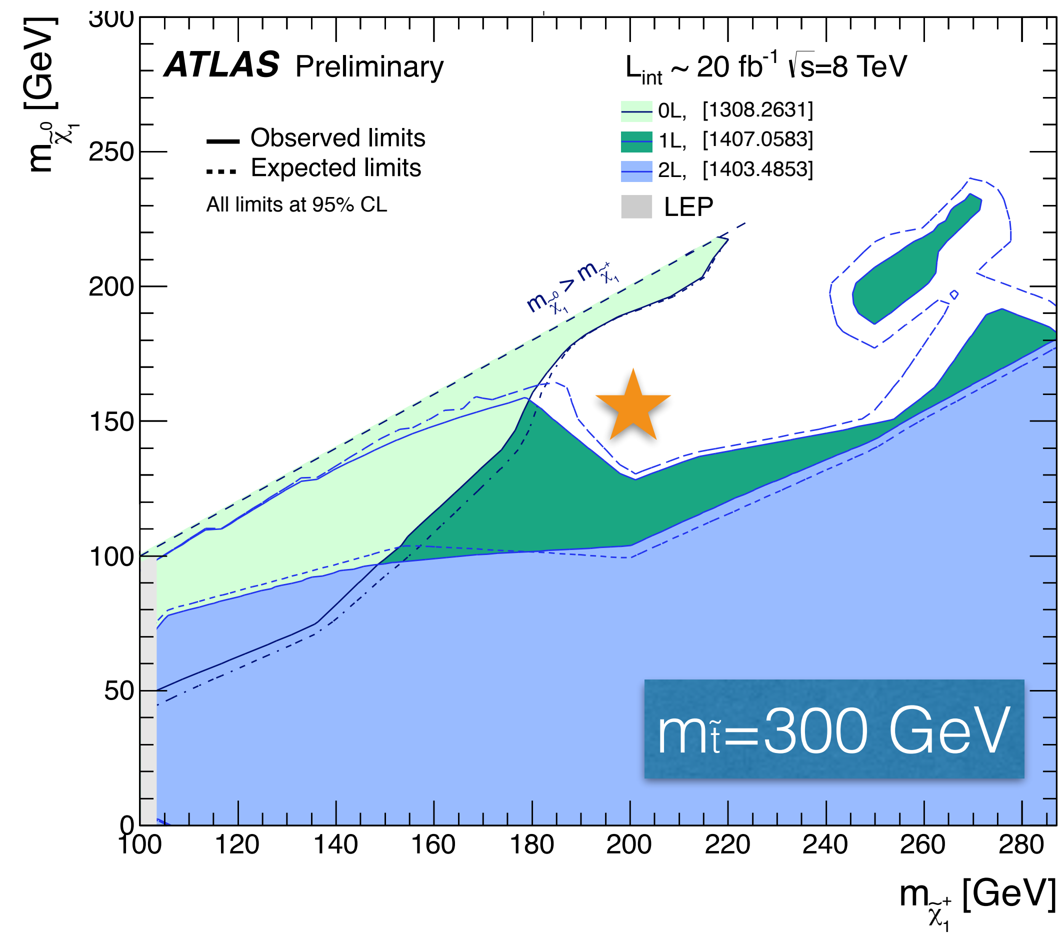
focus on

light ($M \lesssim v$) new physics, subtler signatures

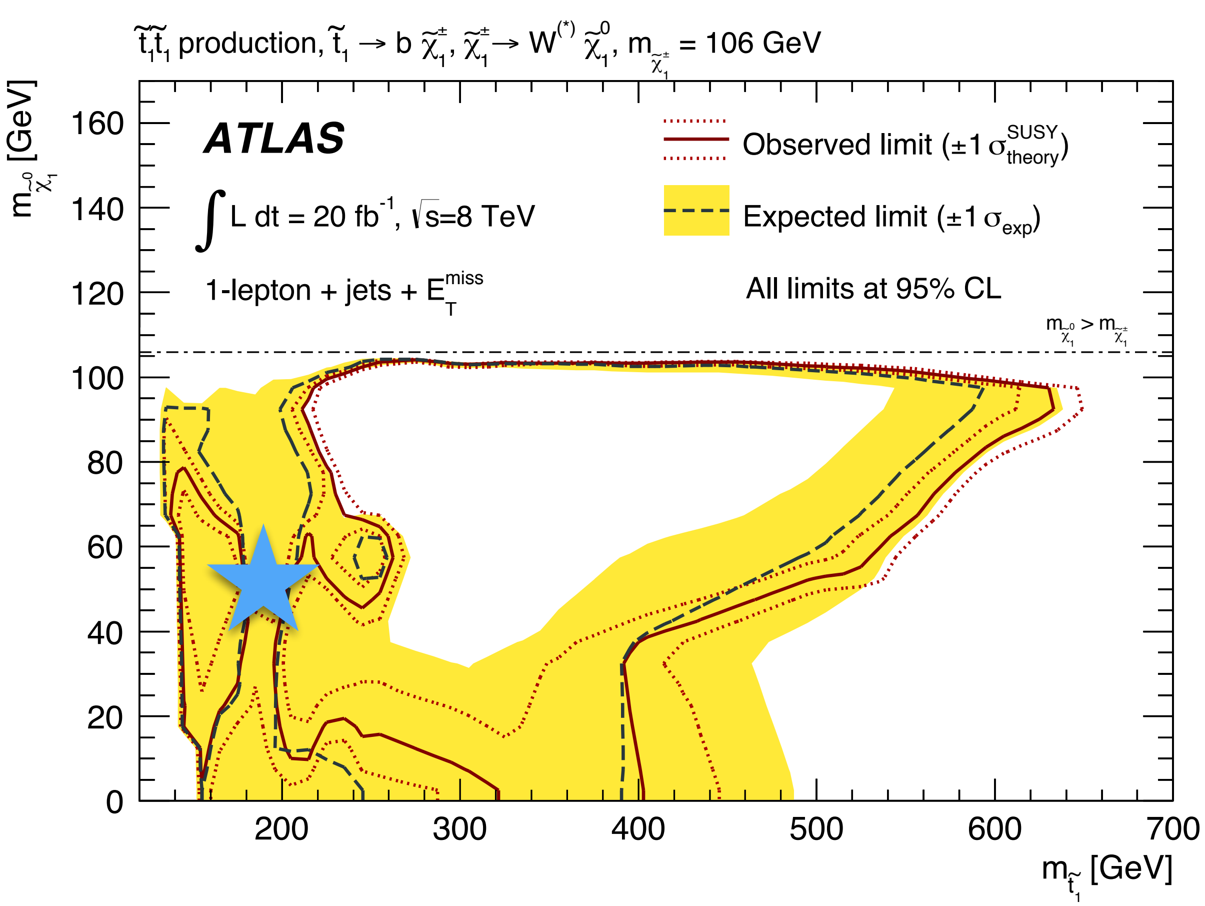
Thank you!



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to b\,\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm} \to W^{(*)}\,\tilde{\chi}_1^0$, $m_{\tilde{\chi}_1^{\pm}}$ = 150 GeV
ATLAS
$\int L\,dt$ = 20 fb^{-1}, $\sqrt{s}$=8 TeV
1-lepton + jets + E_T^{miss}
Observed limit ($\pm 1\,\sigma_{theory}^{SUSY}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
All limits at 95% CL
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^{\pm}}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]

