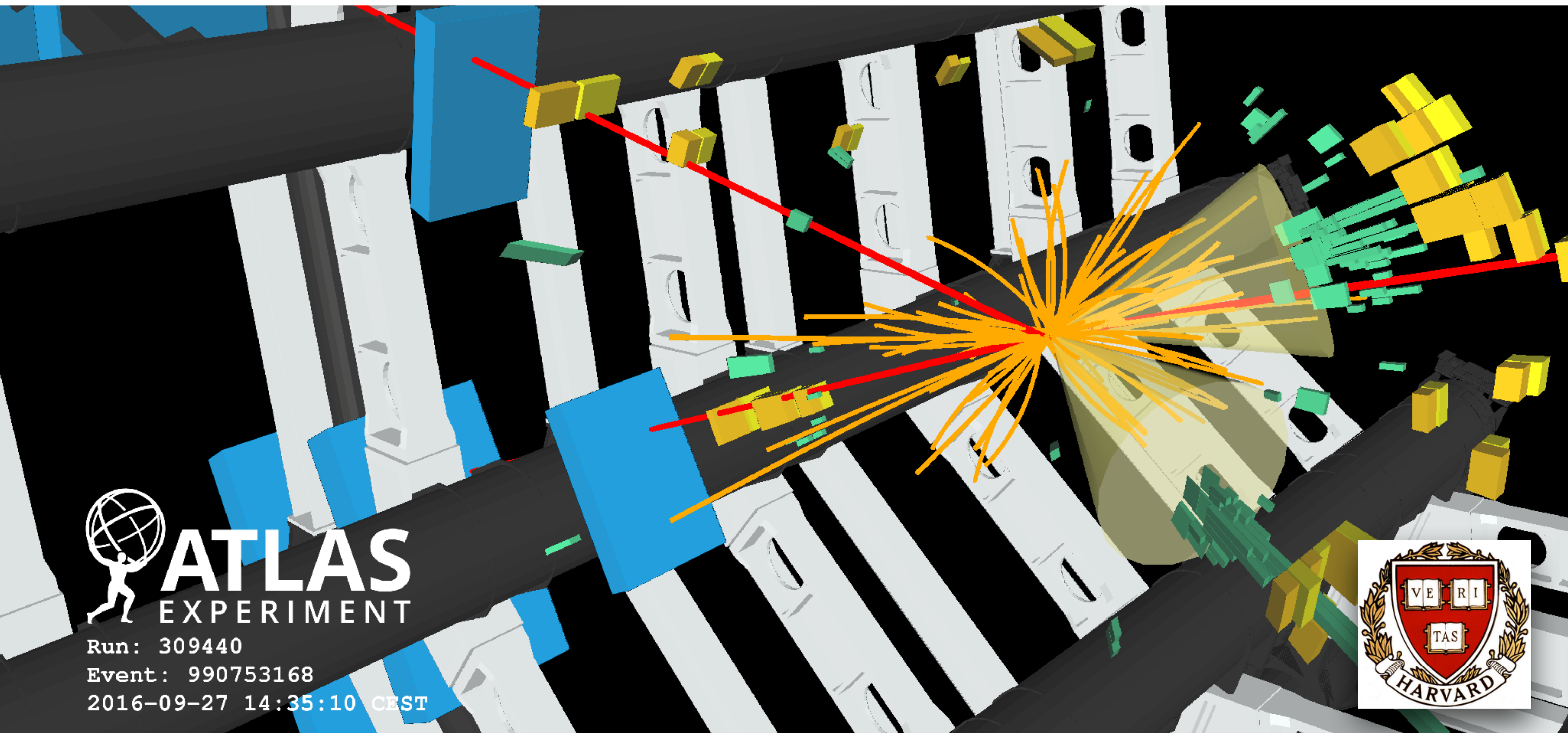
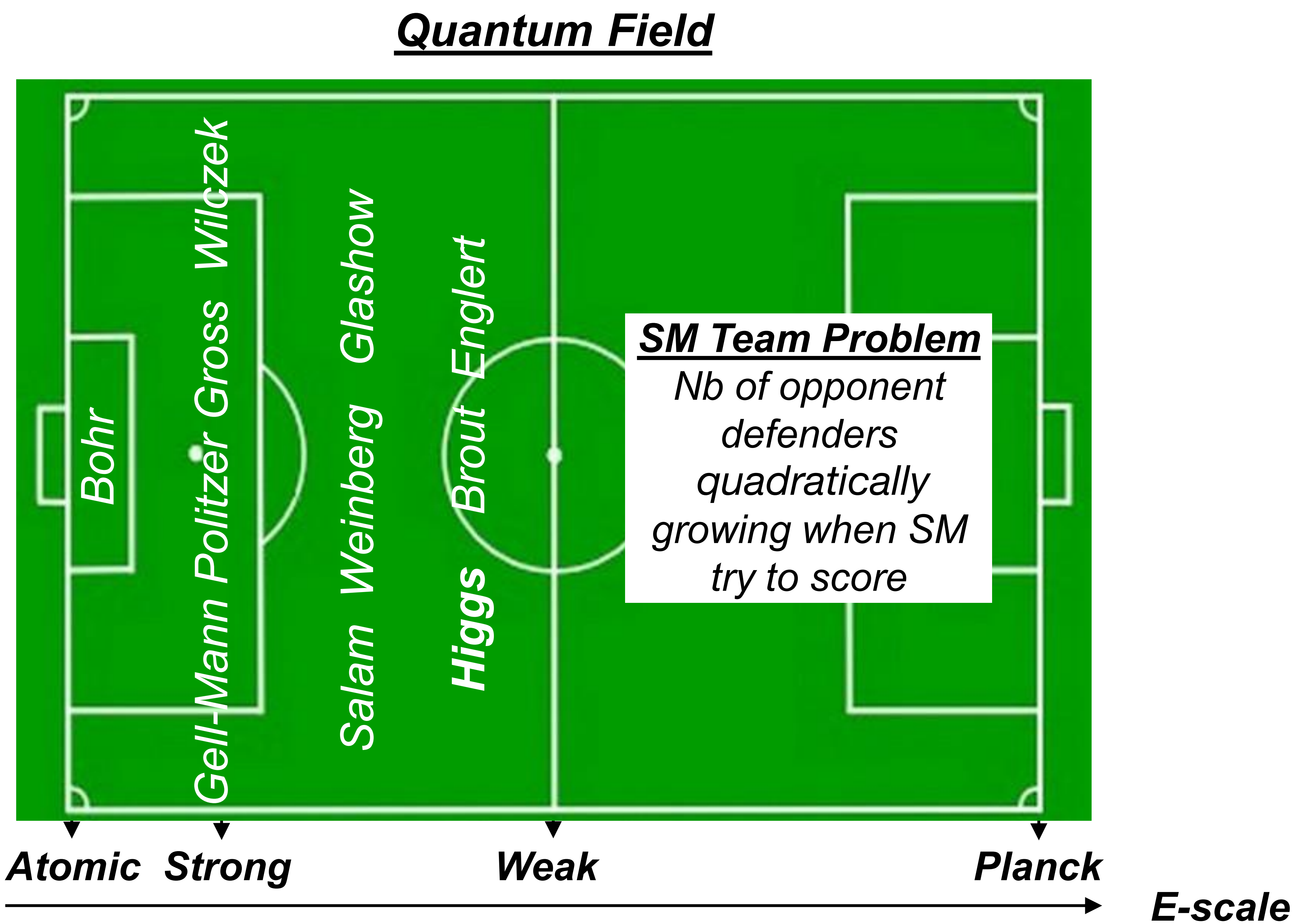
Stefano Zambito, Harvard University

Hunting for Supersymmetry at the LHC

A Dive Into Naturalness… And Beyond

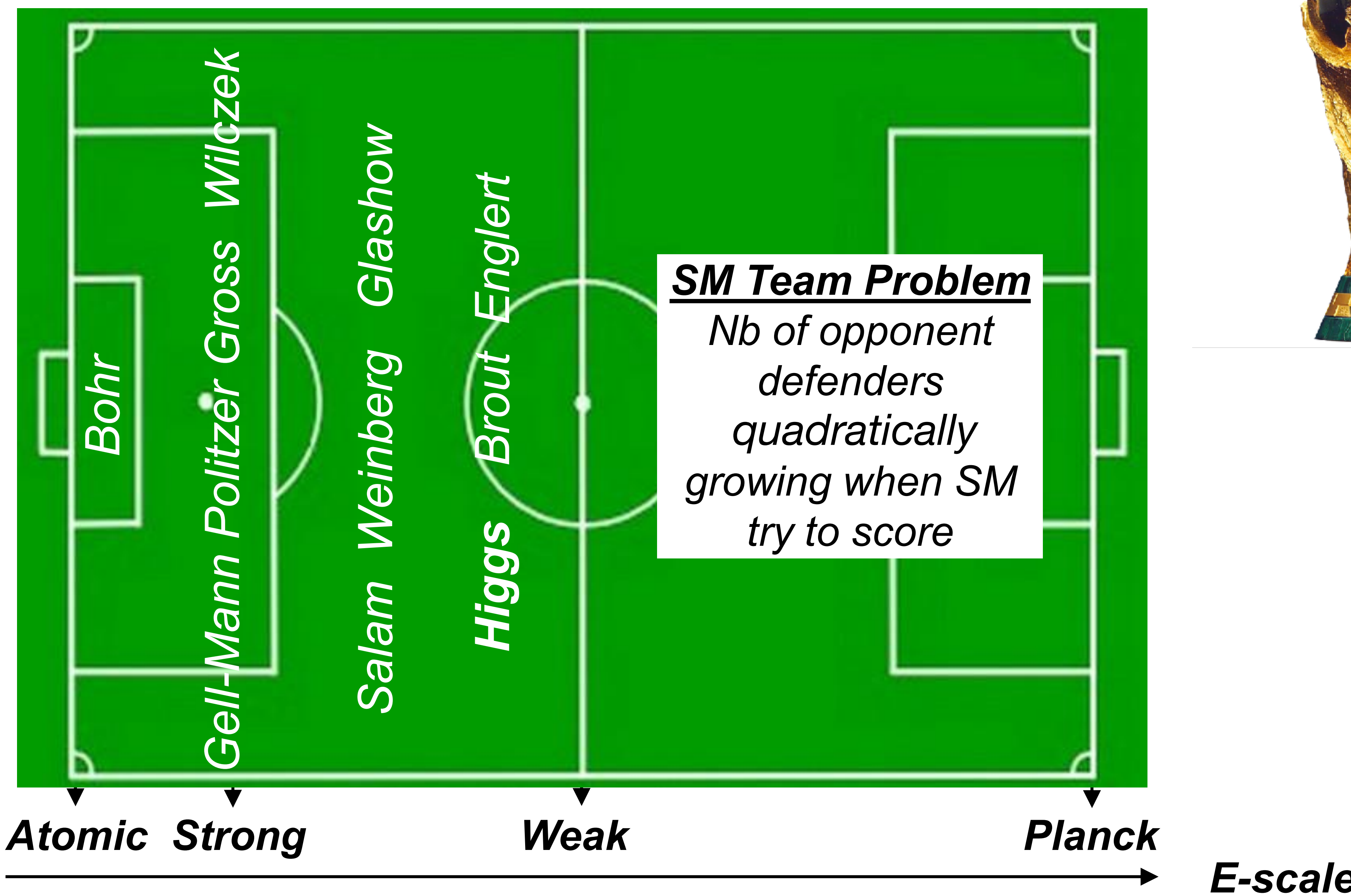


Outline


Quantum Field
Bohr
Gell-Mann Politzer Gross Wilczek
Salam Weinberg Glashow
Higgs Brout Englert
SM Team Problem
Nb of opponent defenders quadratically growing when SM try to score
Atomic
Strong
Weak
Planck
E-scale

Outline

Quantum Field



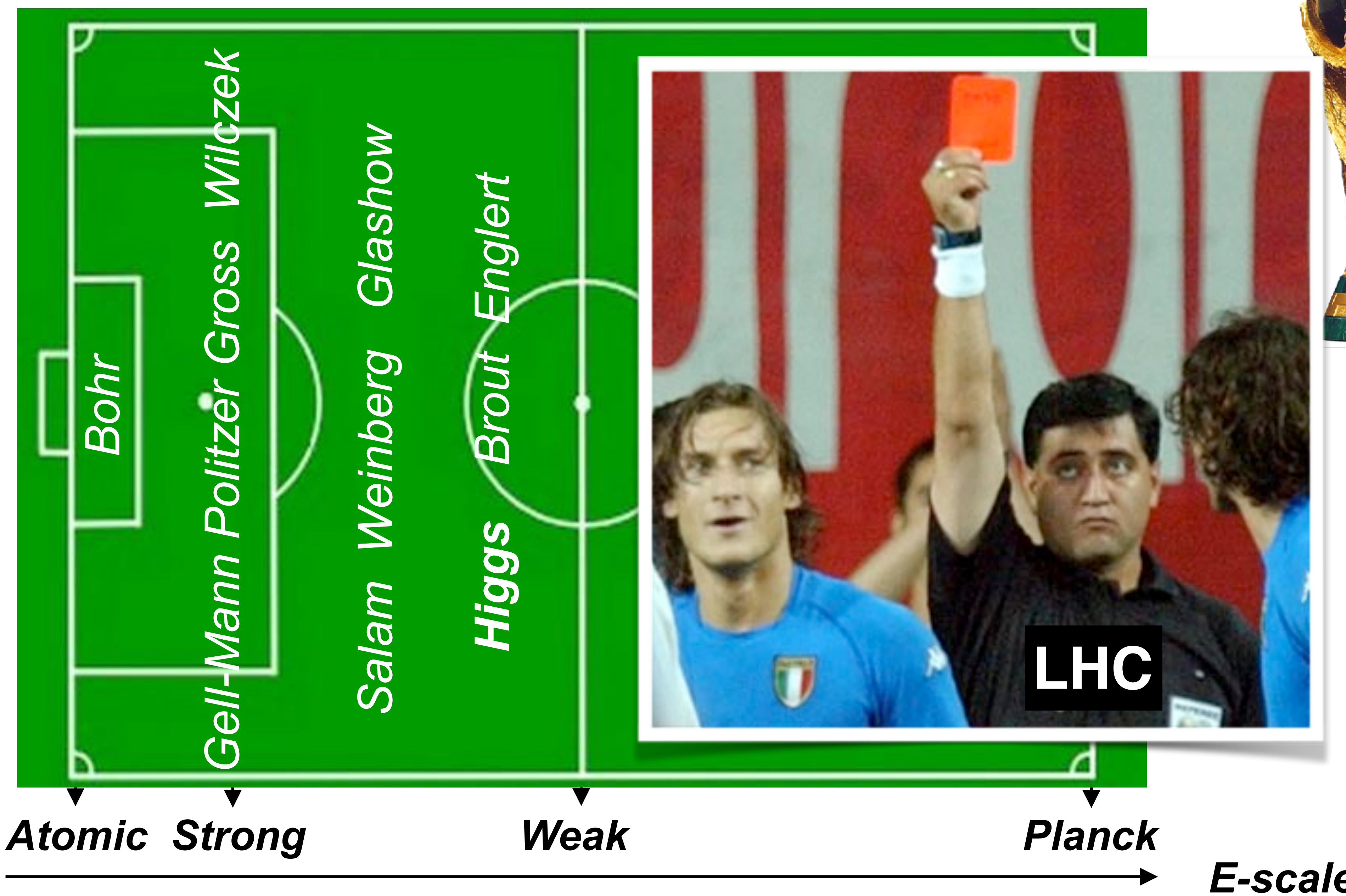
SUSY coach (formed in Poincarè Academy in France*): knows how to annihilate defenders!

Doubling the number of SM team players…

*** great fan of "champagne footbal"!**

Outline

Quantum Field

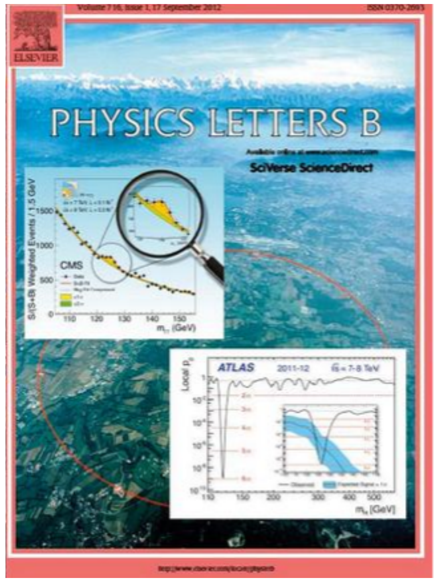


SUSY coach (formed in Poincarè Academy in France*): knows how to annihilate defenders!

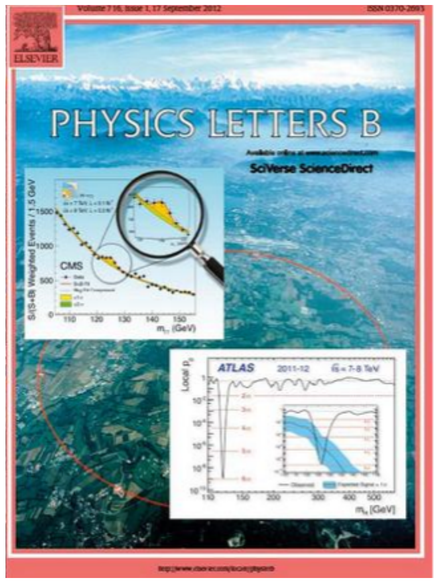
Doubling the number of SM team players… **Will the LHC referee allow that?**

*** great fan of "champagne footbal"!**

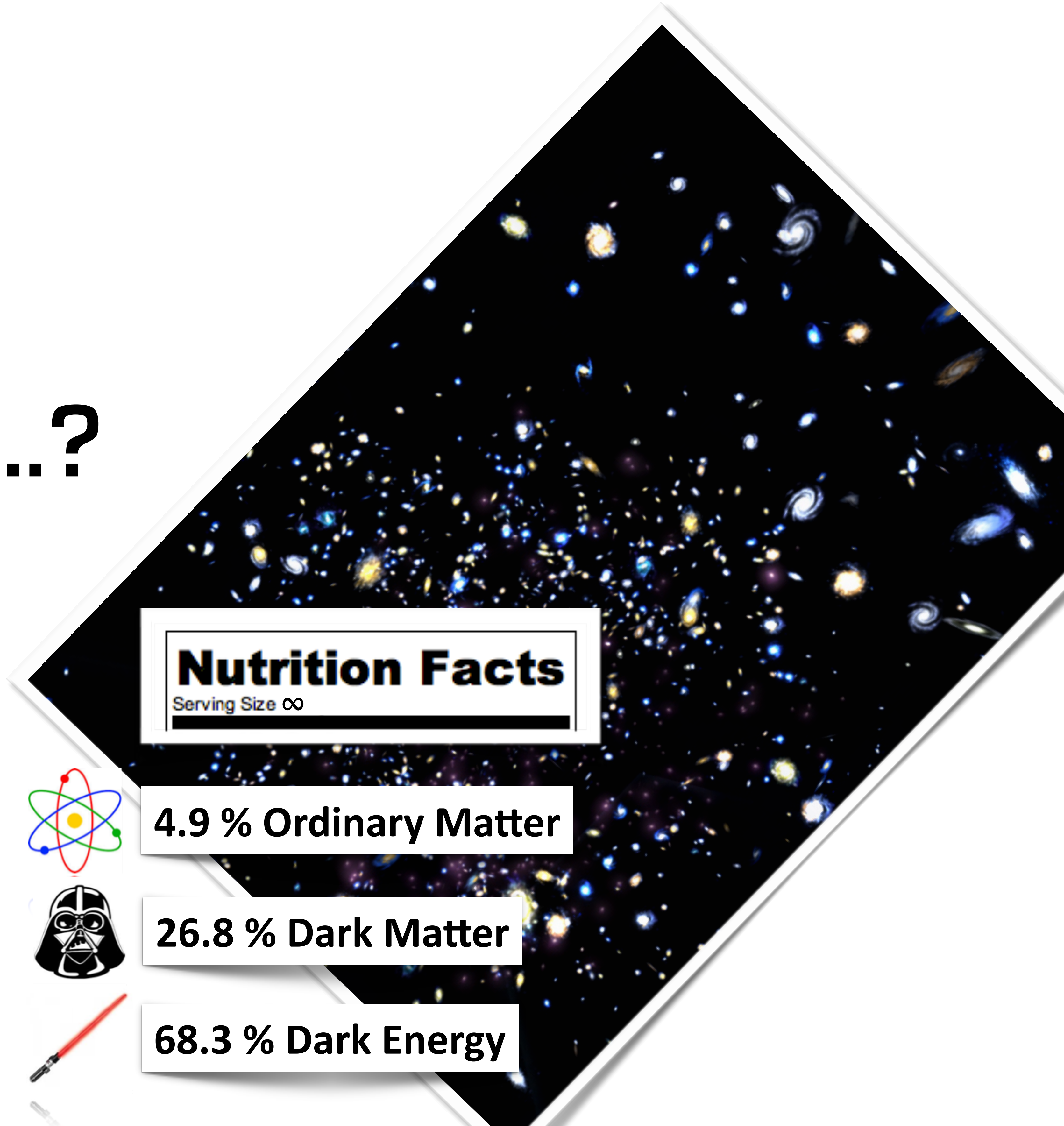
The Standard Model, After The Higgs



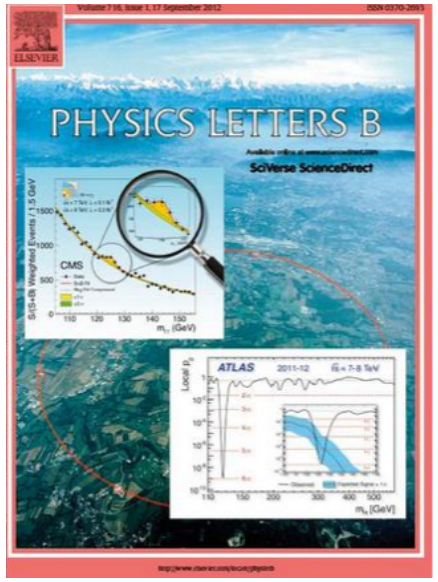
The Standard Model, After The Higgs



…?