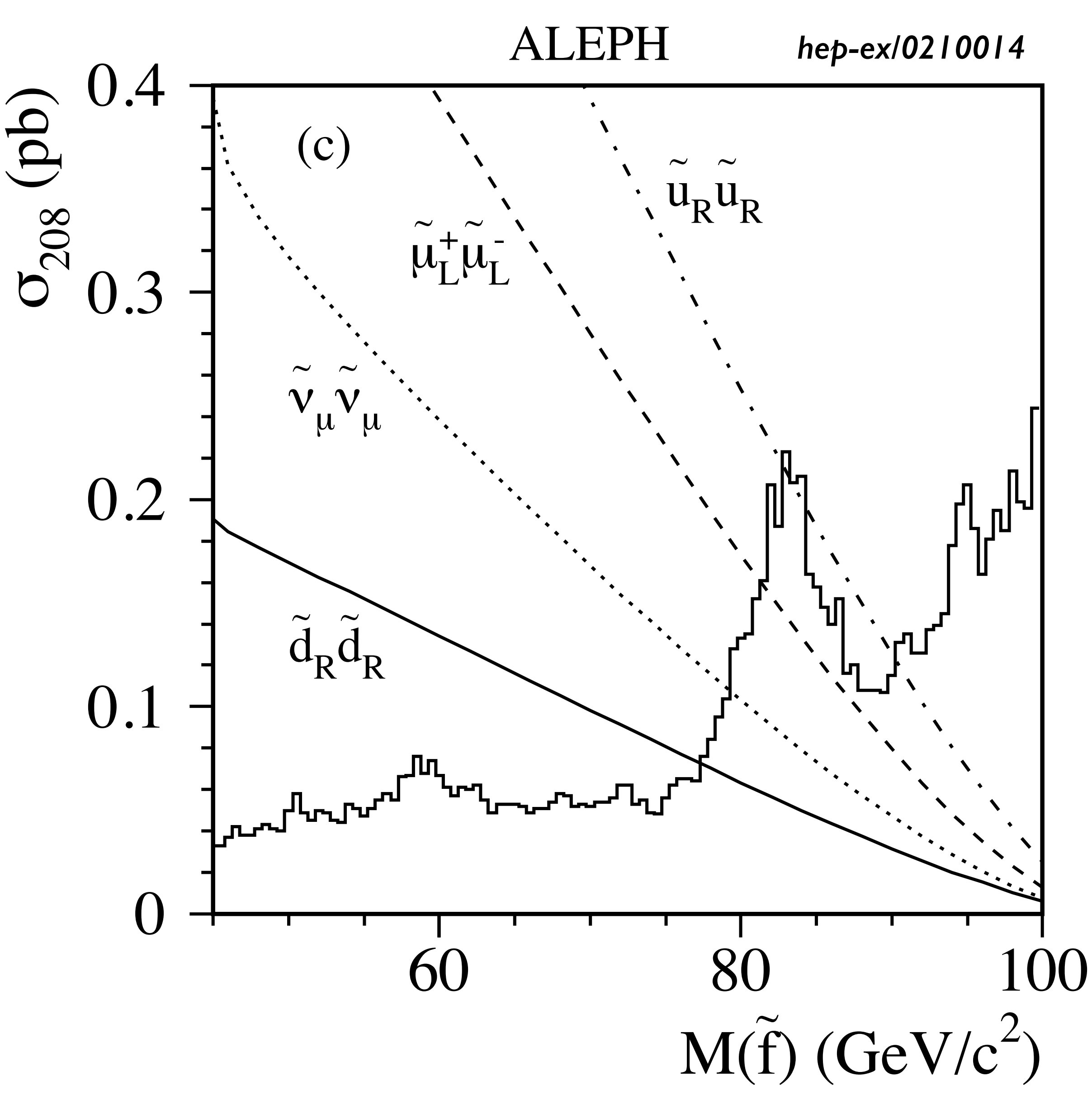


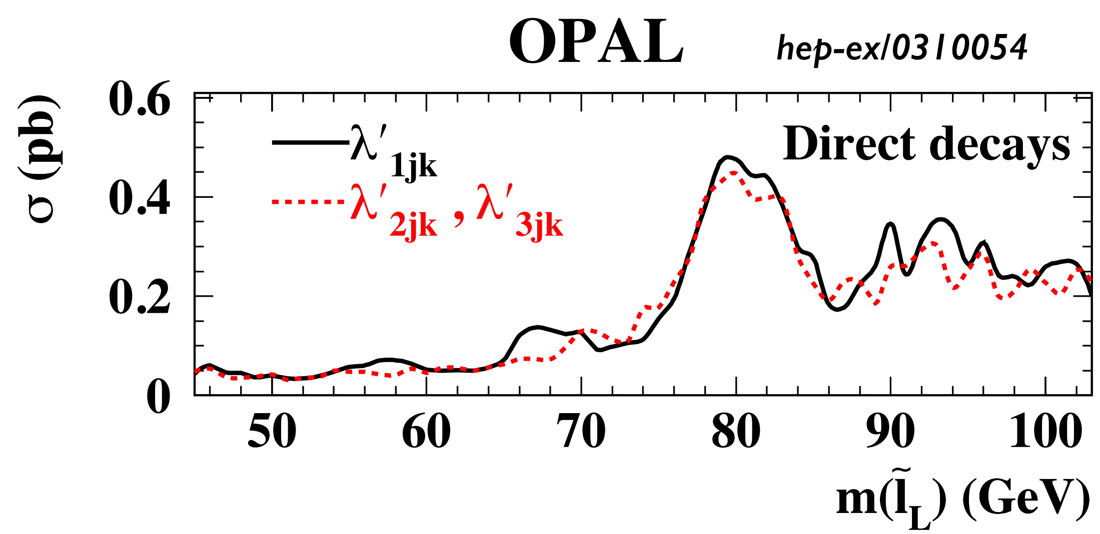
ATLAS Preliminary
L_{int} ~ 20 fb^{-1} $\sqrt{s}$=8 TeV
Observed limits
Expected limits
All limits at 95% CL
0L, [1308.2631]
1L, [1407.0583]
2L, [1403.4853]
LEP
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^{\pm}}$
$m_{\tilde{t}}$=300 GeV
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^{\pm}}$ [GeV]

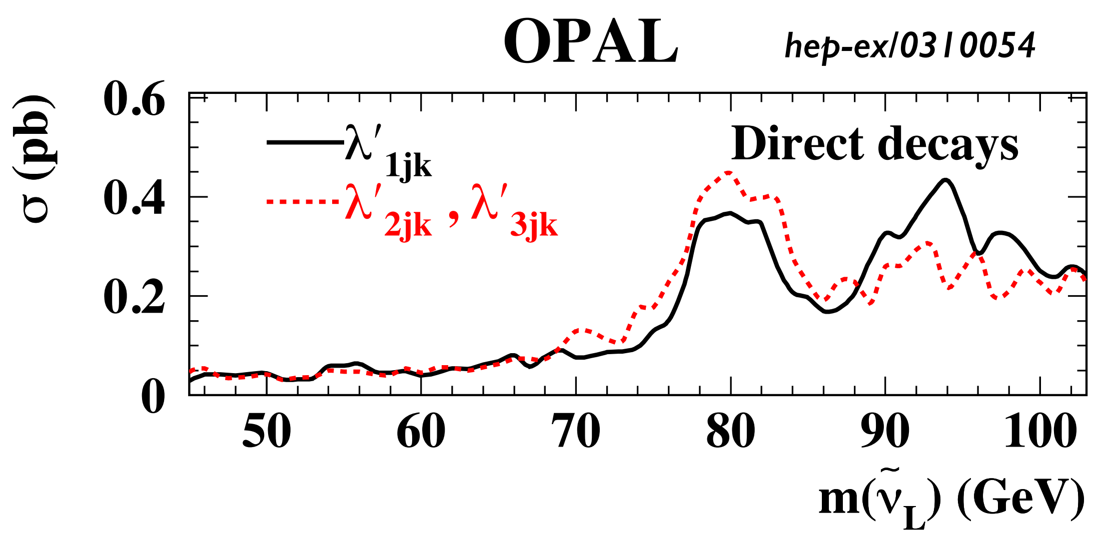


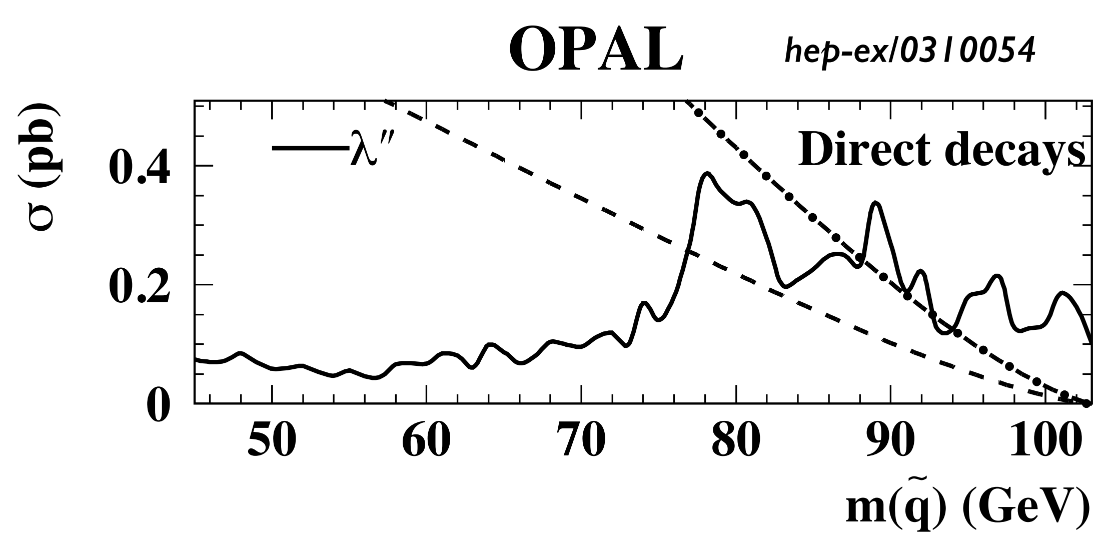
$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to b\,\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm} \to W^{(*)}\,\tilde{\chi}_1^0$, $m_{\tilde{\chi}_1^{\pm}}$ = 106 GeV
ATLAS
$\int L\,dt$ = 20 fb^{-1}, $\sqrt{s}$=8 TeV
1-lepton + jets + E_T^{miss}
Observed limit ($\pm 1\,\sigma_{theory}^{SUSY}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
All limits at 95% CL
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^{\pm}}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]