The Standard Model, After The Higgs

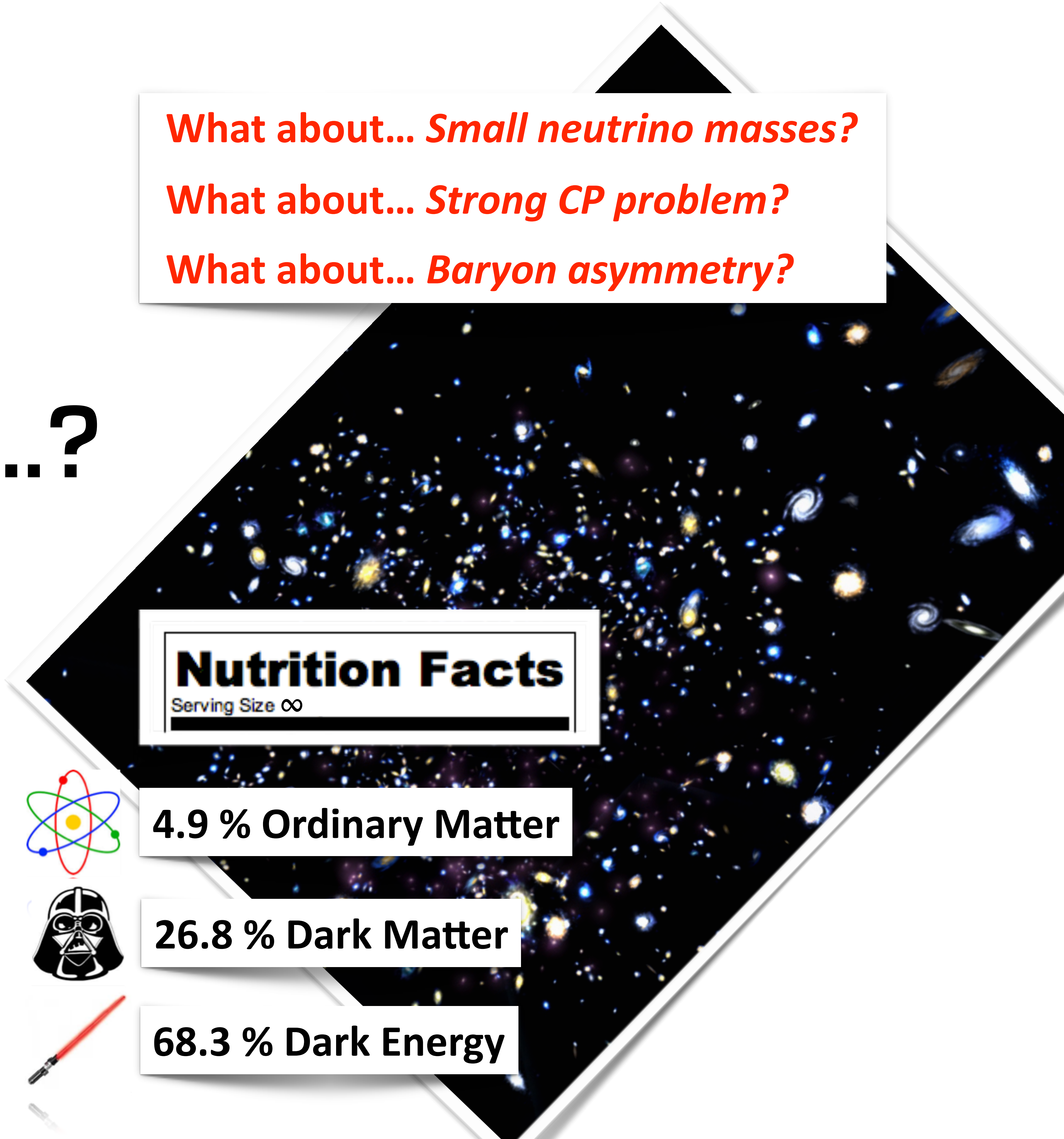


...?

What about… *Small neutrino masses?*

What about… *Strong CP problem?*

What about… *Baryon asymmetry?*



4.9 % Ordinary Matter

26.8 % Dark Matter

68.3 % Dark Energy

	Effective potential		**Dynamic**
Ginzburg-Landau:	$V(\Psi) = \alpha\,|\Psi|^2 + \beta\,|\Psi|^4$	$\longrightarrow$	cooper pairs, etc…
Higgs Potential:	$V(\phi) = m_h^2\,|\phi|^2 + \lambda\,|\phi|^4$	$\longrightarrow$	???

Living On The Edge - The Tough Life Of A 125 GeV H Boson

Effective potential | **Dynamic**

Ginzburg-Landau: $V(\Psi) = \alpha\,|\Psi|^2 + \beta\,|\Psi|^4$ → cooper pairs, etc…

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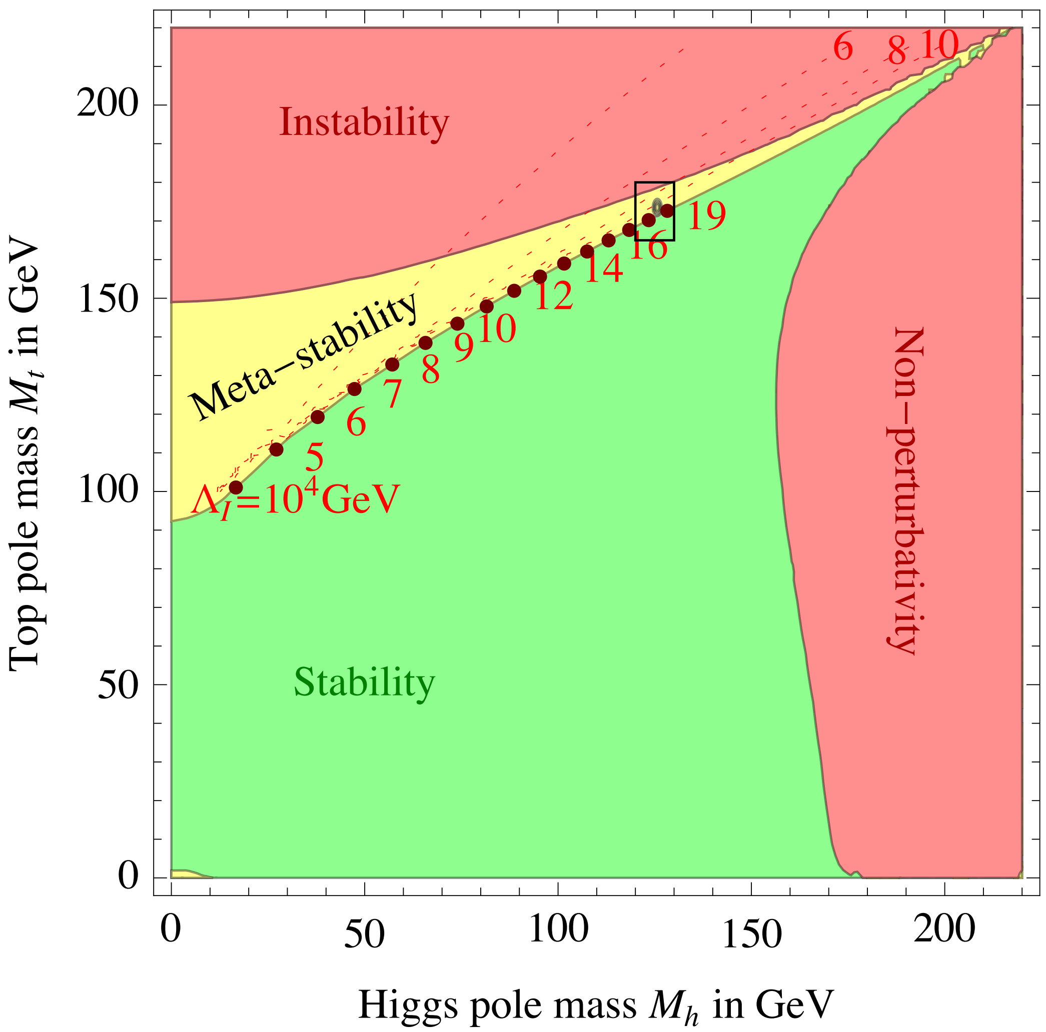

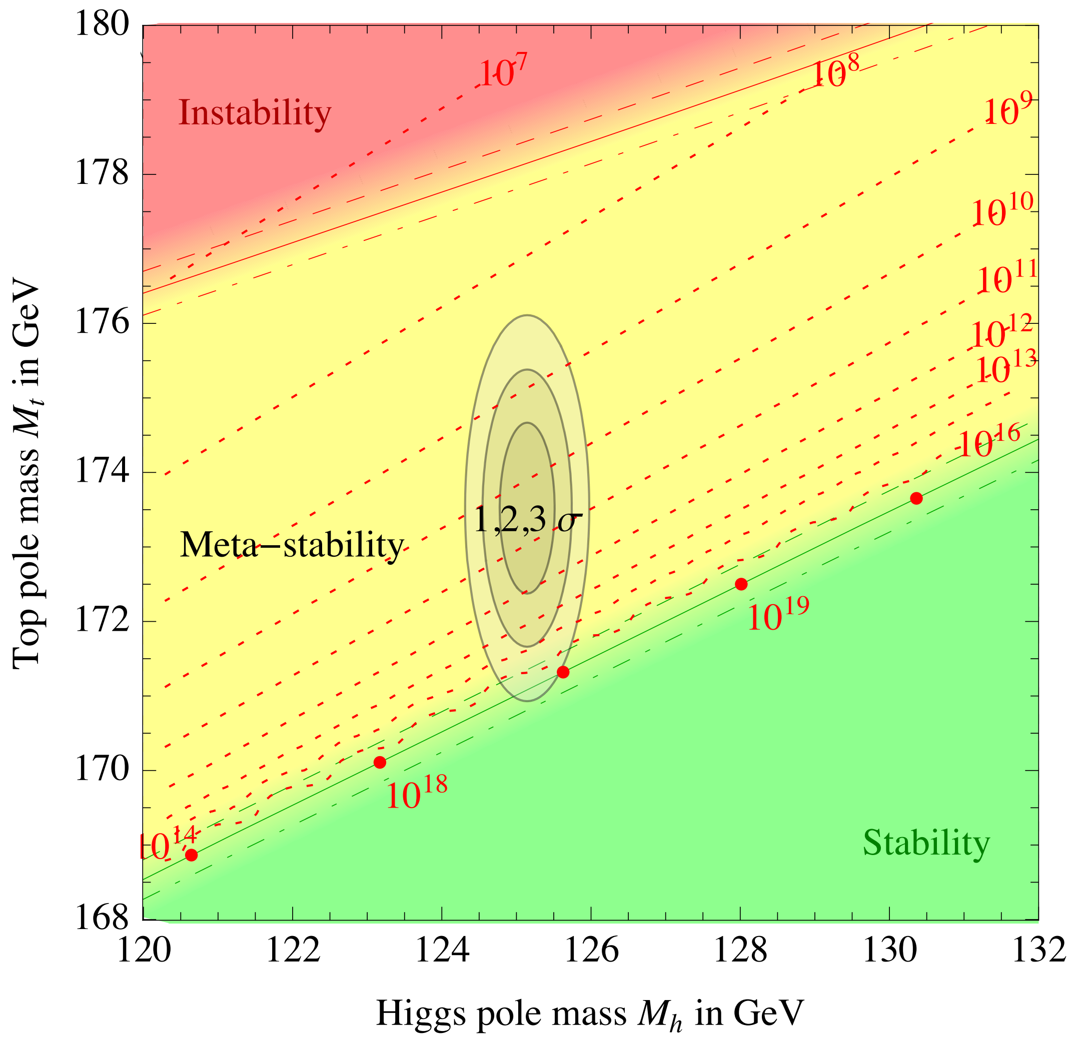

arXiv:1307.3536v4

Living On The Edge - The Tough Life Of A 125 GeV H Boson

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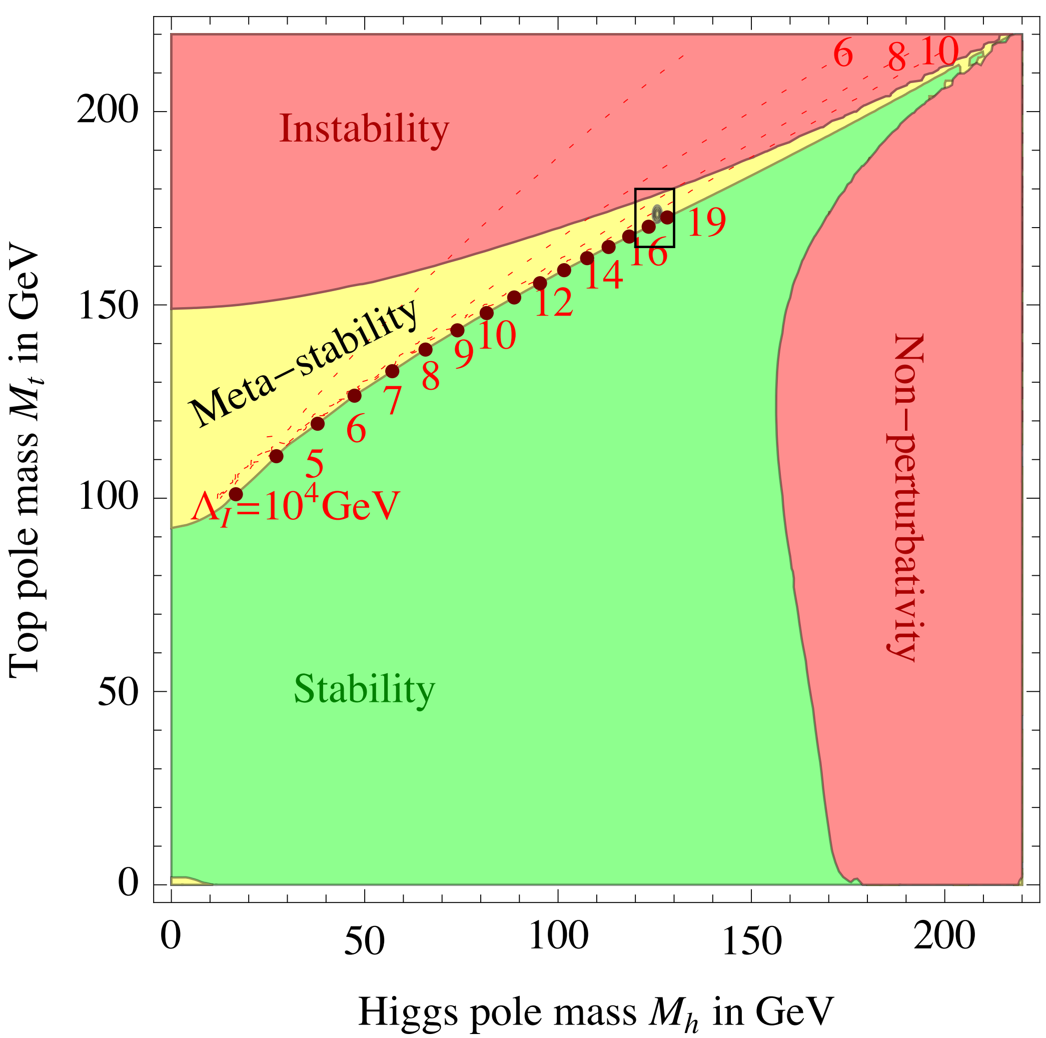
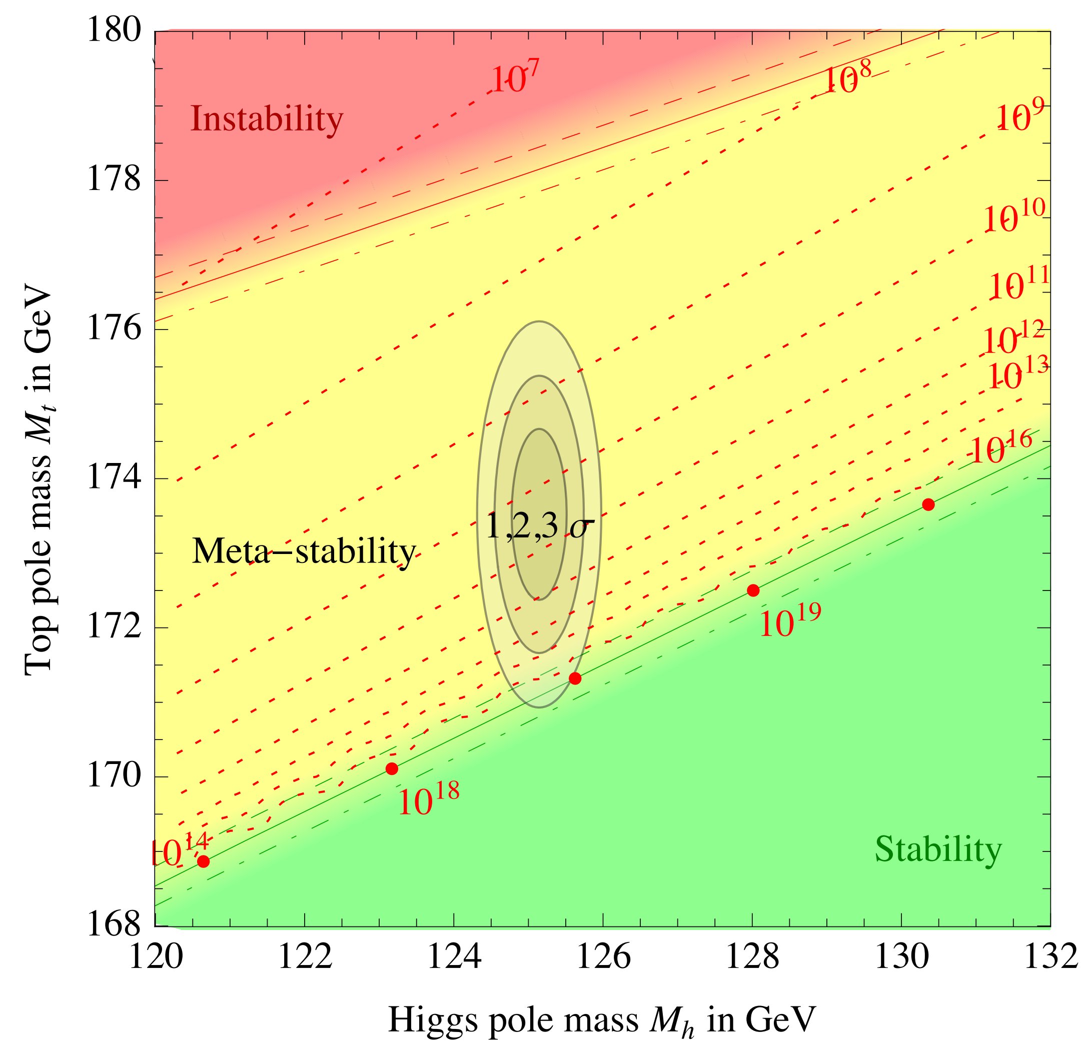




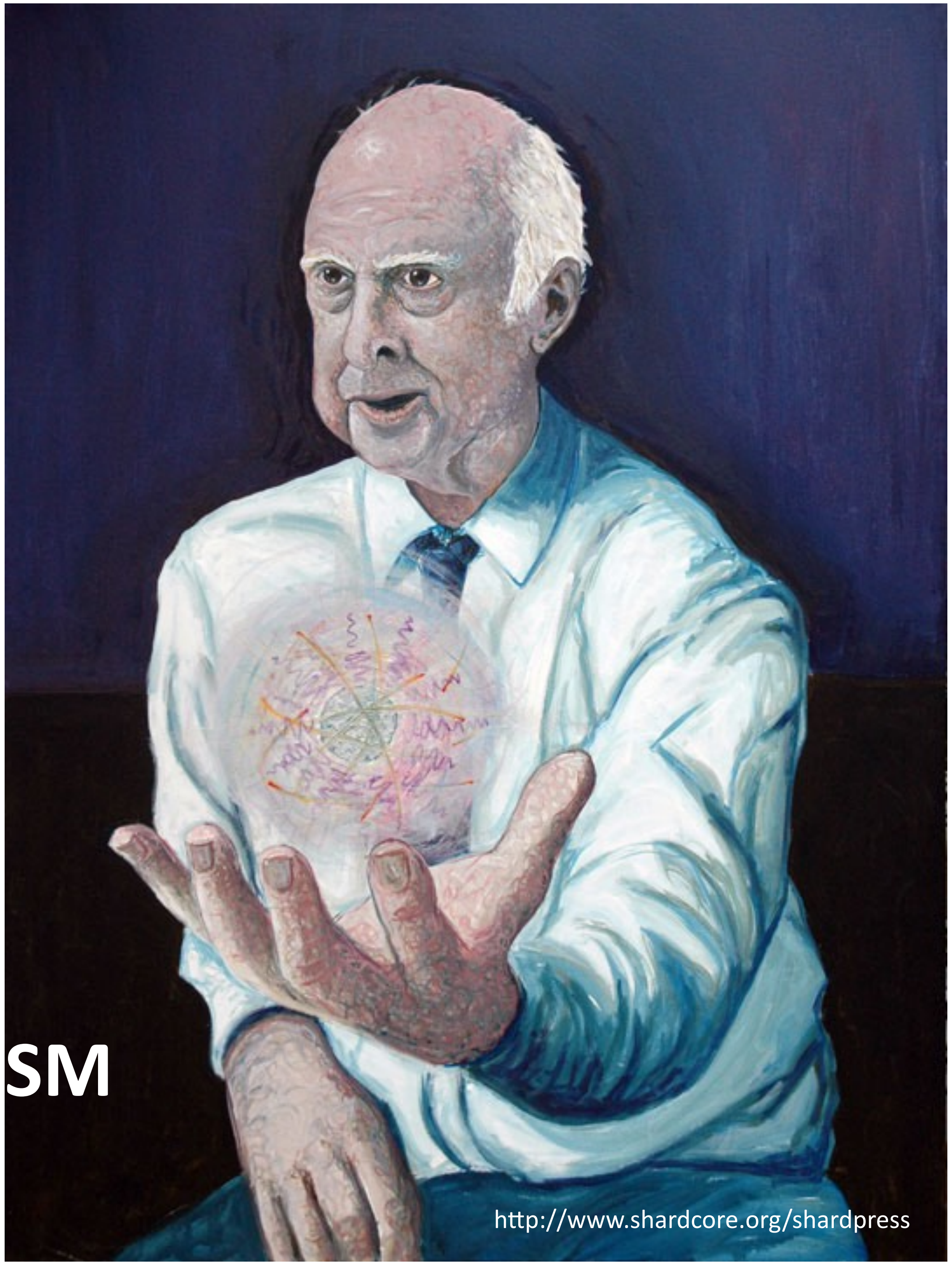
arXiv:1307.3536v4

Why is the Higgs sitting so close to criticality?

In the lab, critical systems are inevitably dragged away from critical point/line…

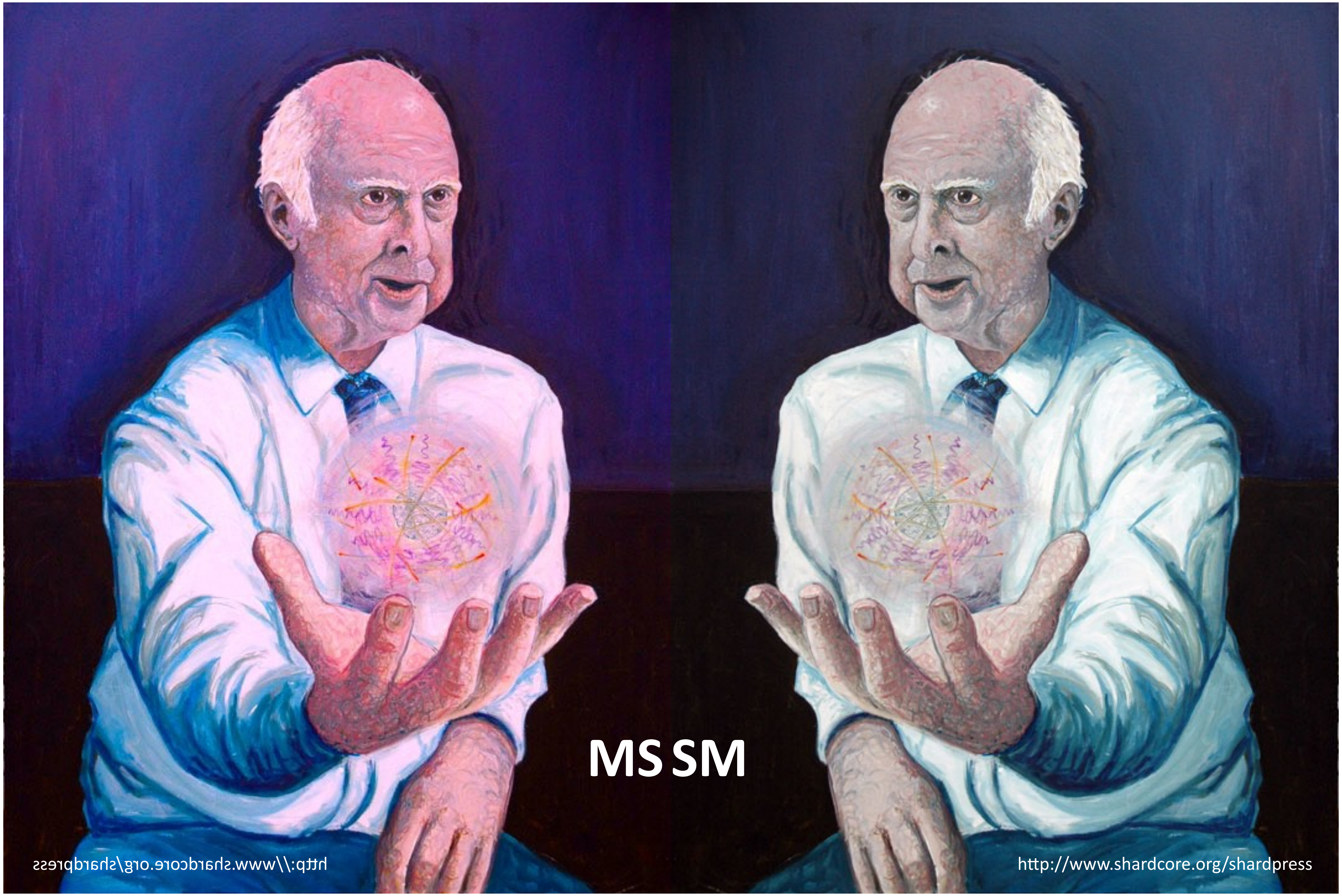
Enhanced Symmetry

Why the Higgs so close to criticality?



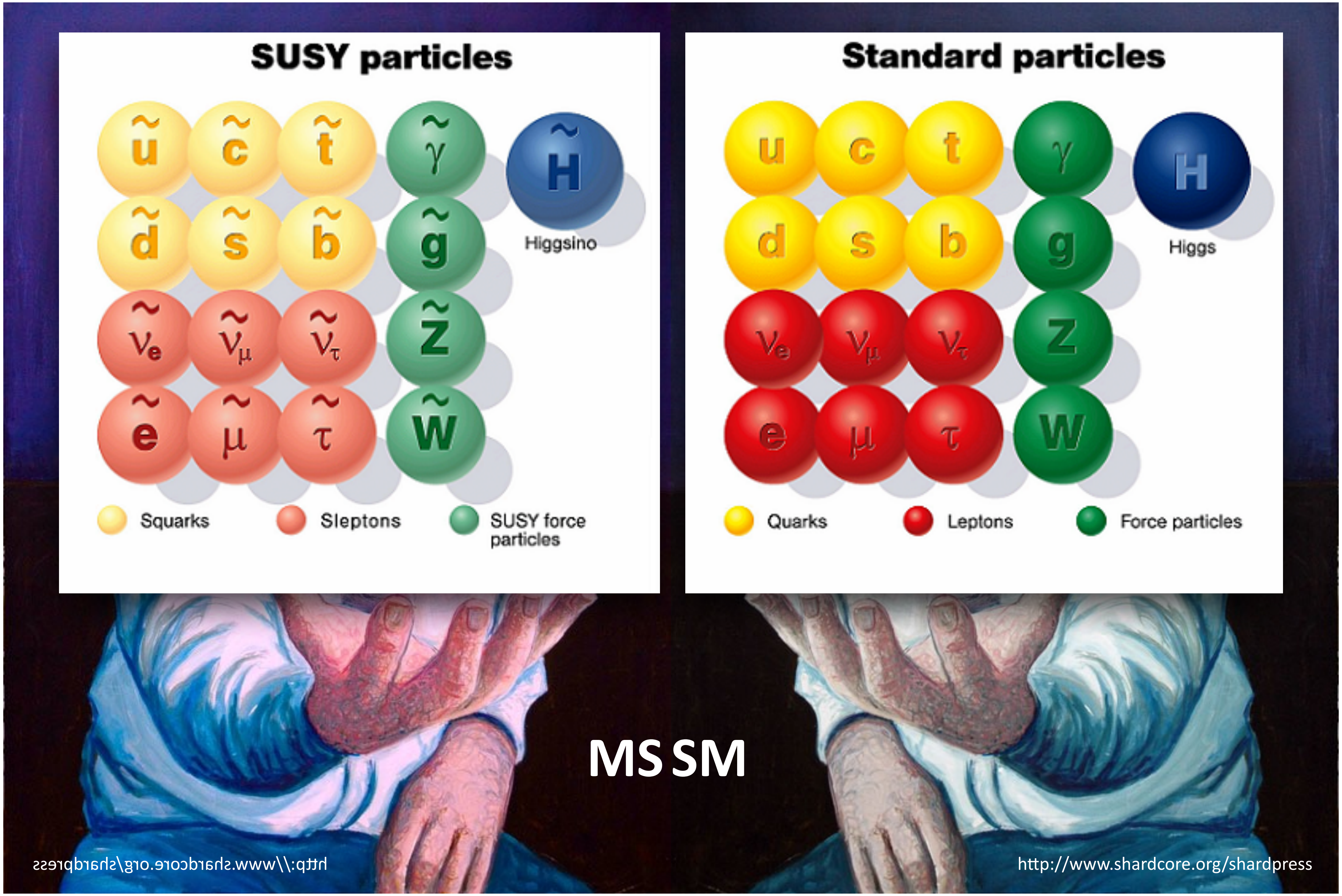
Enhanced Symmetry

Why the Higgs so close to criticality? ➠ Additional symmetry?

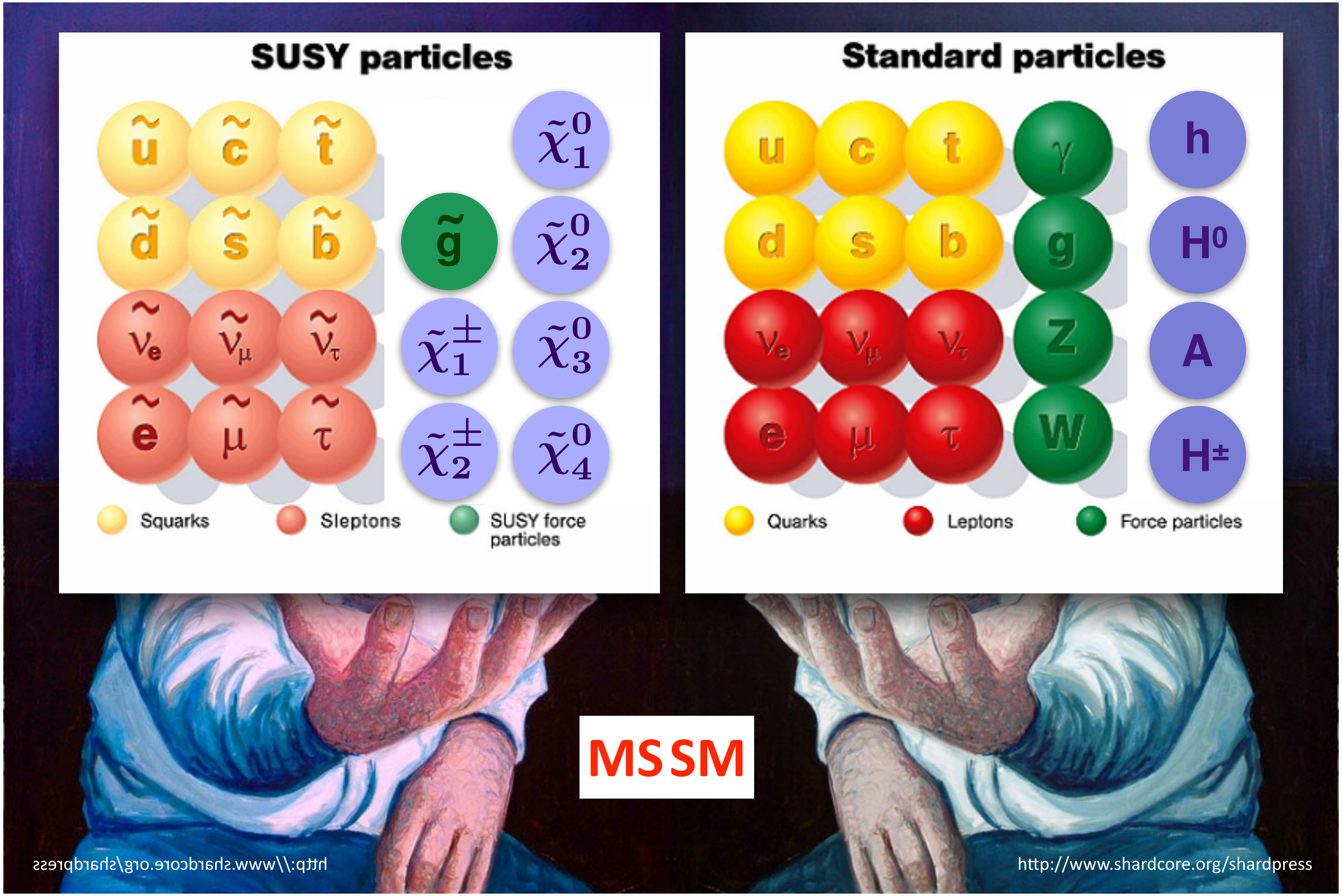


Supersymmetry

Why the Higgs so close to criticality? ➠ Additional symmetry?



Why the Higgs so close to criticality? ➠ Additional symmetry?

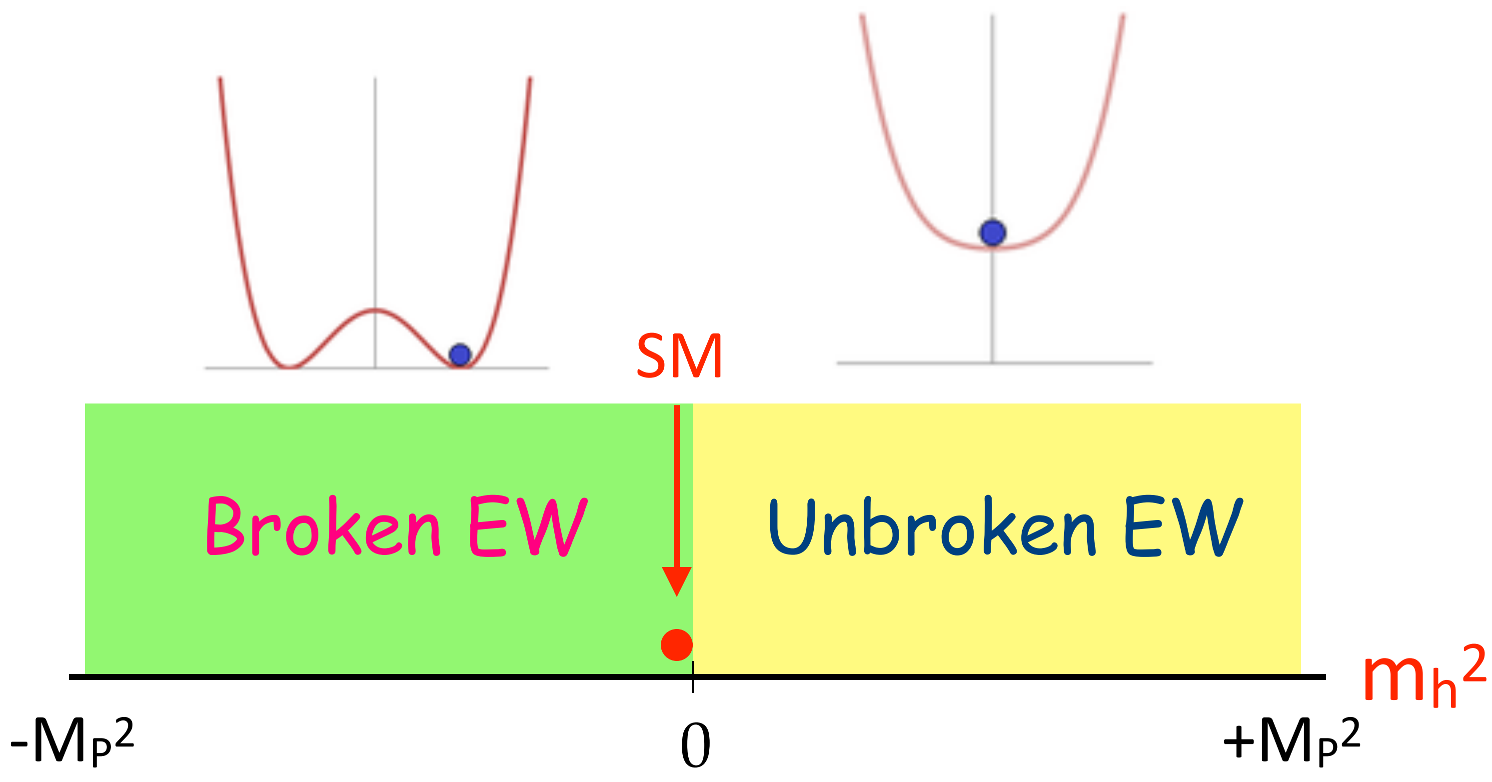


Higgs Naturalness As "Criticality" Condition

Why the Higgs so close to criticality? ➠ Additional symmetry?

Higgs Potential: $V(\phi) = m_h^2\,|\phi|^2 + \lambda\,|\phi|^4$

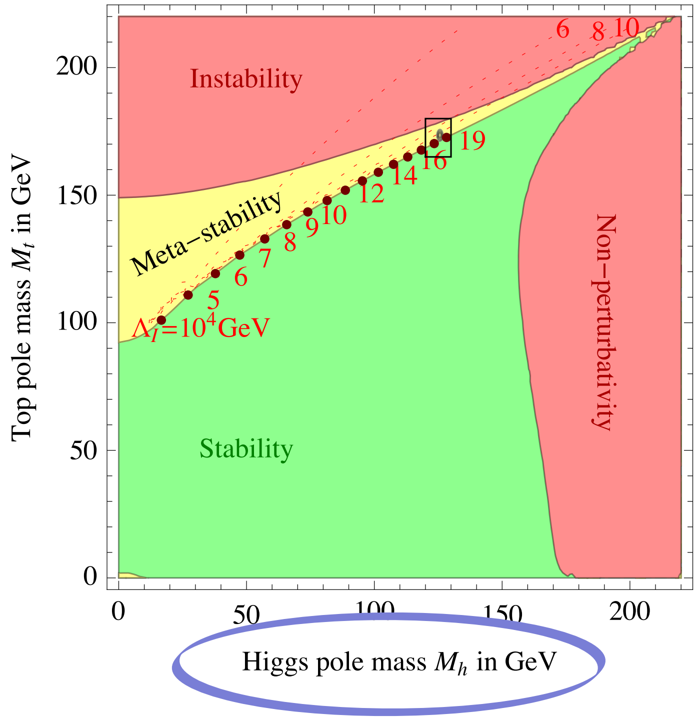
↳ $m^2>0$: symmetric phase; $m^2<0$: broken phase



SUSY predicts $m_h^2=0$; (softly) broken SUSY can allow $m_h^2 \lesssim 0$ ($v \cong 246$ GeV)

G. F. Giudice

Fine Tuning Vs Naturalness

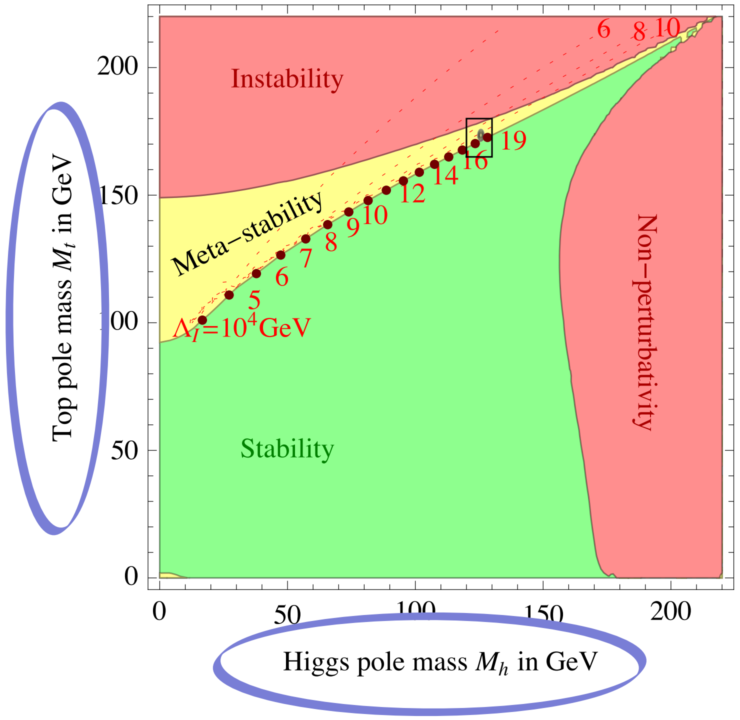


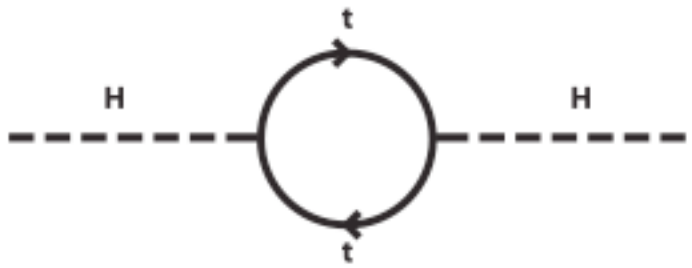
physical m_h: 125 GeV

$$m_h^2 \approx m_{h\,0}^2 - \frac{\lambda_f^2}{8\pi^2} N_c^f \int^{\Lambda} \frac{d^4p}{p^2} + \ldots \approx m_{h\,0}^2 + \frac{\lambda_f^2}{8\pi^2} N_c^f \Lambda^2 + \ldots$$

bare mass — 1-loop correction — ultraviolet cutoff

Fine Tuning Vs Naturalness





main "SM" term: top's loop ($\lambda_t \approx 1$)

physical m_h: 125 GeV

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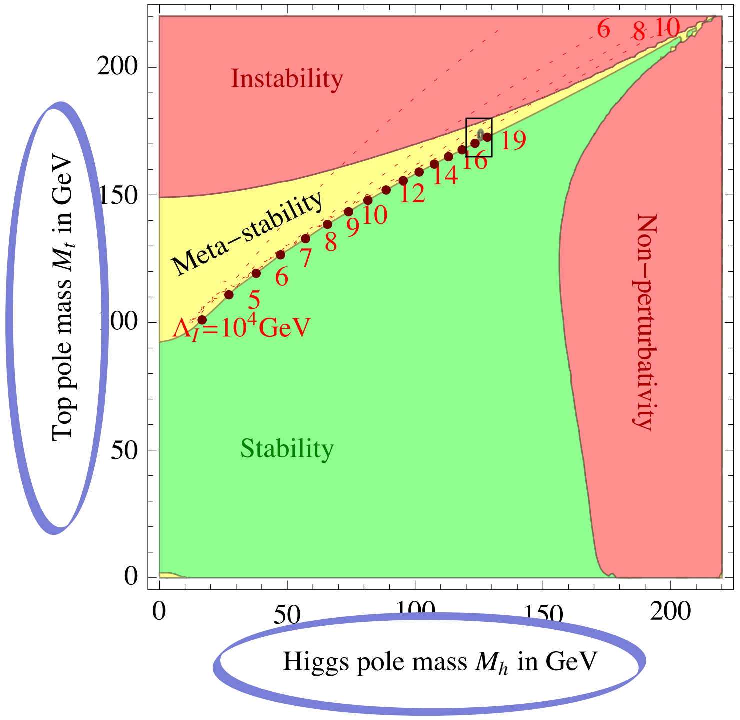
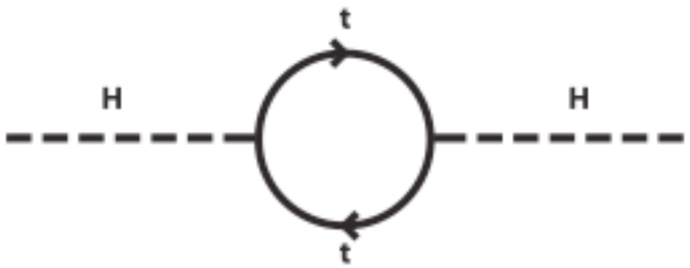
bare mass

1-loop correction

ultraviolet cutoff

Fine Tuning Vs Naturalness





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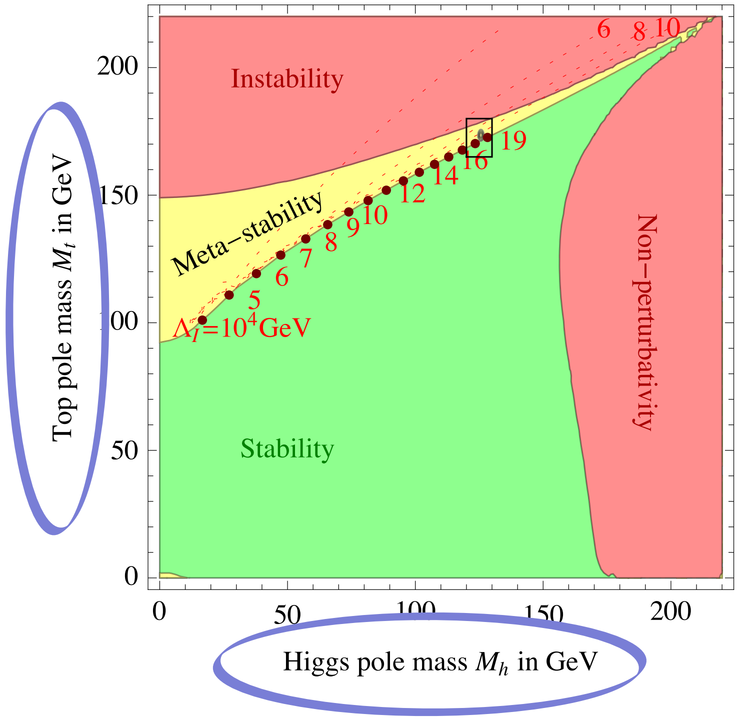
bare mass

1-loop correction

ultraviolet cutoff

***Fine tuning**: if Λ ≈ plank mass, need cancellation between bare mass and corrections across <u>many</u> orders of magnitude to get 125 GeV!*