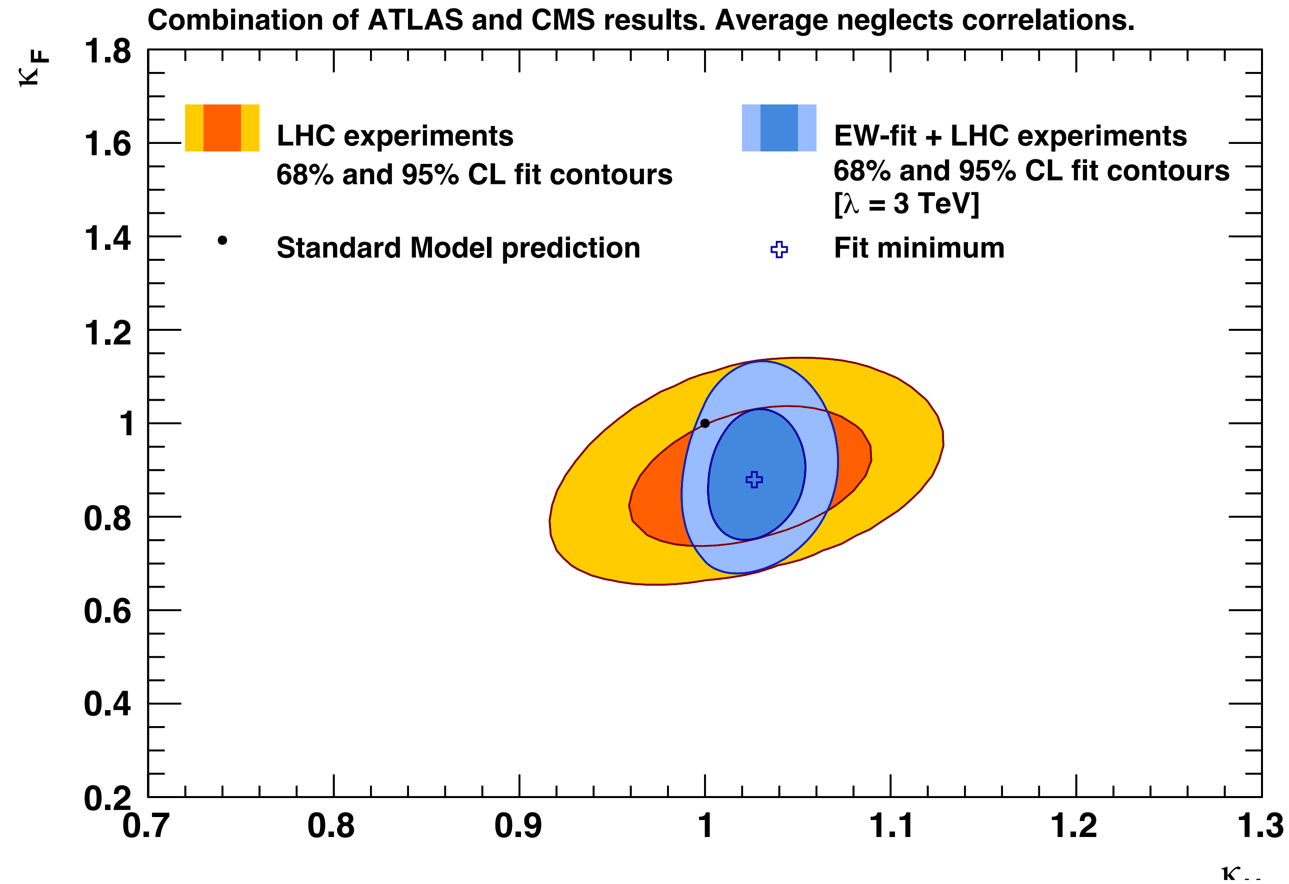
$e^+e^- \to 4j$ limits

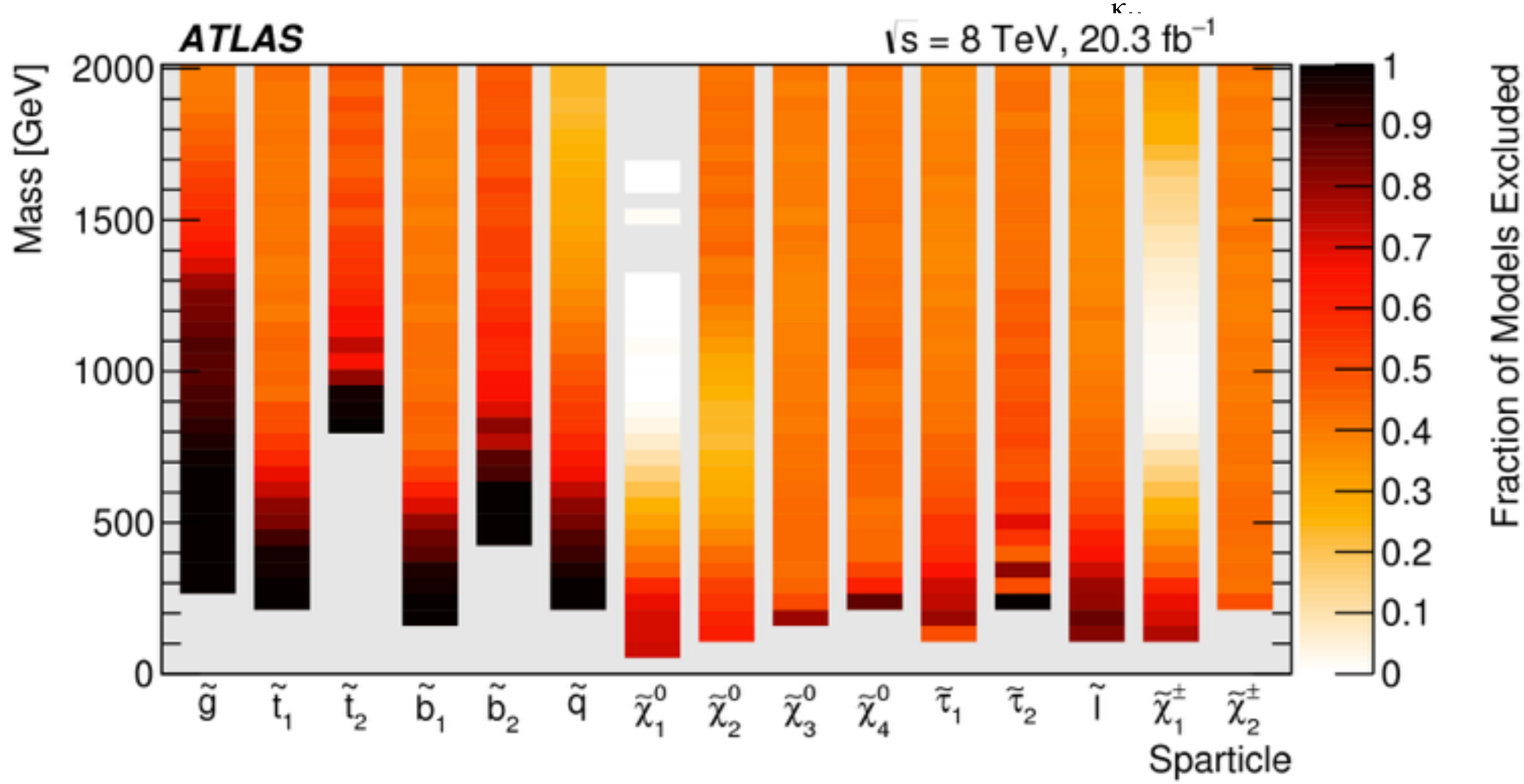









Combination of ATLAS and CMS results. Average neglects correlations.
LHC experiments
68% and 95% CL fit contours
EW-fit + LHC experiments
68% and 95% CL fit contours
[λ = 3 TeV]
Standard Model prediction
Fit minimum
κF
κV


ATLAS
√s = 8 TeV, 20.3 fb⁻¹
Mass [GeV]
Fraction of Models Excluded
Sparticle

BSM Top FCNC overview

1311.2028, ATL-PHYS-PUB-2013-012, CMS-PAS-FTR-13-016

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

$t \to cH \to \gamma\gamma$