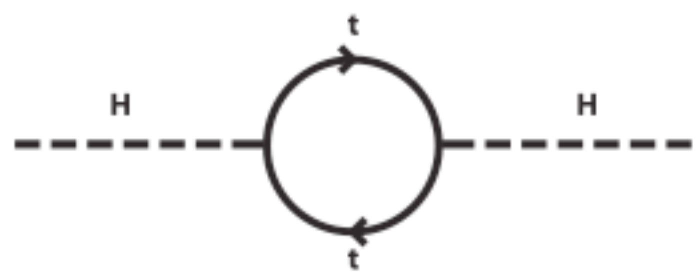
Fine Tuning Vs Naturalness



Hierarchy problem: SUSY's solution

stop's loop (opposite sign)

+



main "SM" term: top's loop ($\lambda_t \approx 1$)

physical m_h: 125 GeV

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bare mass

1-loop correction

ultraviolet cutoff

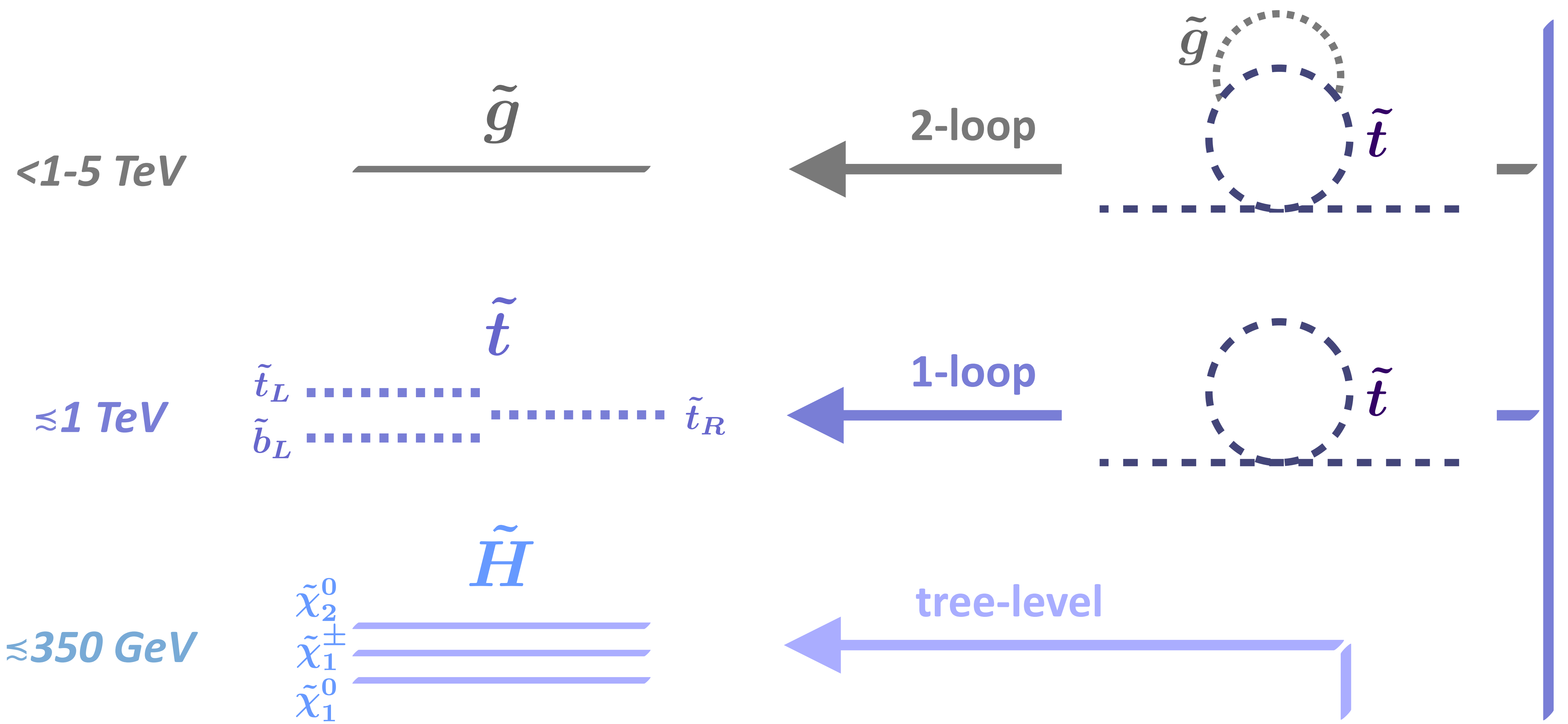
natural cancellation (*)

~~***Fine tuning**: if Λ ~ plank mass …*~~

(*) provided a light stop!

Natural SUSY Spectrum

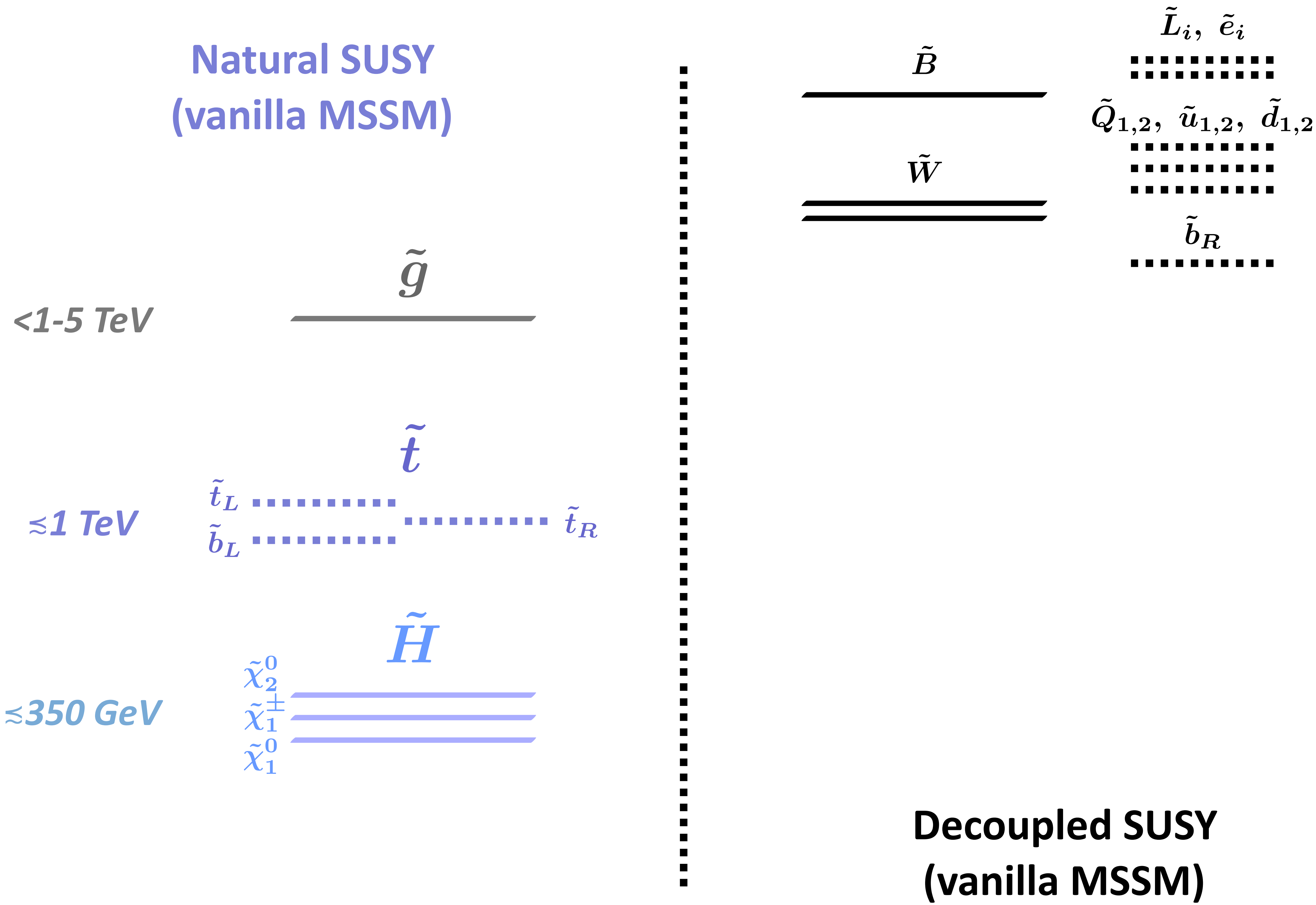
Natural SUSY (vanilla MSSM)



$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

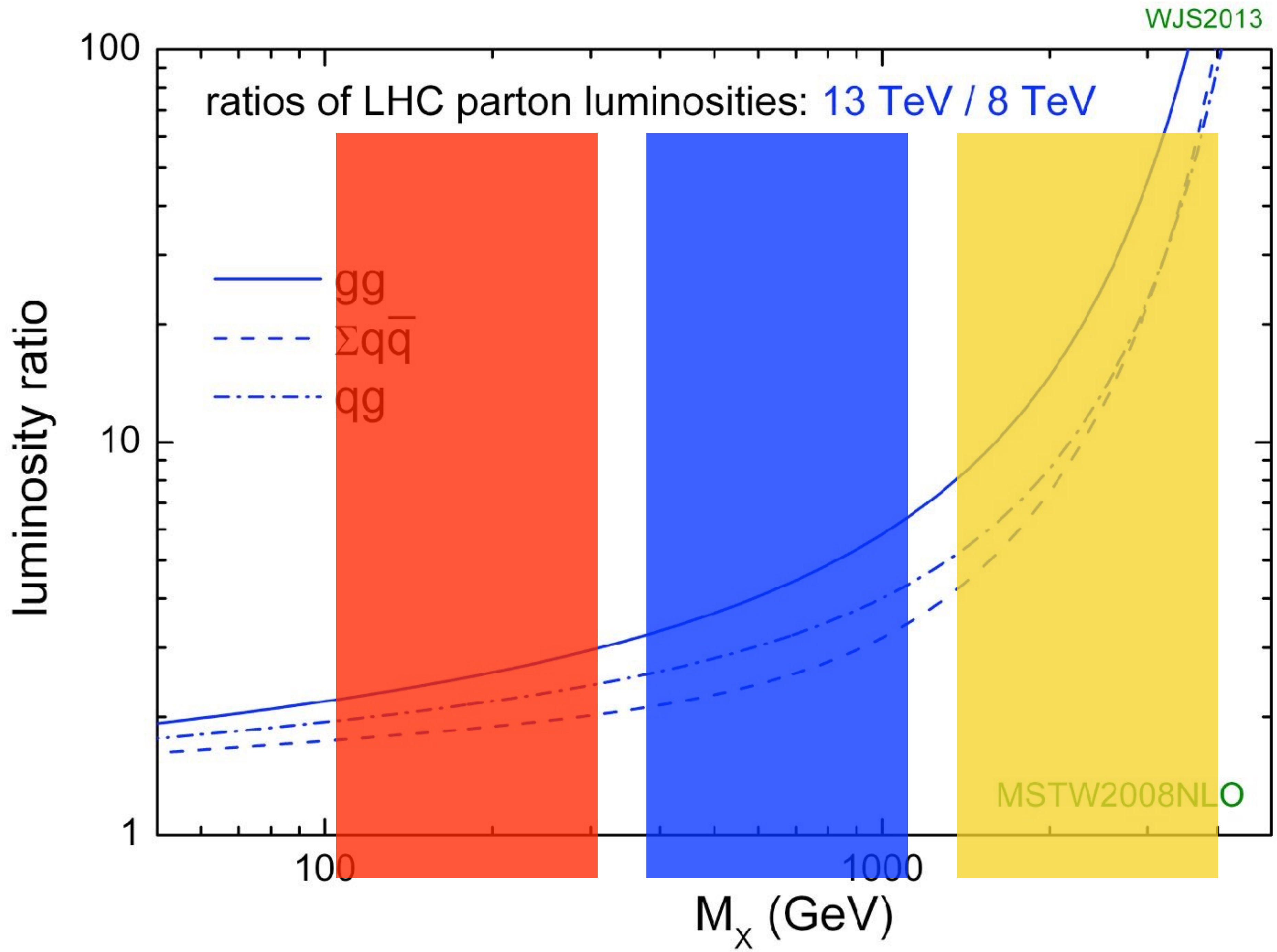
arXiv:1110.6926v1

Natural SUSY Spectrum



arXiv:1110.6926v1

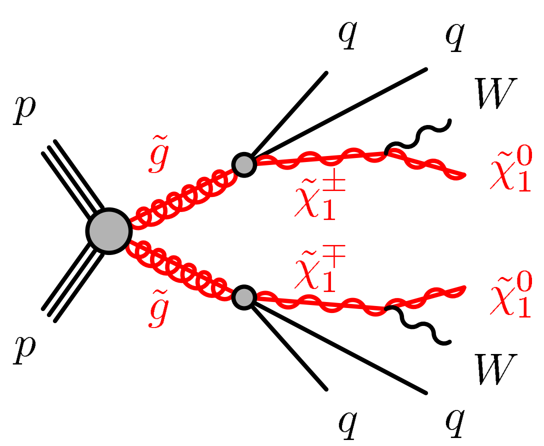
Hunting For SUSY @ √s=13 TeV



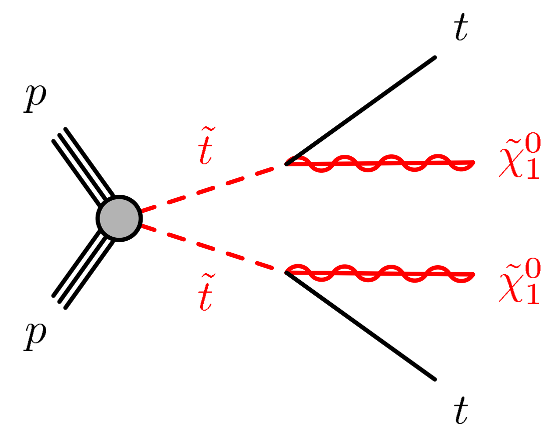
higgsinos / EWK-inos *scalar top* *gluinos / squarks*

SUSY After √s=7 & 8 TeV LHC

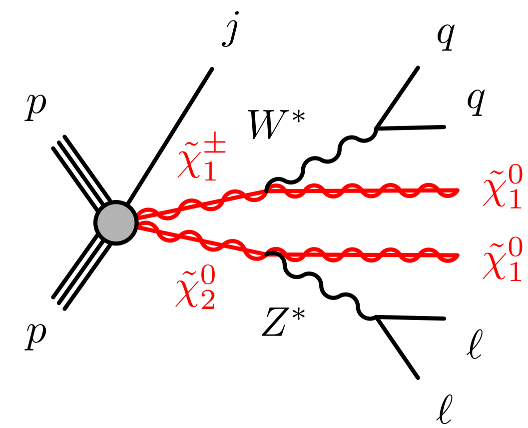
gluinos



scalar top



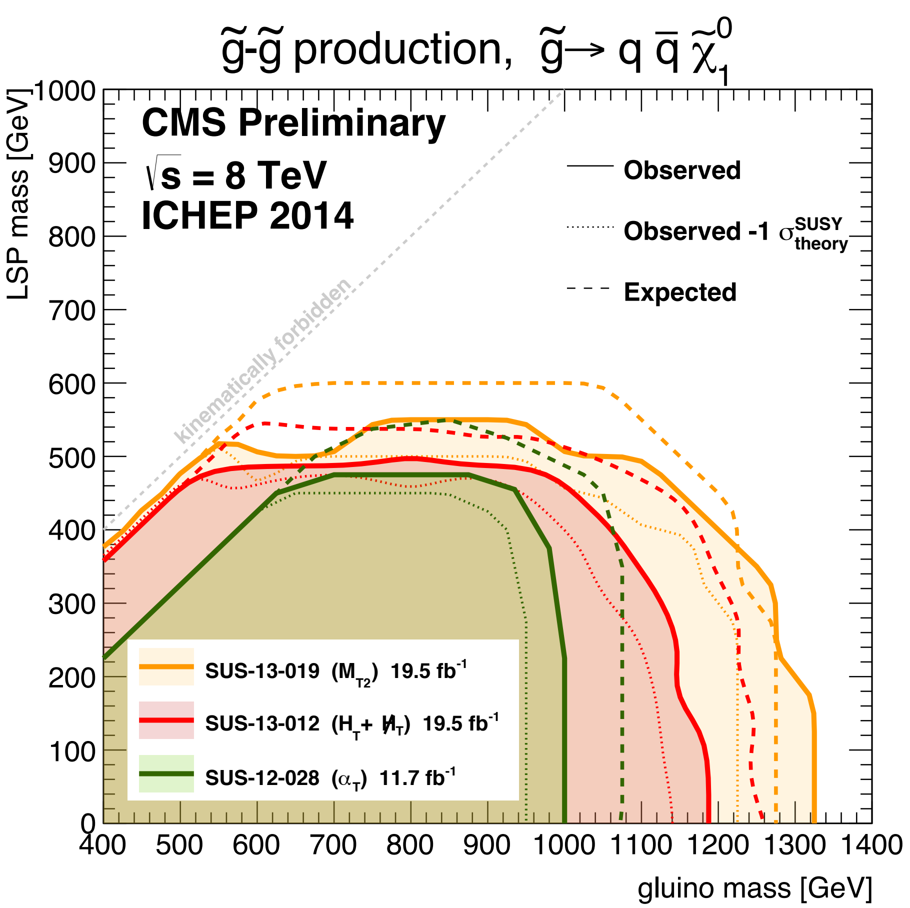
higgsinos

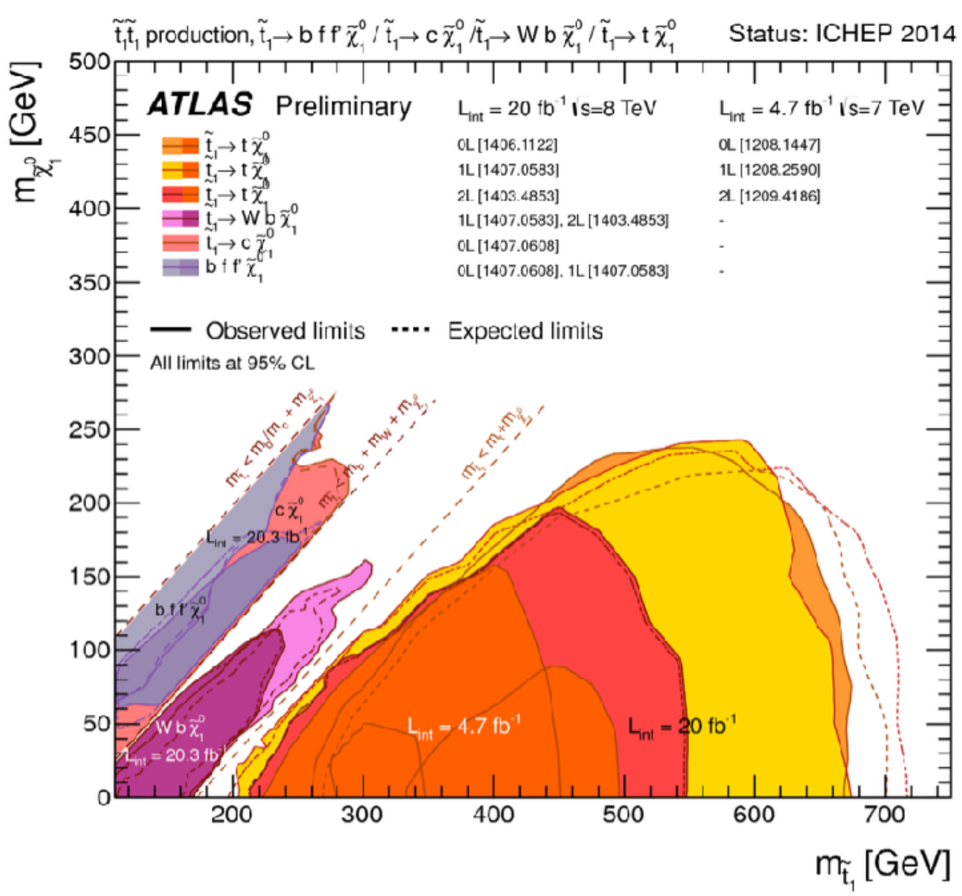


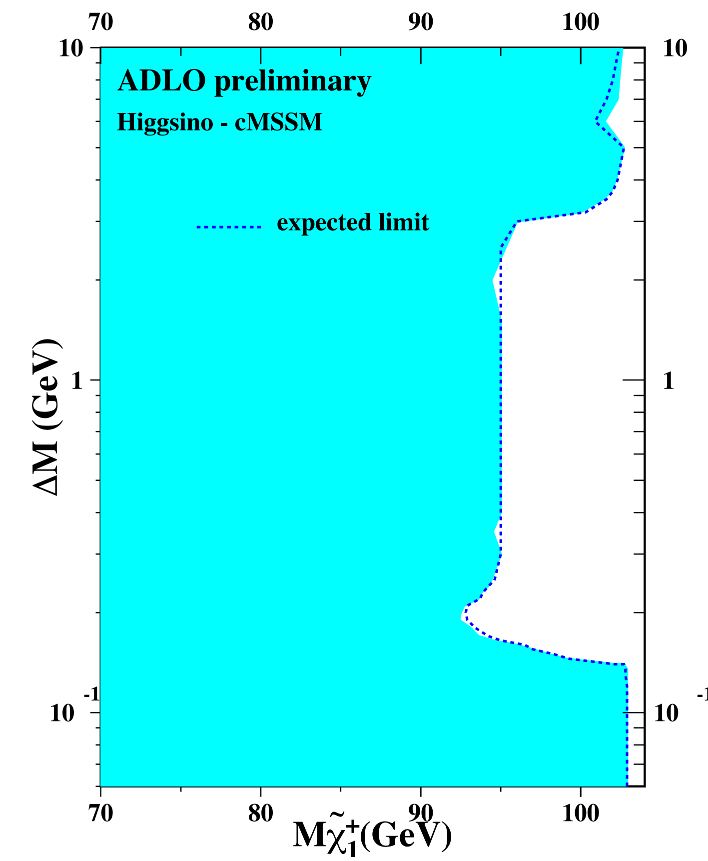
excluded m<1.3 TeV

excluded m<650 GeV

excluded m<110 GeV

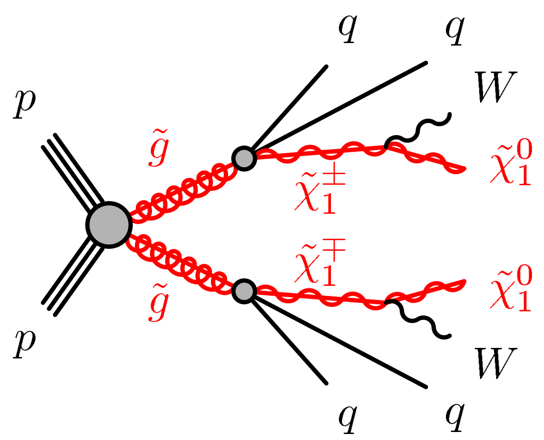




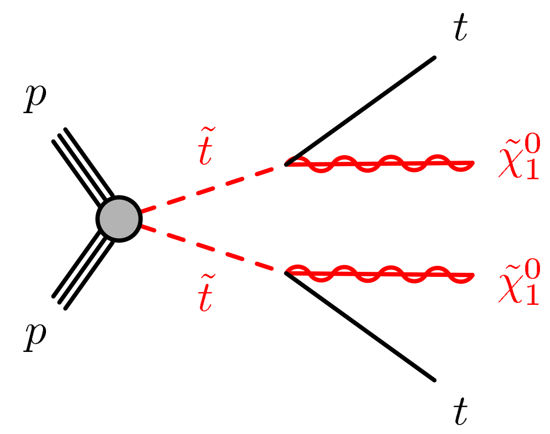


SUSY After √s=7 & 8 TeV LHC

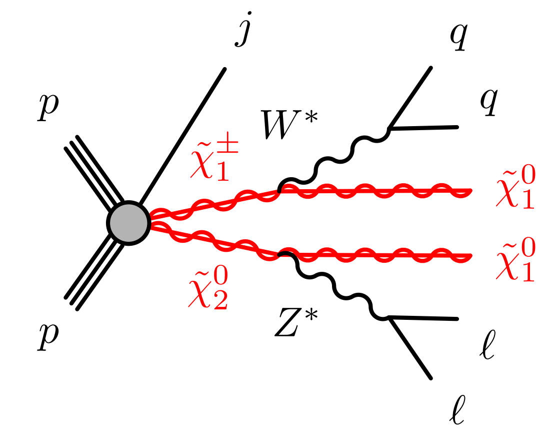
gluinos



scalar top

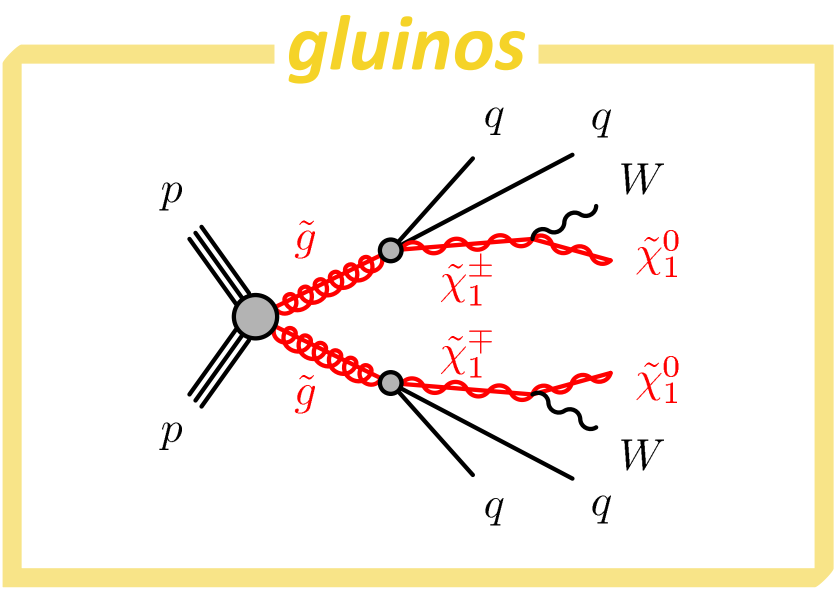


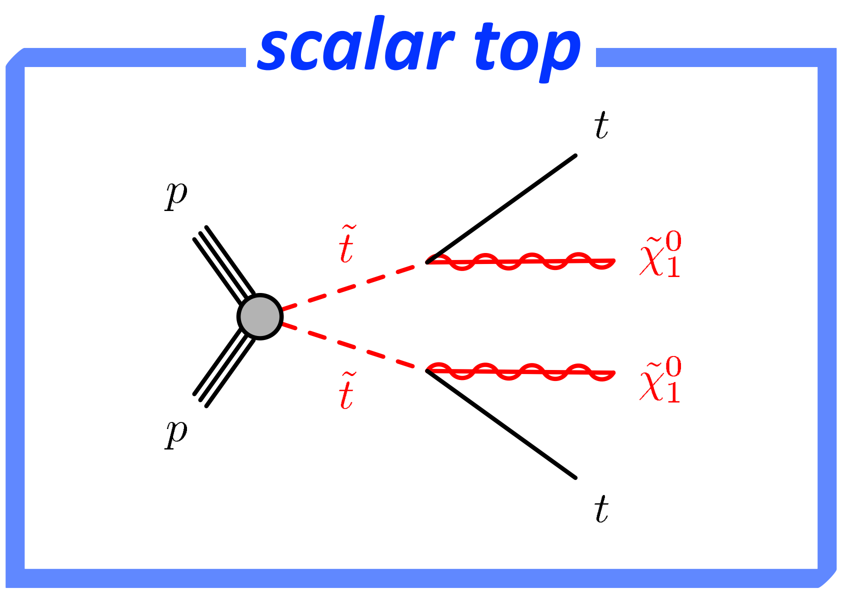
higgsinos

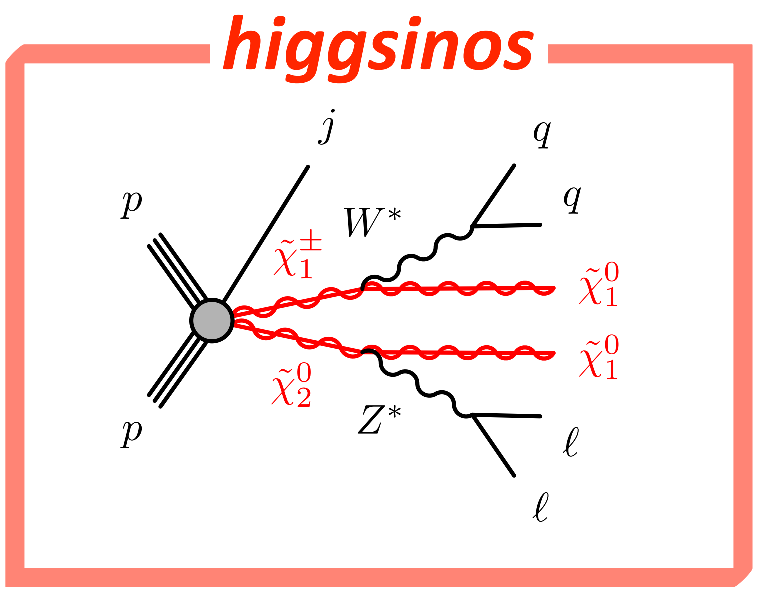


Simplified models **to cope with complex, model-dependent phenomenology**

SUSY After √s=7 & 8 TeV LHC



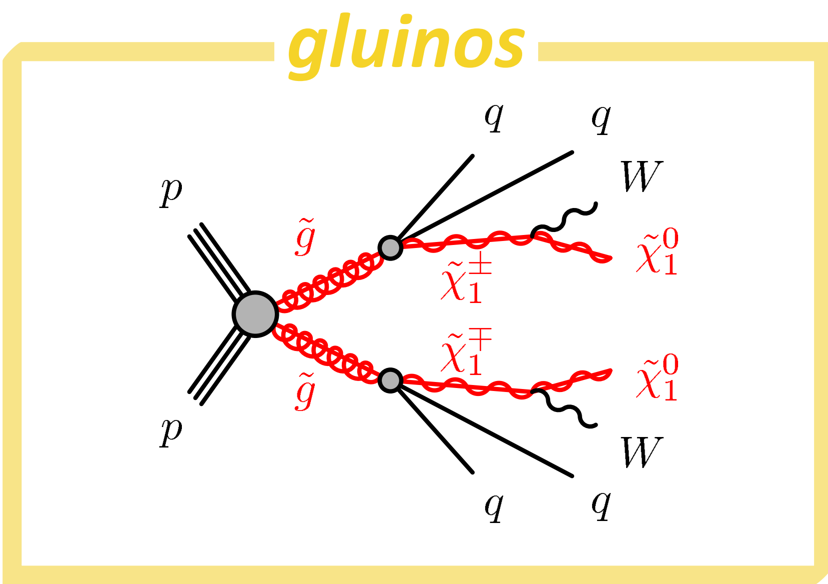


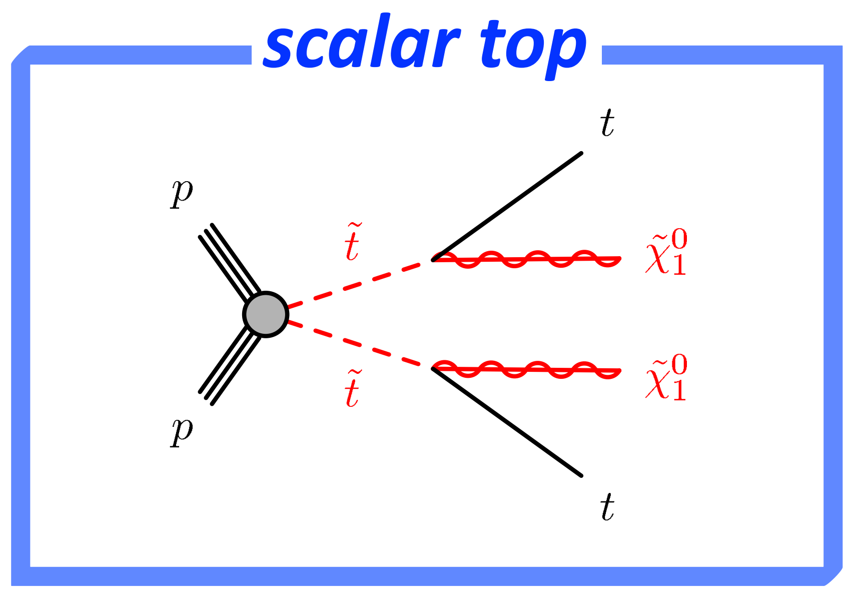


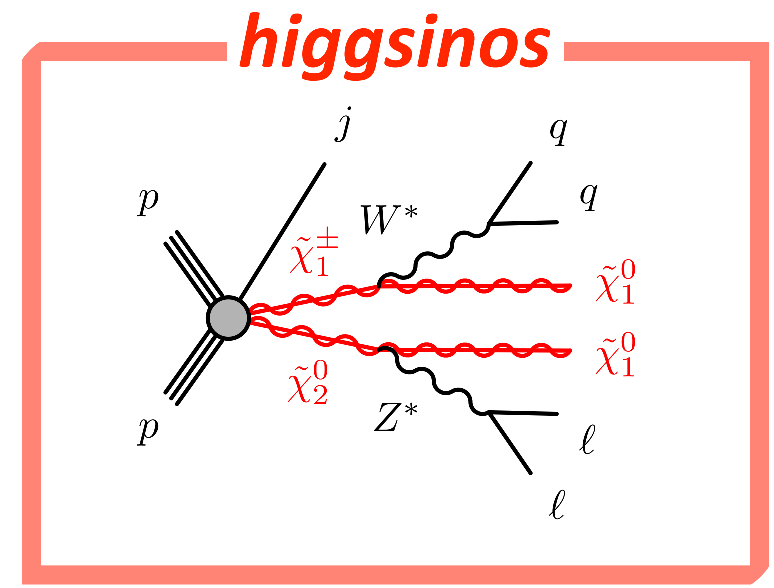
Simplified models **to cope with complex, model-dependent phenomenology**

branching ratios in decay vertices **set to 100%** (except for SM particles)

SUSY After √s=7 & 8 TeV LHC







Simplified models **to cope with complex, model-dependent phenomenology**

branching ratios in decay vertices **set to 100%** (except for SM particles)

"R-parity" conservation assumed: SUSY particles produced in pairs, and lightest neutralino doesn't decay: dark matter candidate!

(models with"R-parity" violation not covered in this talk)

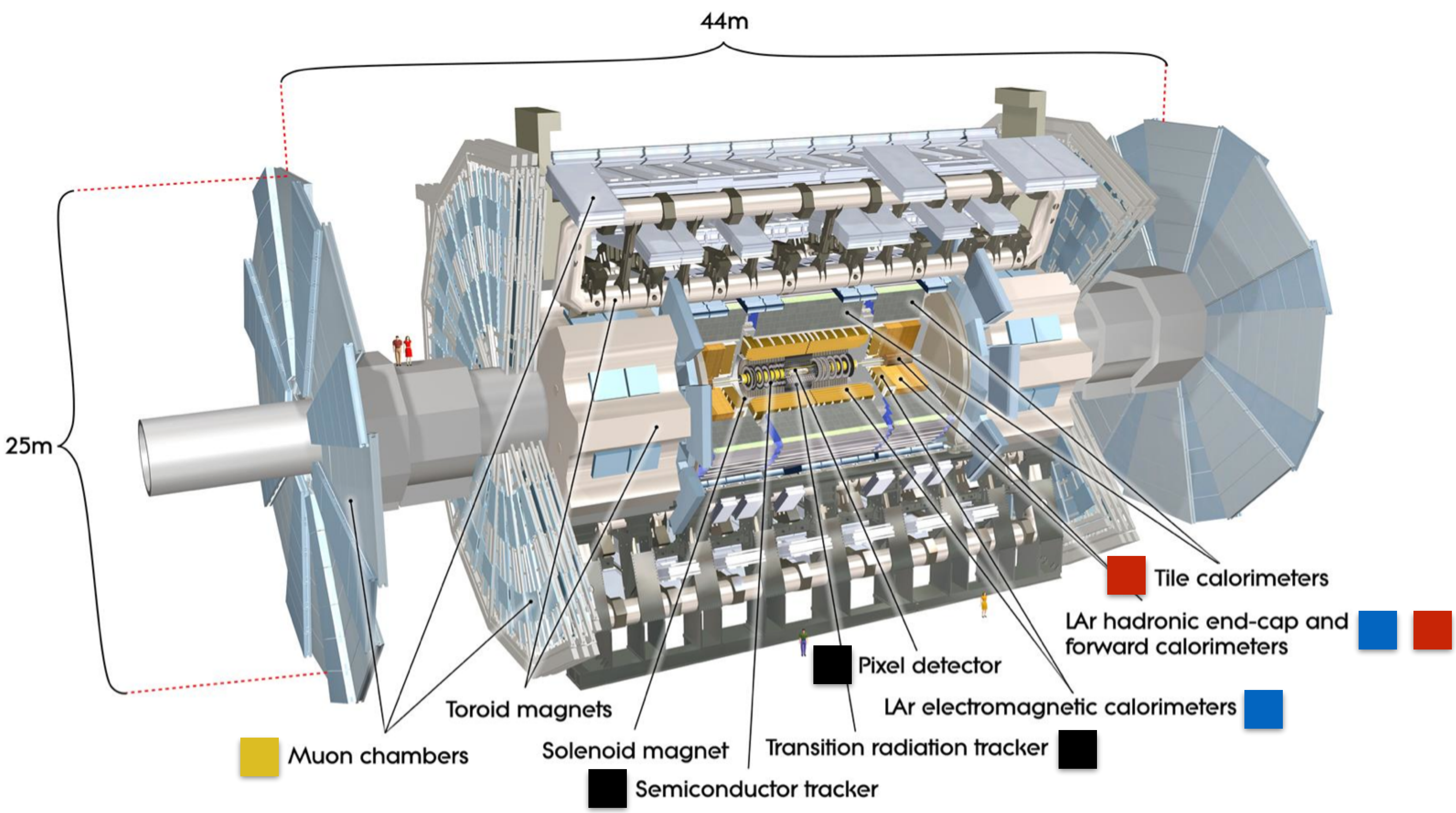
The ATLAS Detector

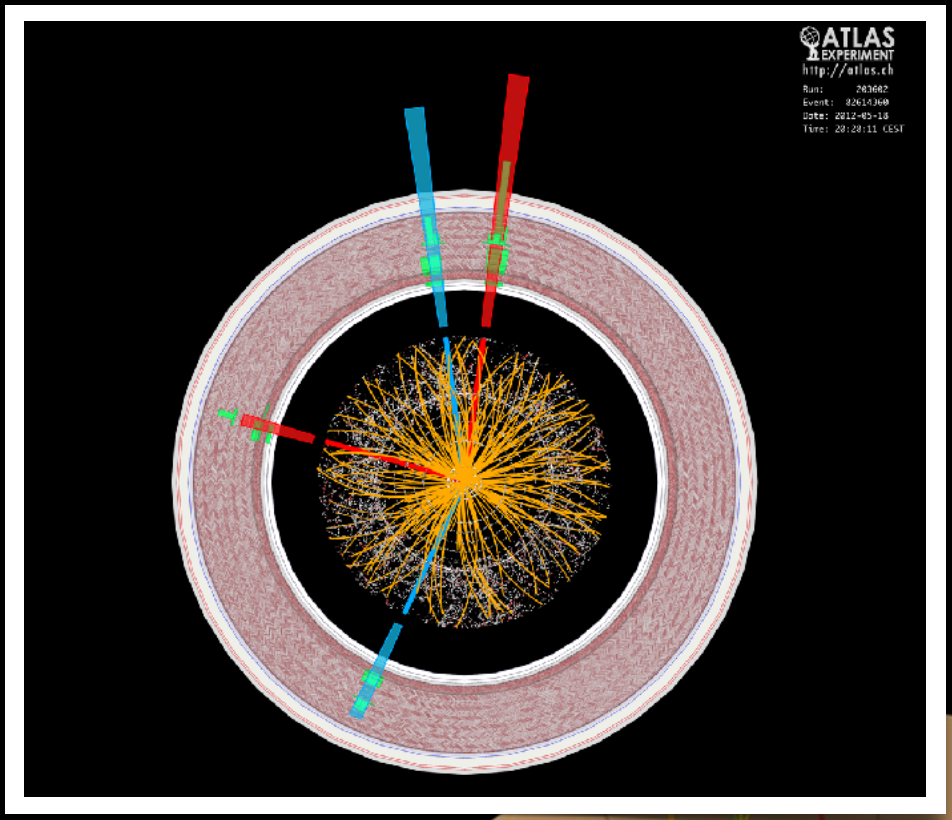
Inner detector (ID): tracks ➟ charged particles & vertices

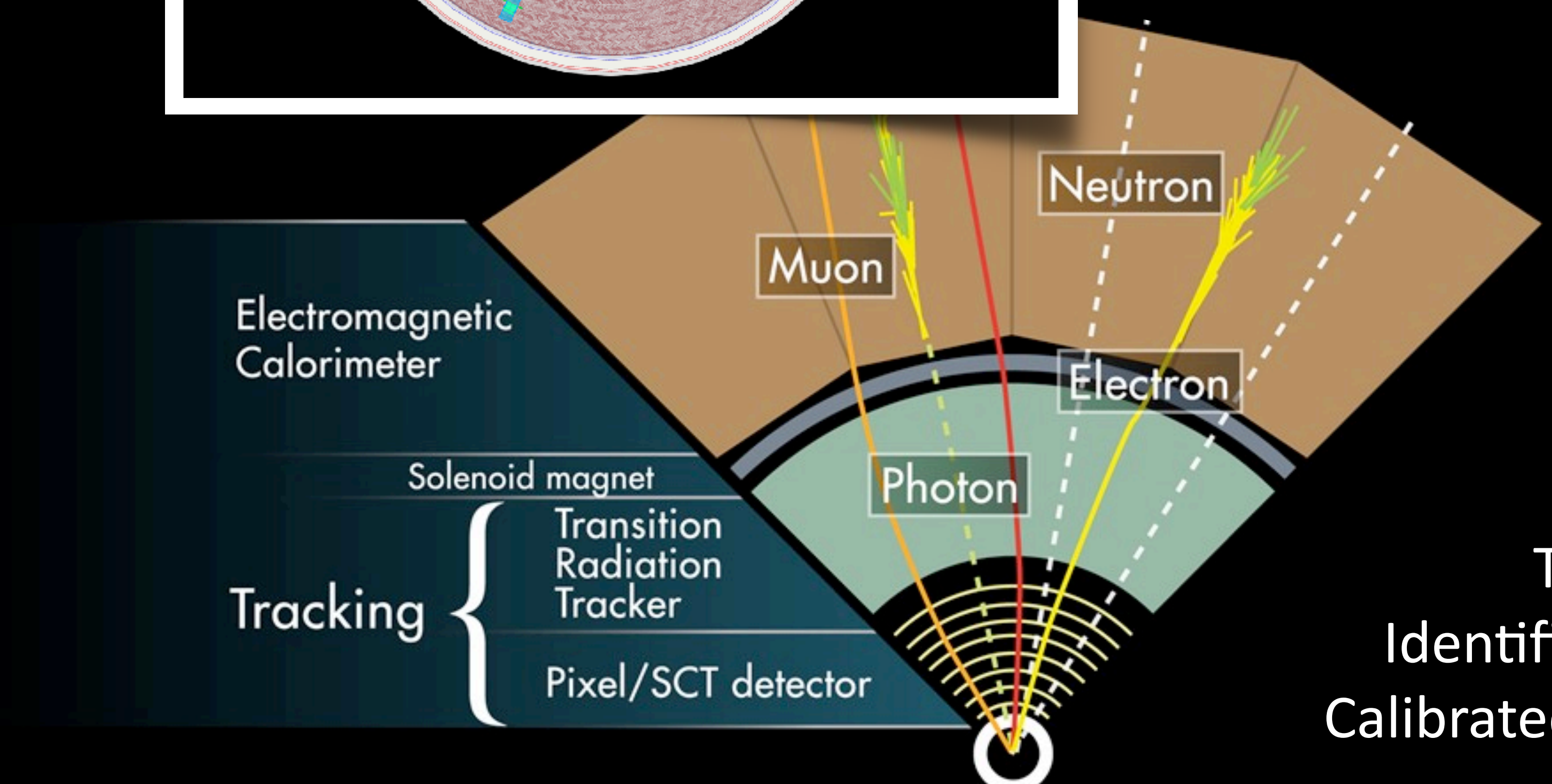
EM calorimeter: energy depositions ➟ electrons and photons

Hadronic calorimeter: energy depositions ➟ jets of hadrons

Muon spectrometer (MS): tracks ➟ muons





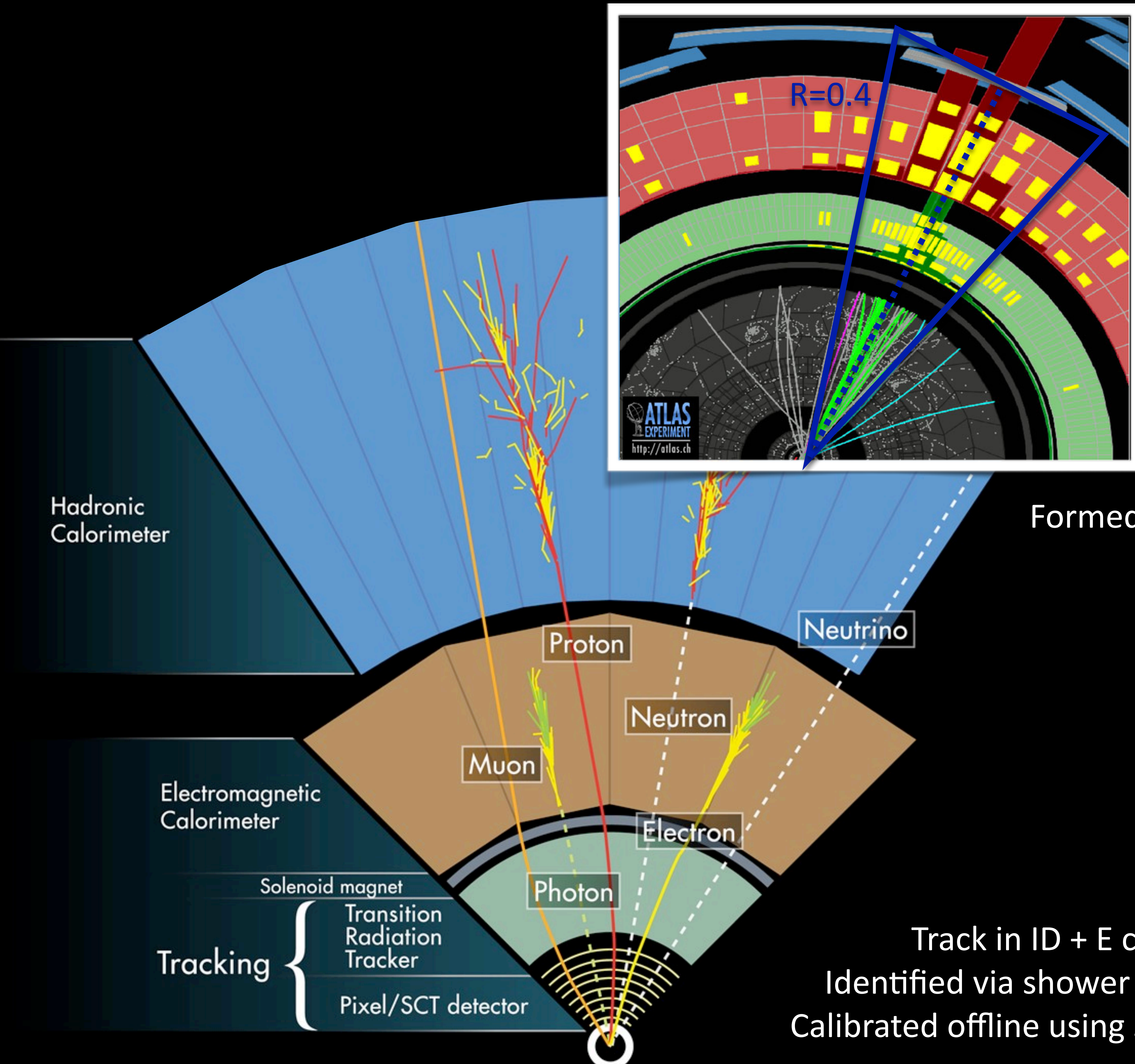


Electrons

Track in ID + E cluster in EM calorimeter

Identified via shower shape + radiation in TRT

Calibrated offline using standard candles (J/Ψ,Z)



Jets of hadrons

Formed from energy clusters in EM + HAD calorimeters

(anti-k_T R=0.4)

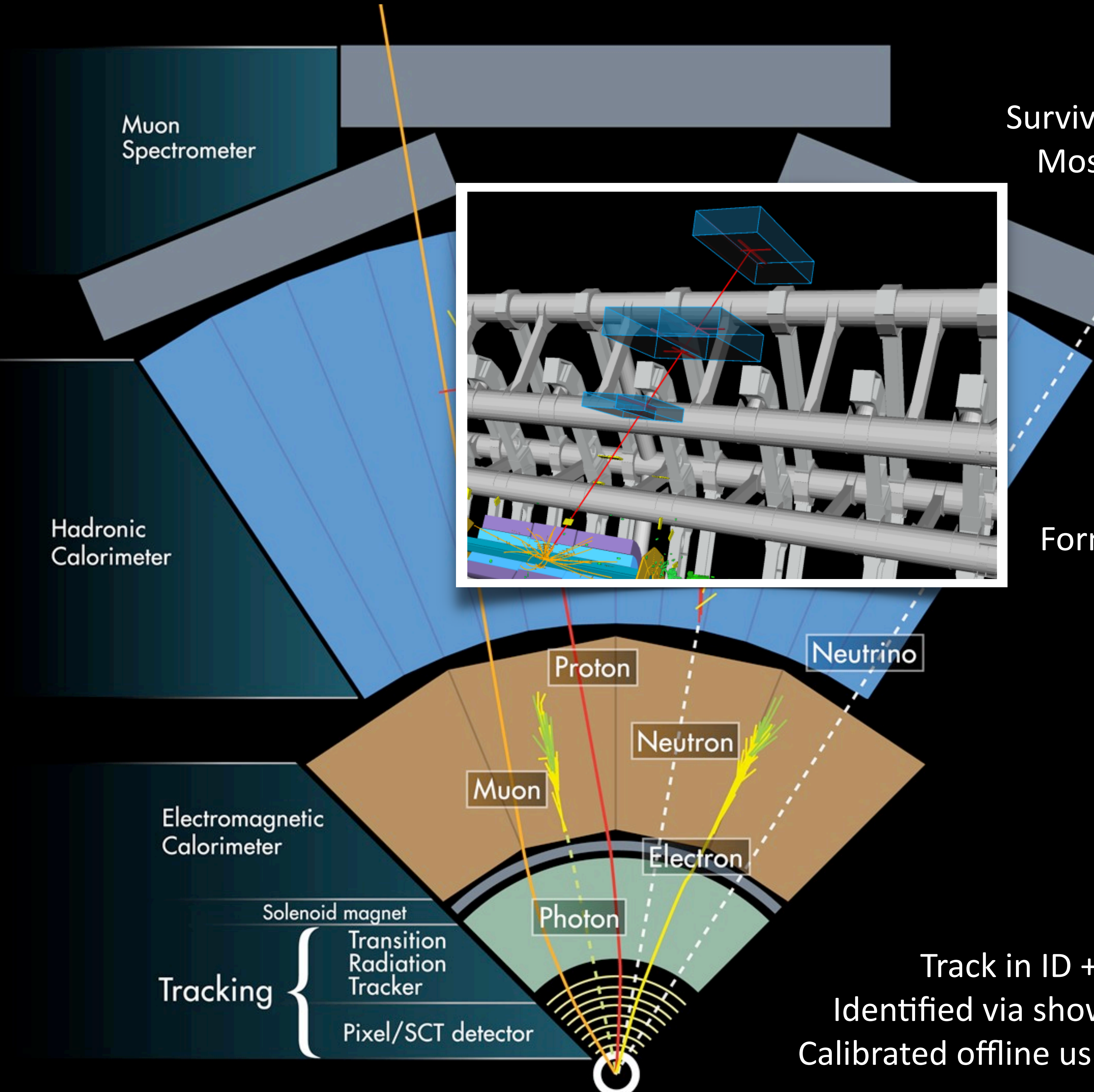
Calibrated offline

Electrons

Track in ID + E cluster in EM calorimeter

Identified via shower shape + radiation in TRT

Calibrated offline using standard candles (J/Ψ,Z)



Muons

Survive calorimeters - E_{loss}≈3 GeV
Mostly formed as ID +MS tracks
Calibrated offline (J/Ψ,Z)

Jets of hadrons

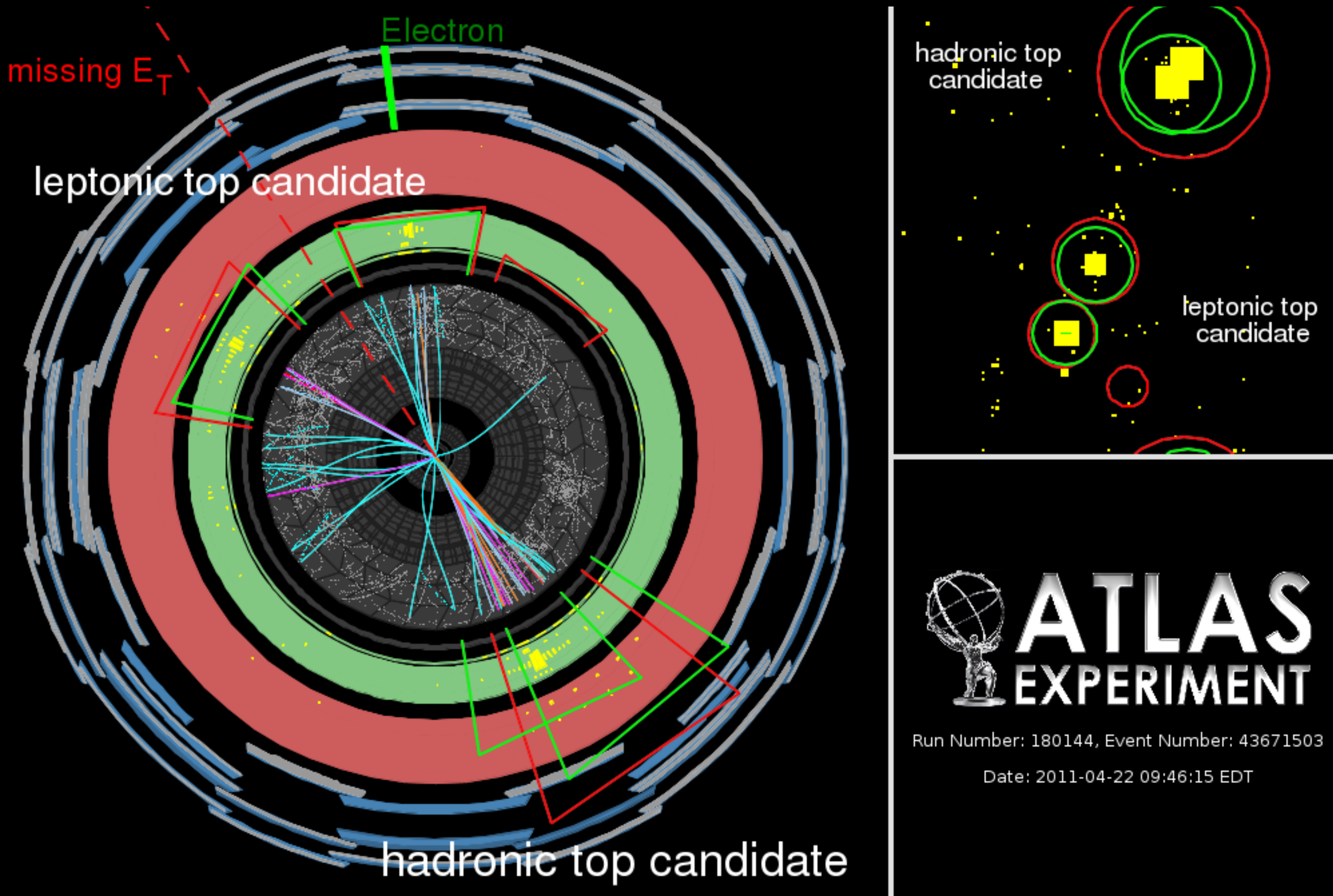
Formed from energy clusters in EM + HAD calorimeters
(anti-k_T R=0.4)
Calibrated offline

Electrons

Track in ID + E cluster in EM calorimeter
Identified via shower shape + radiation in TRT
Calibrated offline using standard candles (J/Ψ,Z)

Missing transverse energy: $\not{E}_T = |\vec{p}_{T,miss}|$

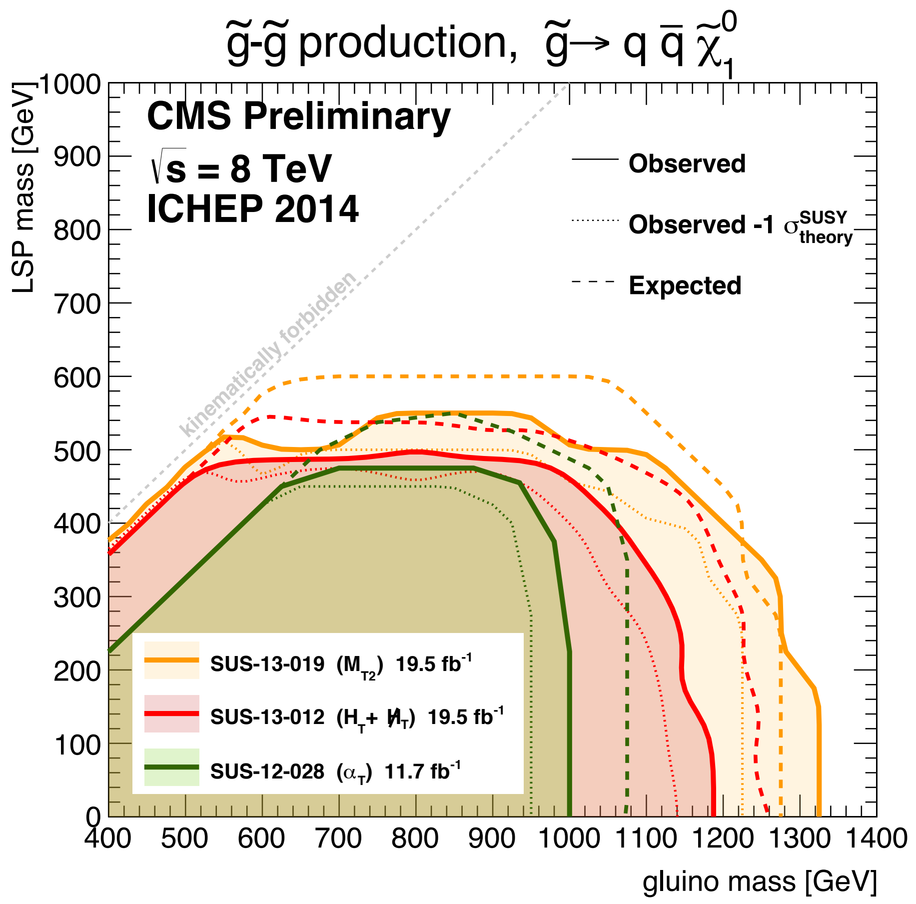
negative vector sum of transverse momenta of all reconstructed & identified particles + all remaining tracks



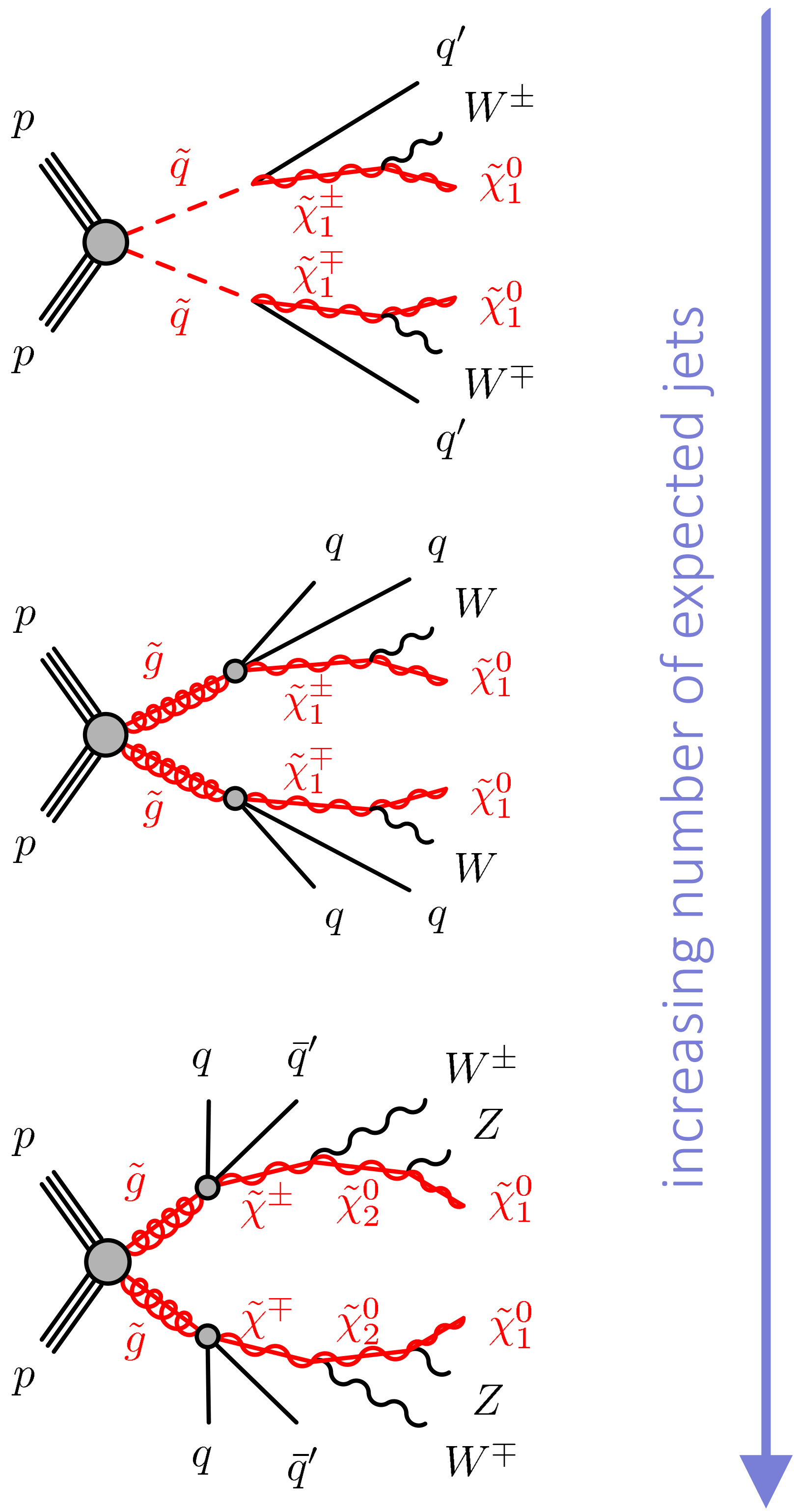
Hunting for Natural SUSY at the LHC

Part I - The Gluinos

Excluded up to 1.3 TeV after the LHC run1

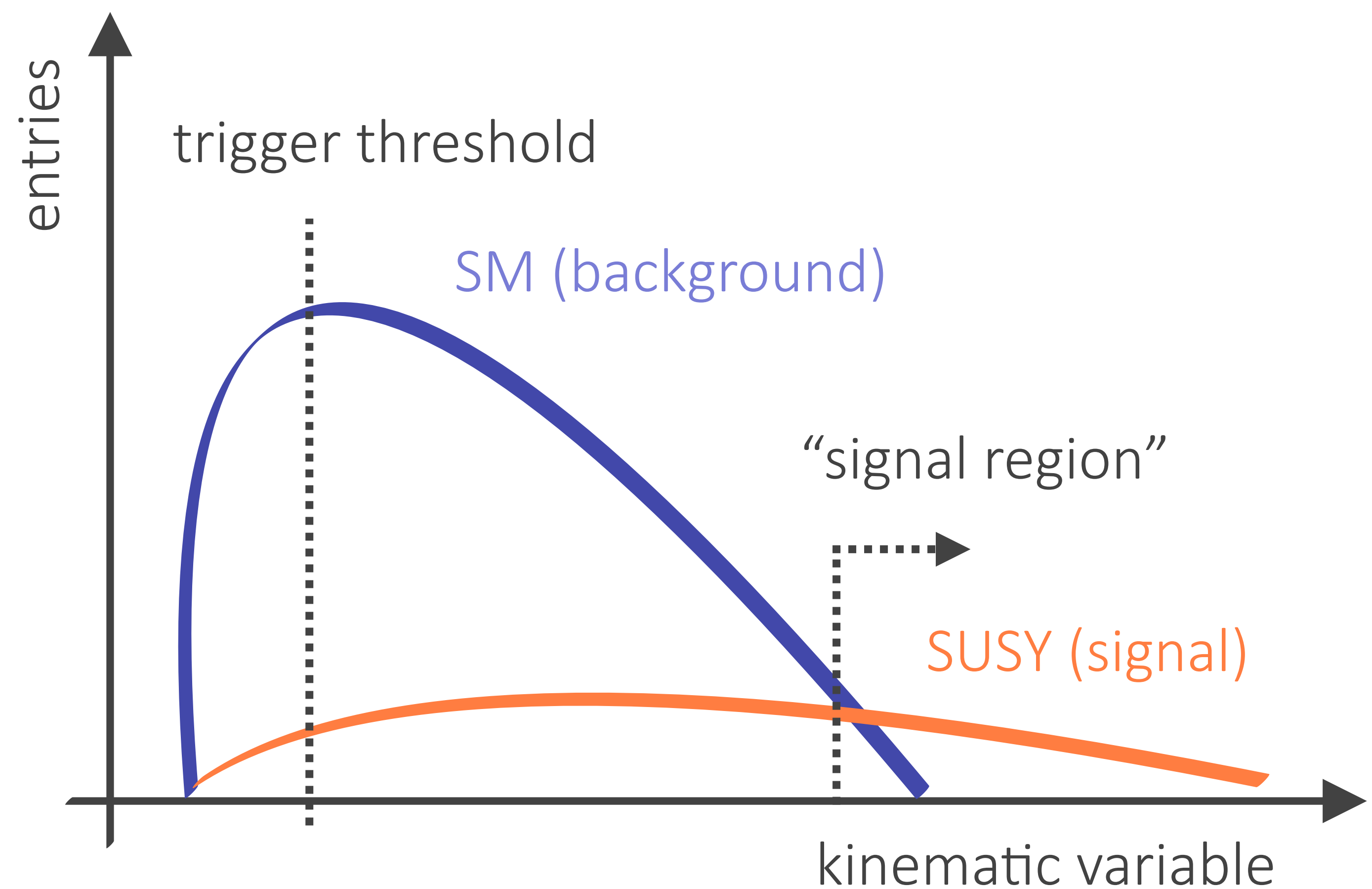


Hunting Gluinos & Squarks

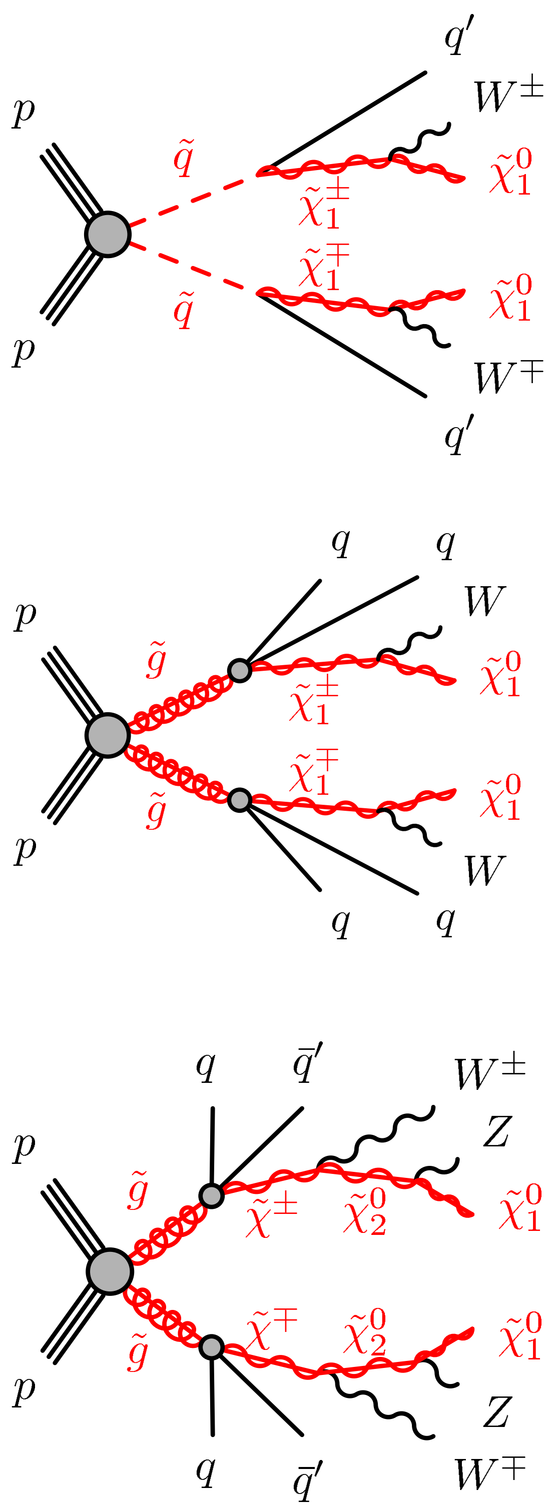


Select interesting events:

- one electron or muon from $W \to \ell\nu$ decay
- many jets from gluinos/squarks decay chain
- large E_T^{miss} from undetected neutralinos



Hunting Gluinos & Squarks



increasing number of expected jets

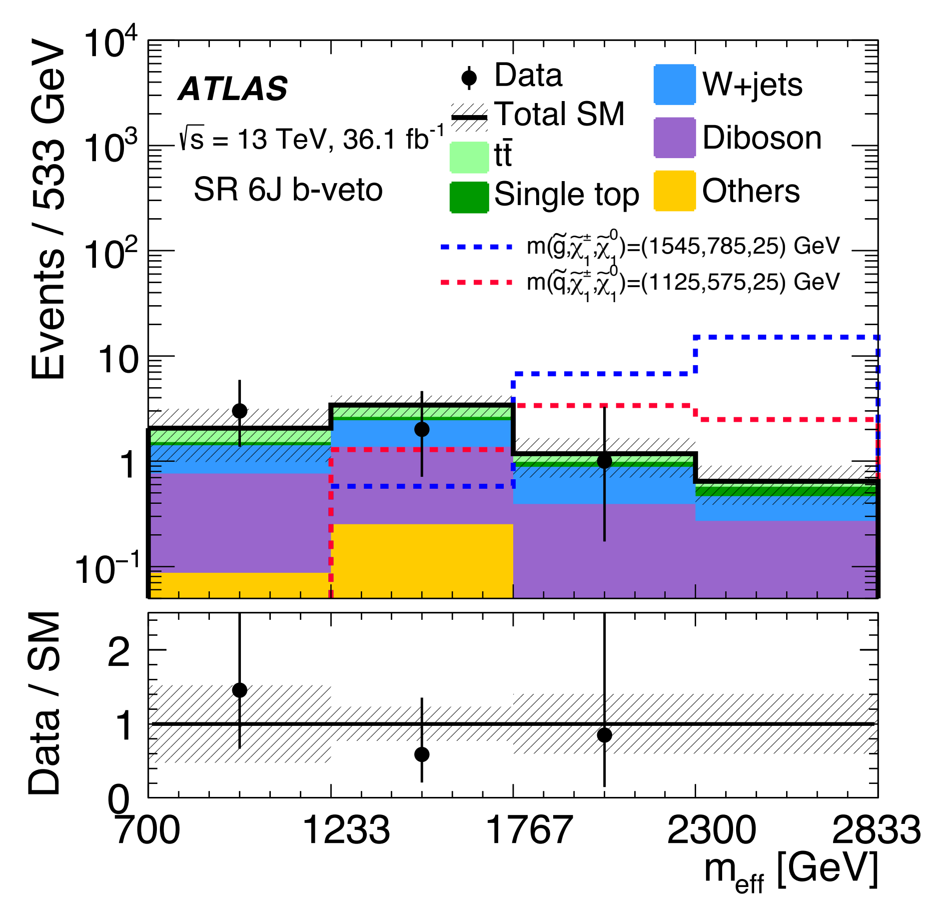
Select interesting events:

- one electron or muon from $W \rightarrow \ell\nu$ decay
- many jets from gluinos/squarks decay chain
- large E_T^{miss} from undetected neutralinos

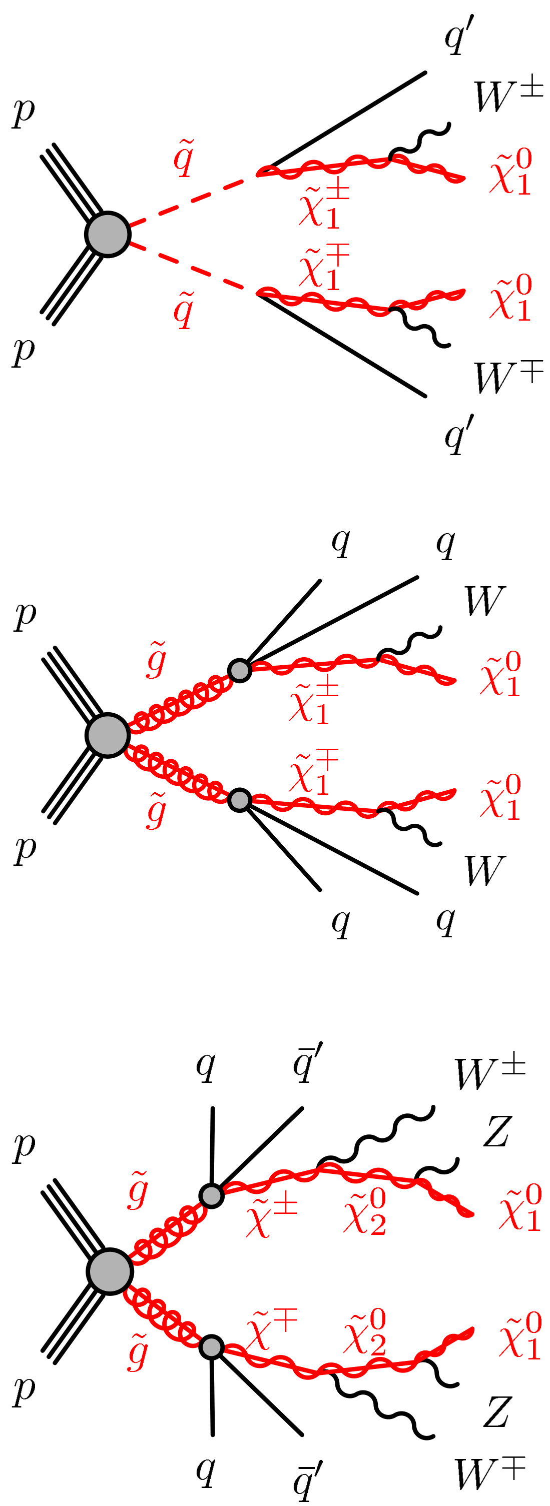
effective mass

$$m_{\mathrm{eff}}^{incl} = H_T + E_{\mathrm{T}}^{\mathrm{miss}} = \sum p_T^{\ell} + \sum p_T^{jet} + E_{\mathrm{T}}^{\mathrm{miss}}$$

sensitive to SUSY mass scale



Hunting Gluinos & Squarks



increasing number of expected jets

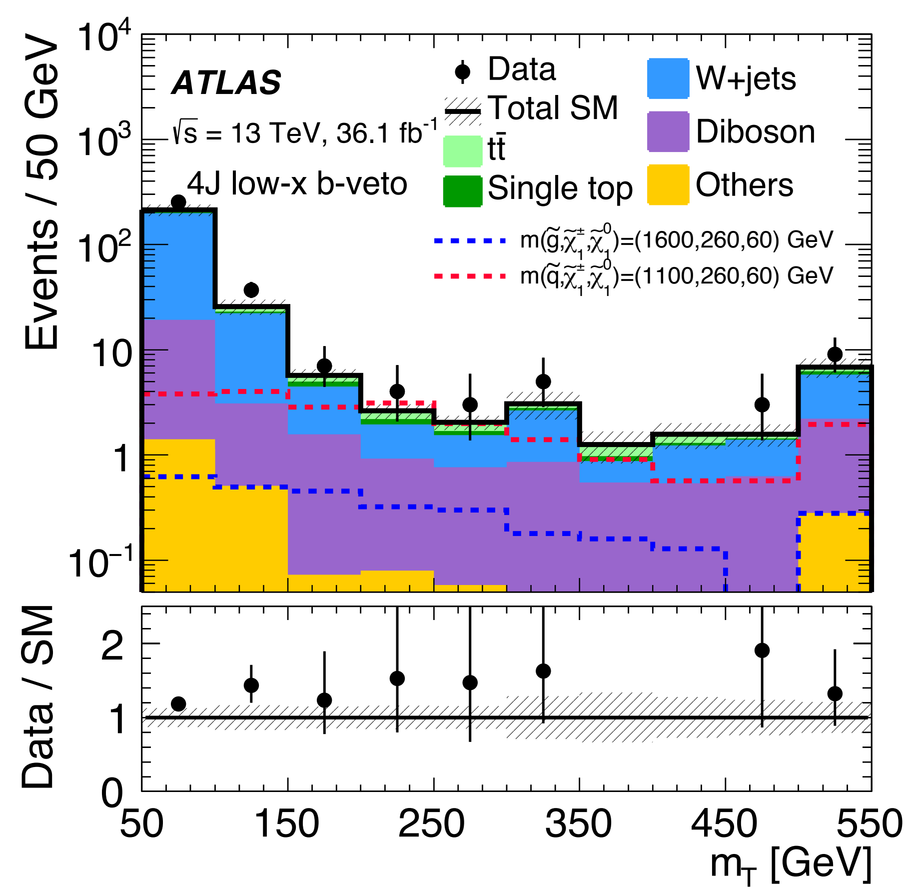
Select interesting events:

- one electron or muon from $W \rightarrow \ell\nu$ decay
- many jets from gluinos/squarks decay chain
- large E_T^{miss} from undetected neutralinos

transverse mass

$$m_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{miss} \cdot (1 - cos(\Delta\phi(\ell, E_T^{miss})))}$$

edge at m_W for backgrounds with on-shell W

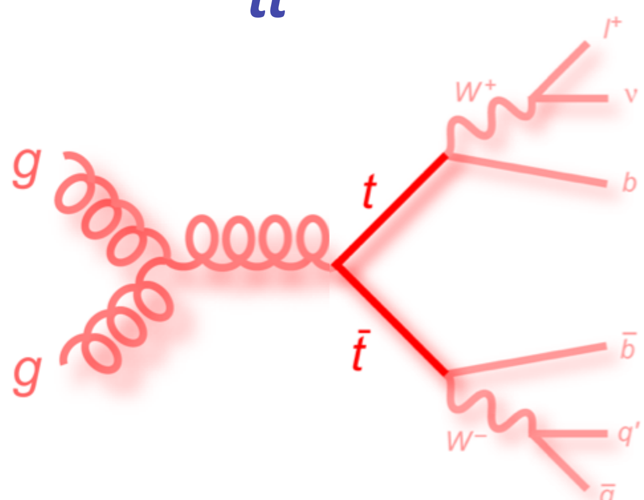


Main Backgrounds

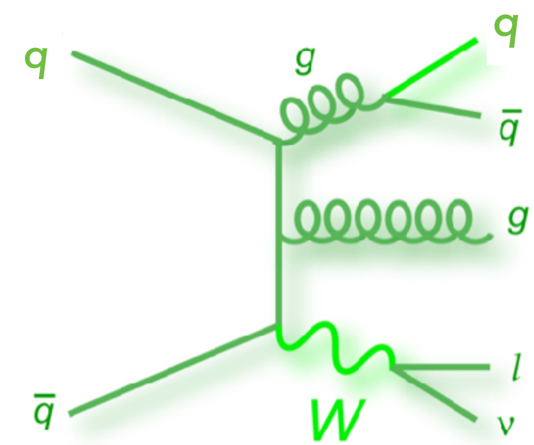
Experimental signature involves large E_T^{miss}, many jets and 1 isolated lepton

Control (CR) and validation (VR) regions used to extract / x-check background predictions

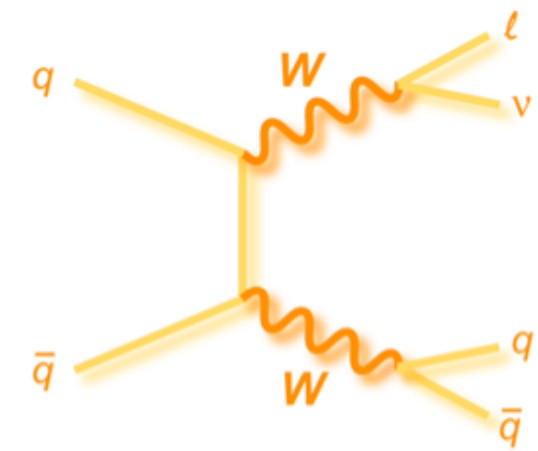
$t\bar{t}$

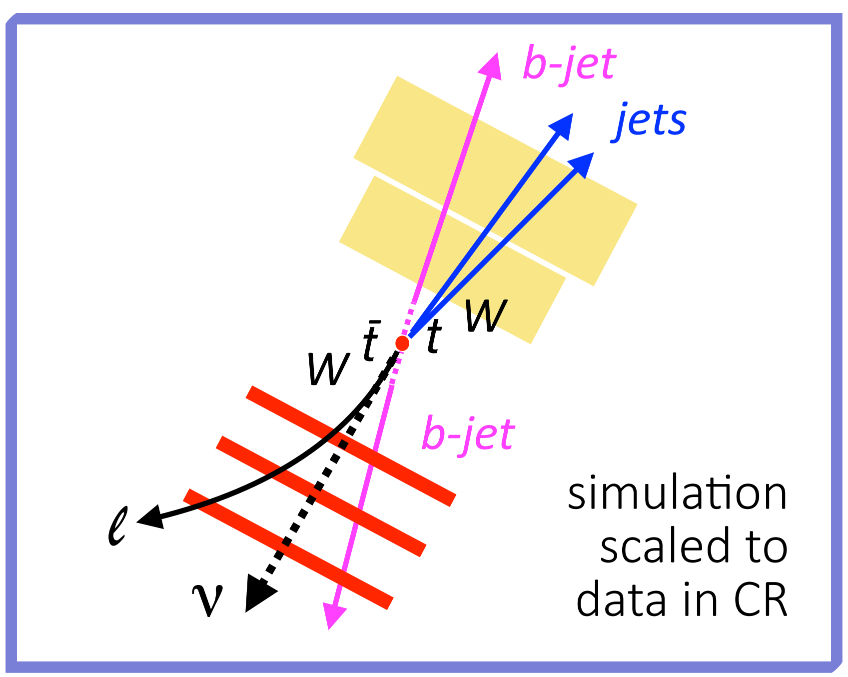


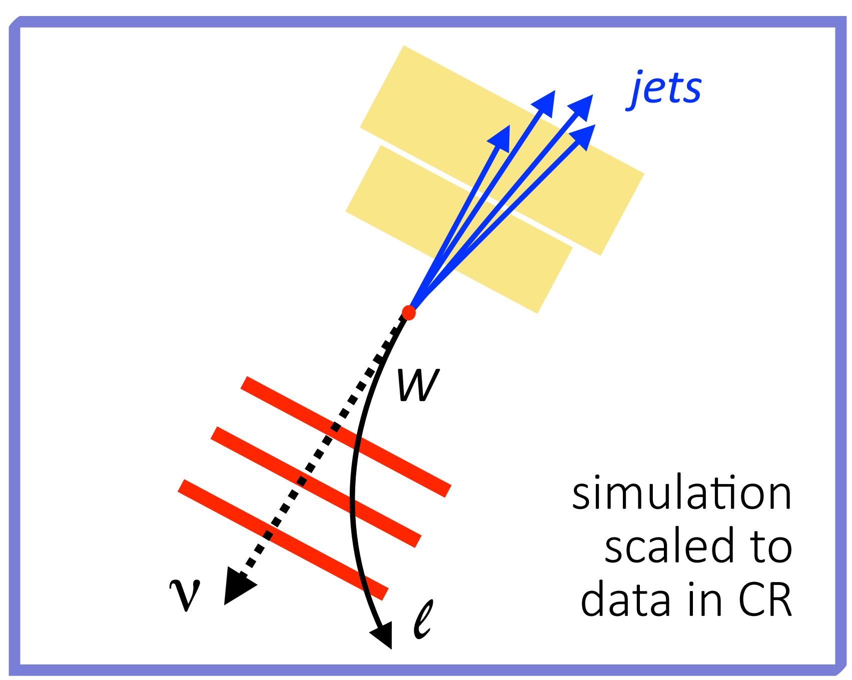
W+jets

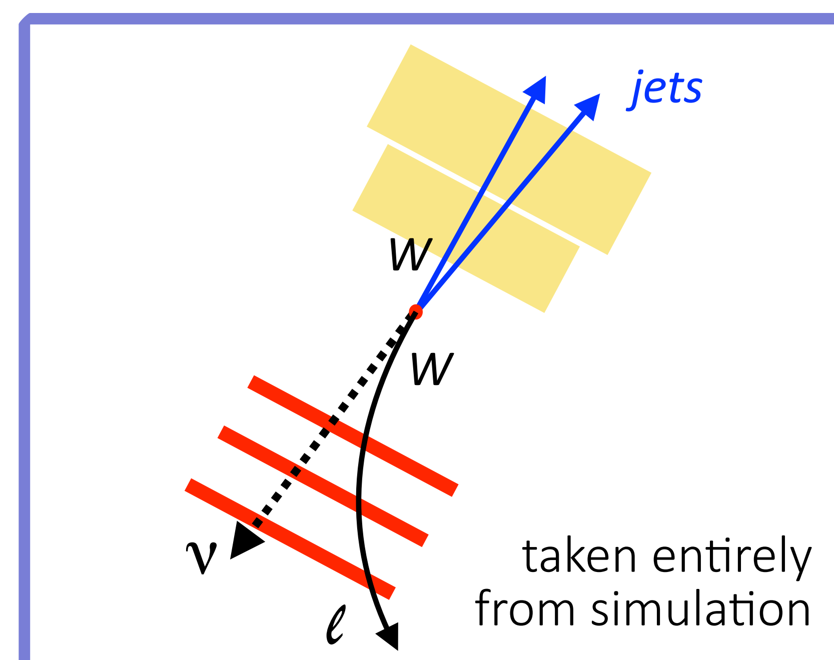


Diboson





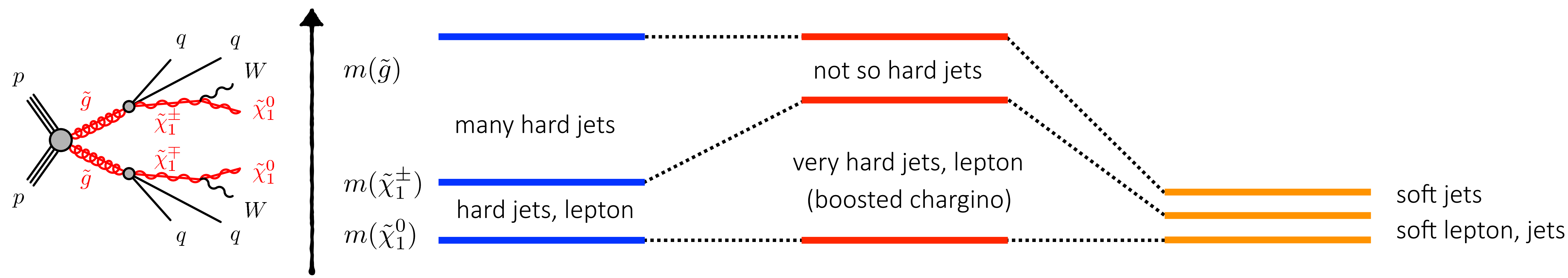


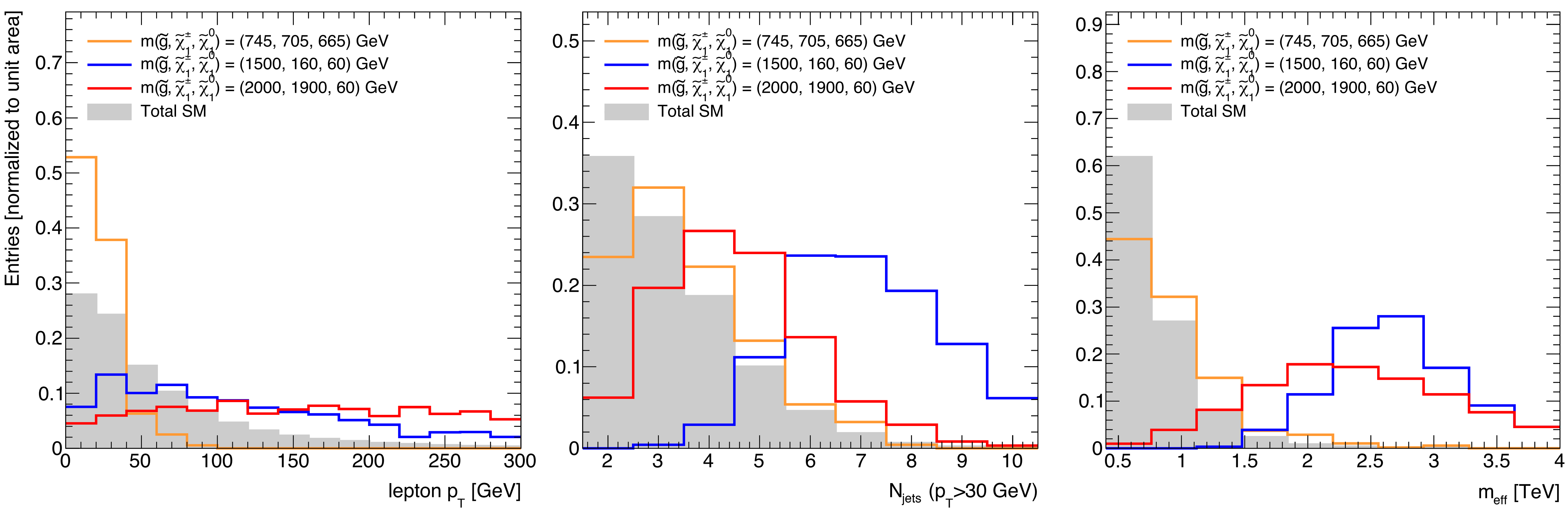


Signal Selection

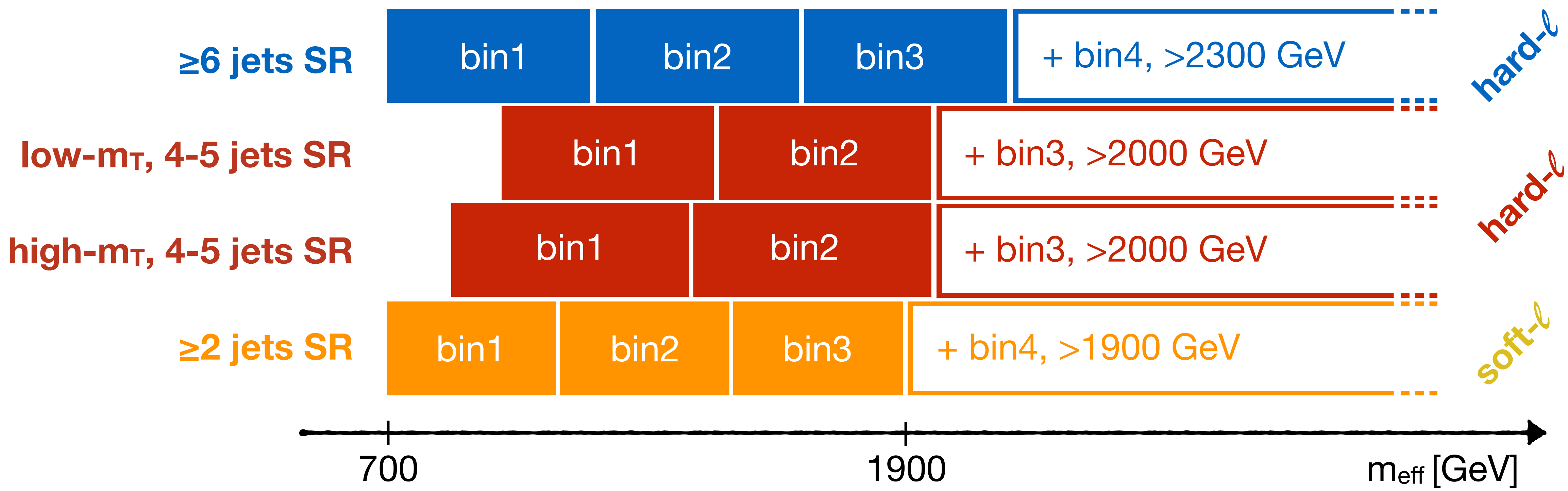
The challenge: signal kinematics *strongly* depend on *sparticles' masses*!

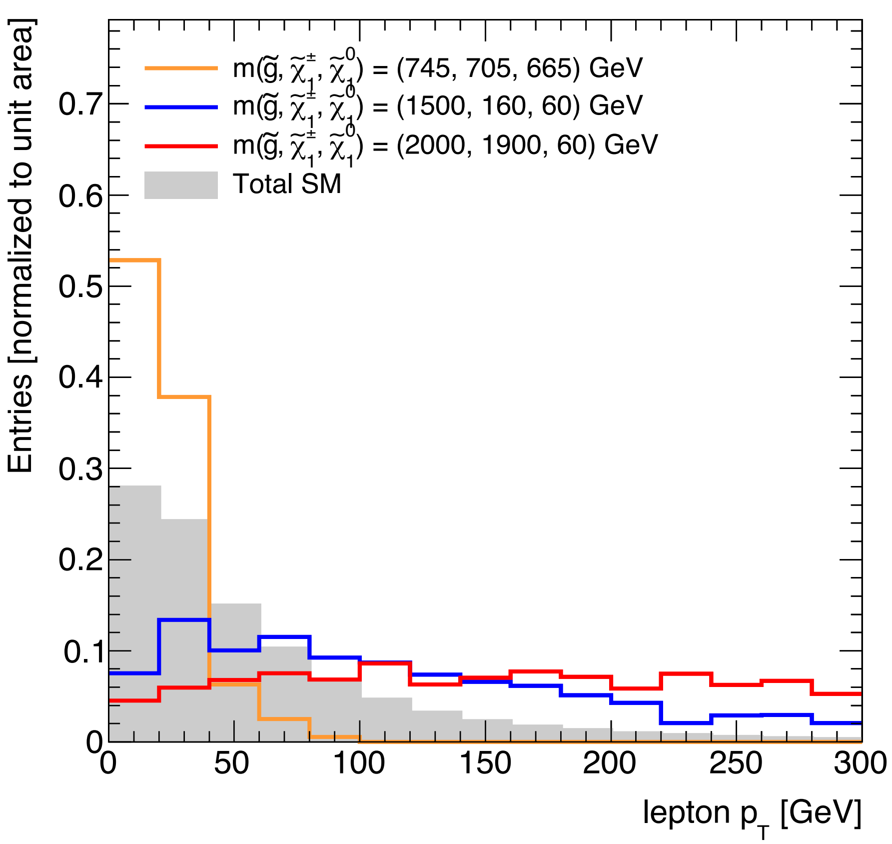
targeting whole parameter space in one analysis is very complicated…

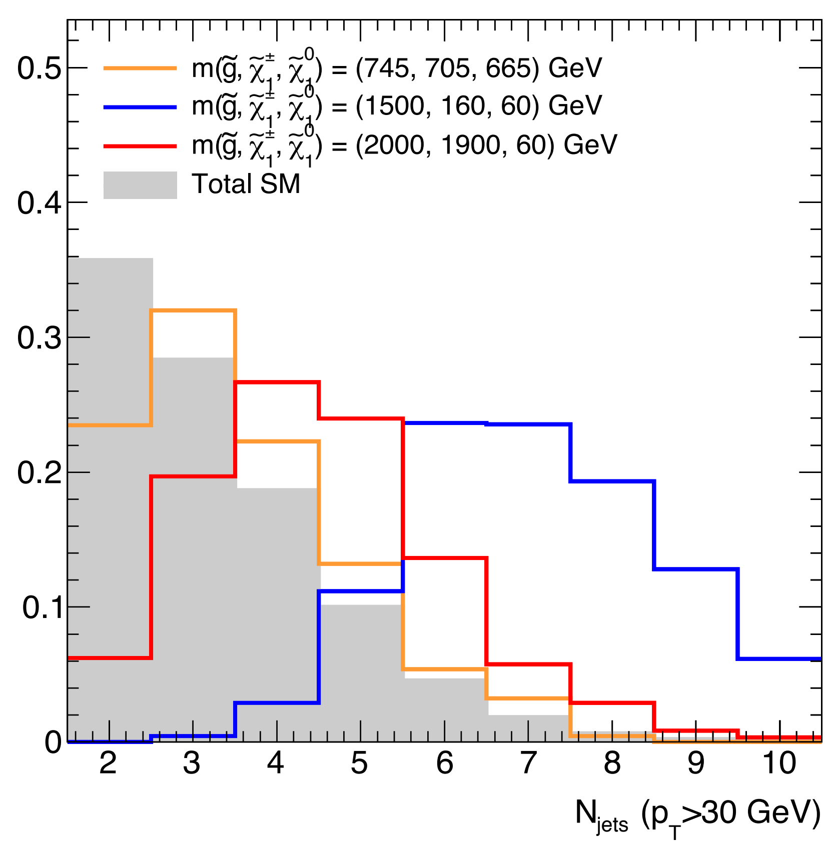


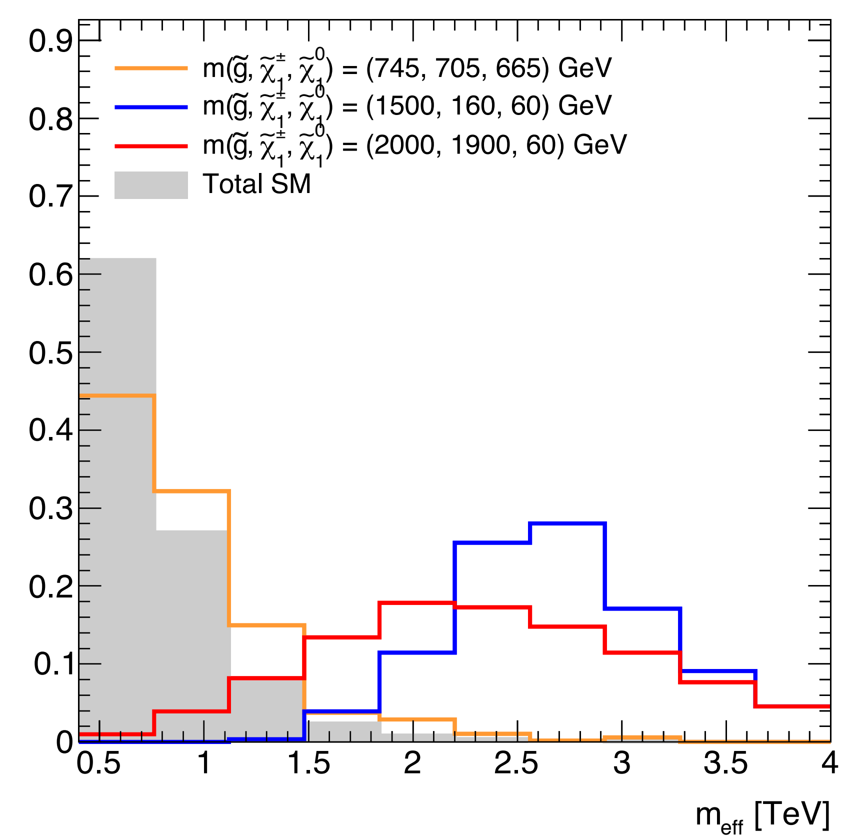


Signal Selection: Multi-Bin Fit









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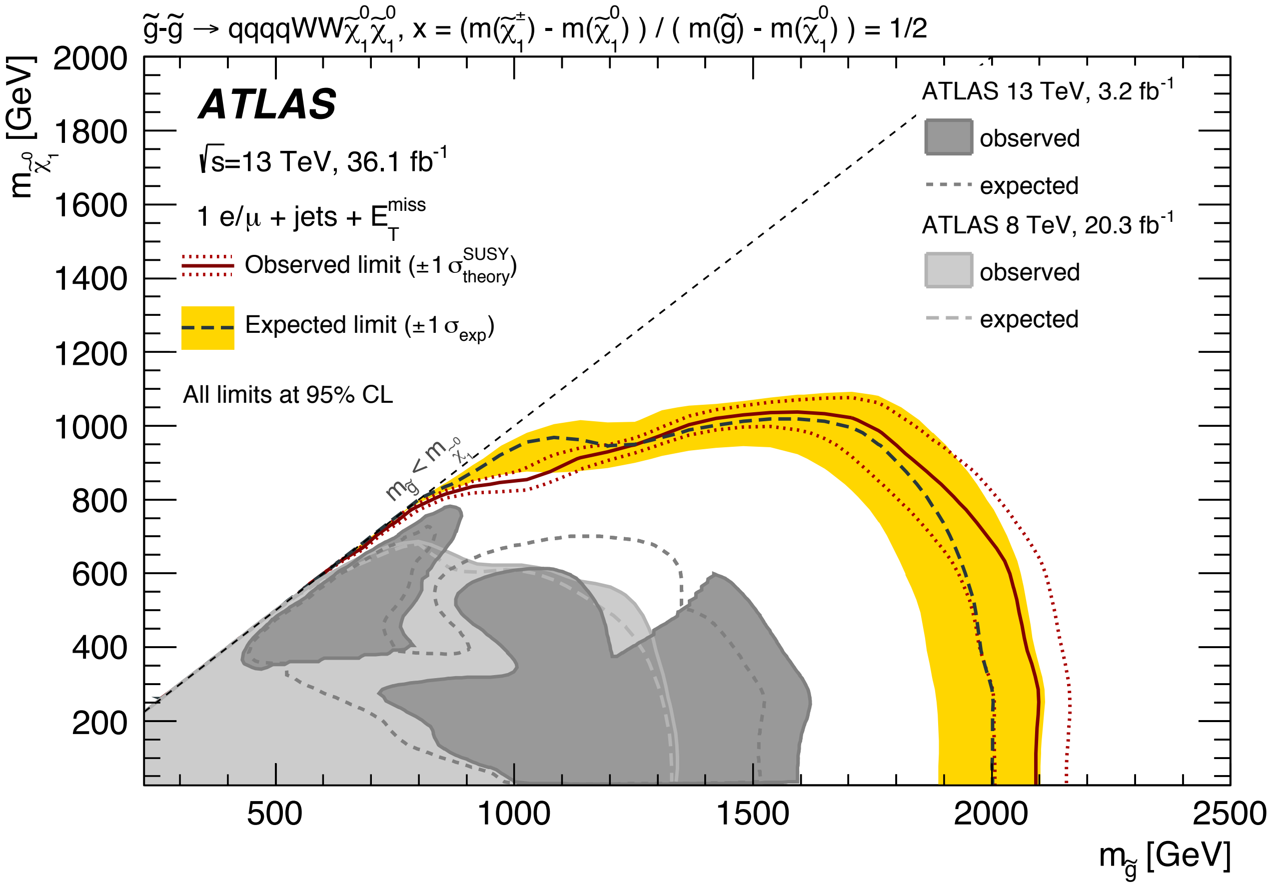
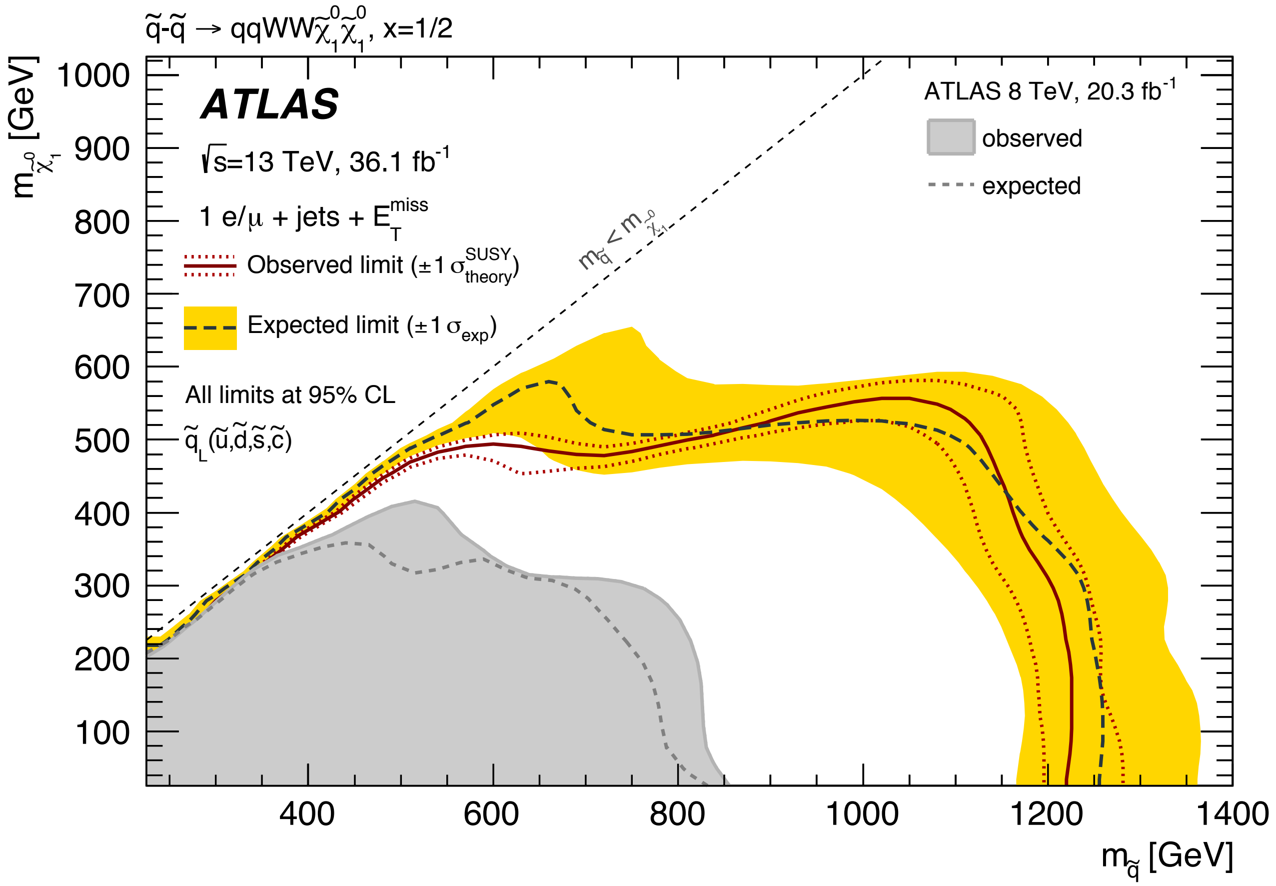
Results: 95% CL Limits

Observed event yields (*simplified SR* for model-independent limits)

SR_{disc}	2J	4J high-x	4J low-x (gluino)	4J low-x (squark)	6J (gluino)	6J (squark)	9J
Observed events	80	16	24	50	0	28	4
Fitted bkg events	67 ± 6	17.7 ± 2.7	17.2 ± 3.2	47 ± 7	2.6 ± 0.6	23.4 ± 3.1	3.1 ± 1.6
S^{95}_{exp}	$21.6^{+9.2}_{-5.6}$	$10.8^{+3.7}_{-3.0}$	$11.8^{+4.8}_{-2.7}$	$19.9^{+7.5}_{-5.6}$	$4.5^{+1.8}_{-1.0}$	$12.7^{+5.0}_{-4.0}$	$6.0^{+2.2}_{-1.2}$
$p(s=0)$	0.10	0.50	0.10	0.35	0.50	0.21	0.34

Exclusions: simulated SUSY signal rejected, or not, via fit to pseudo/observed data

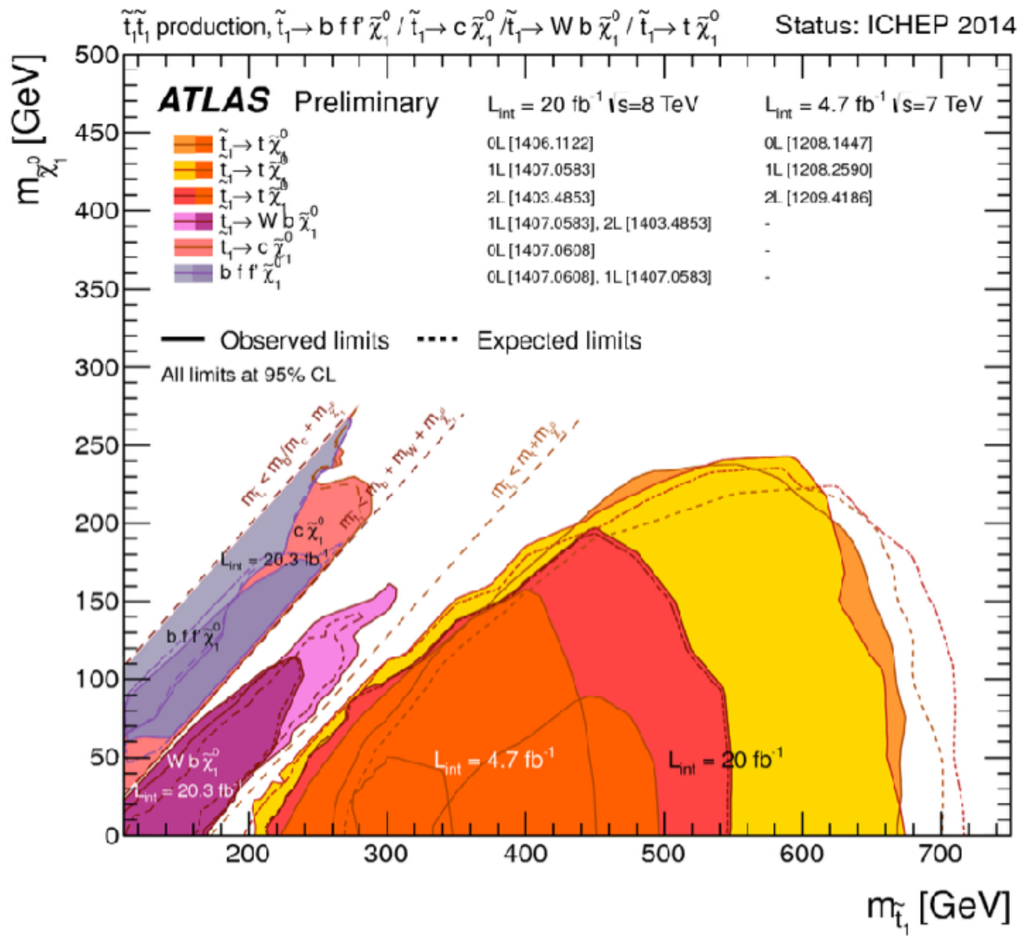




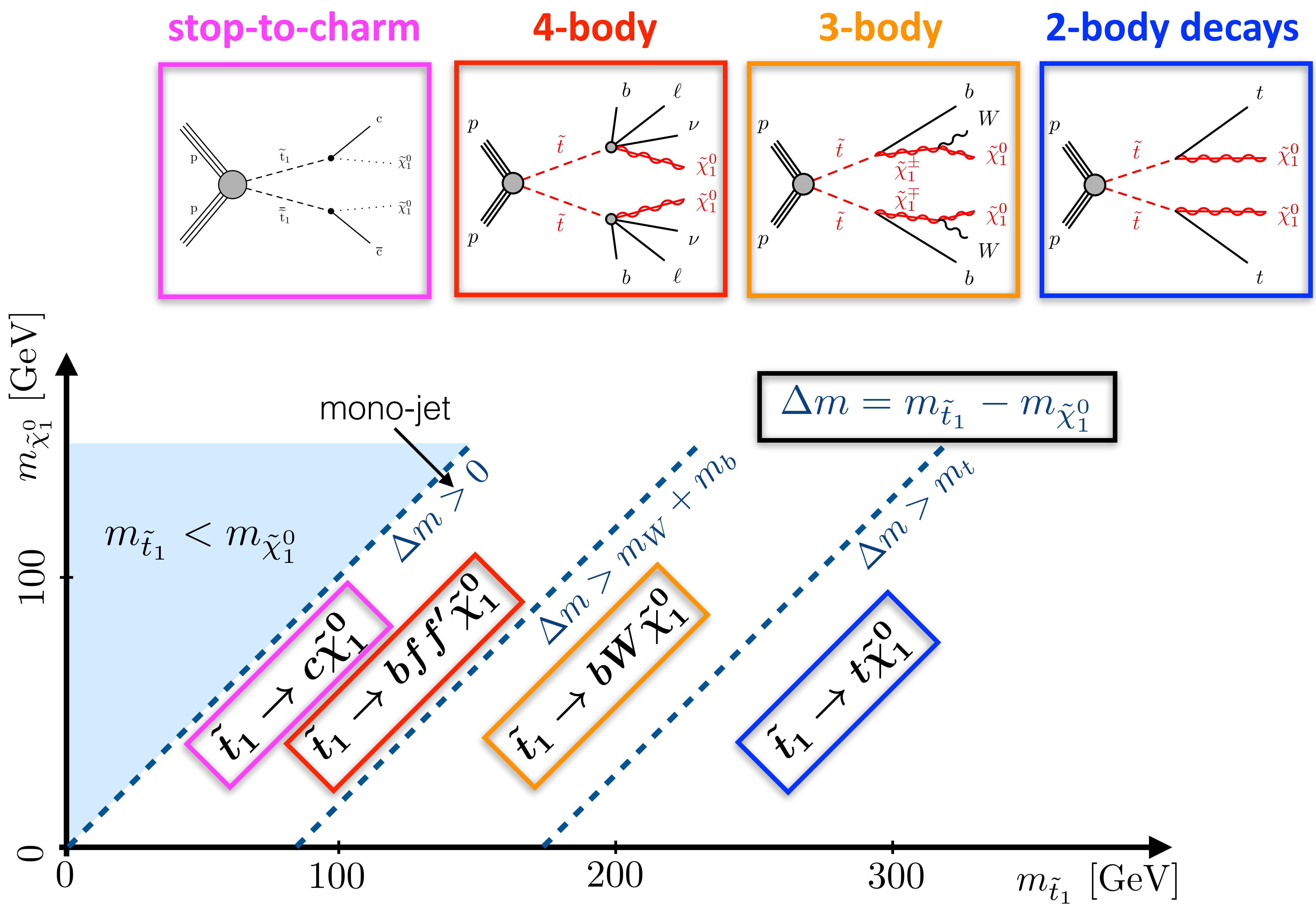
Hunting for Natural SUSY at the LHC

Part II - The Stops

Excluded up to 650 GeV after the LHC run1



Hunting Stops: Decays



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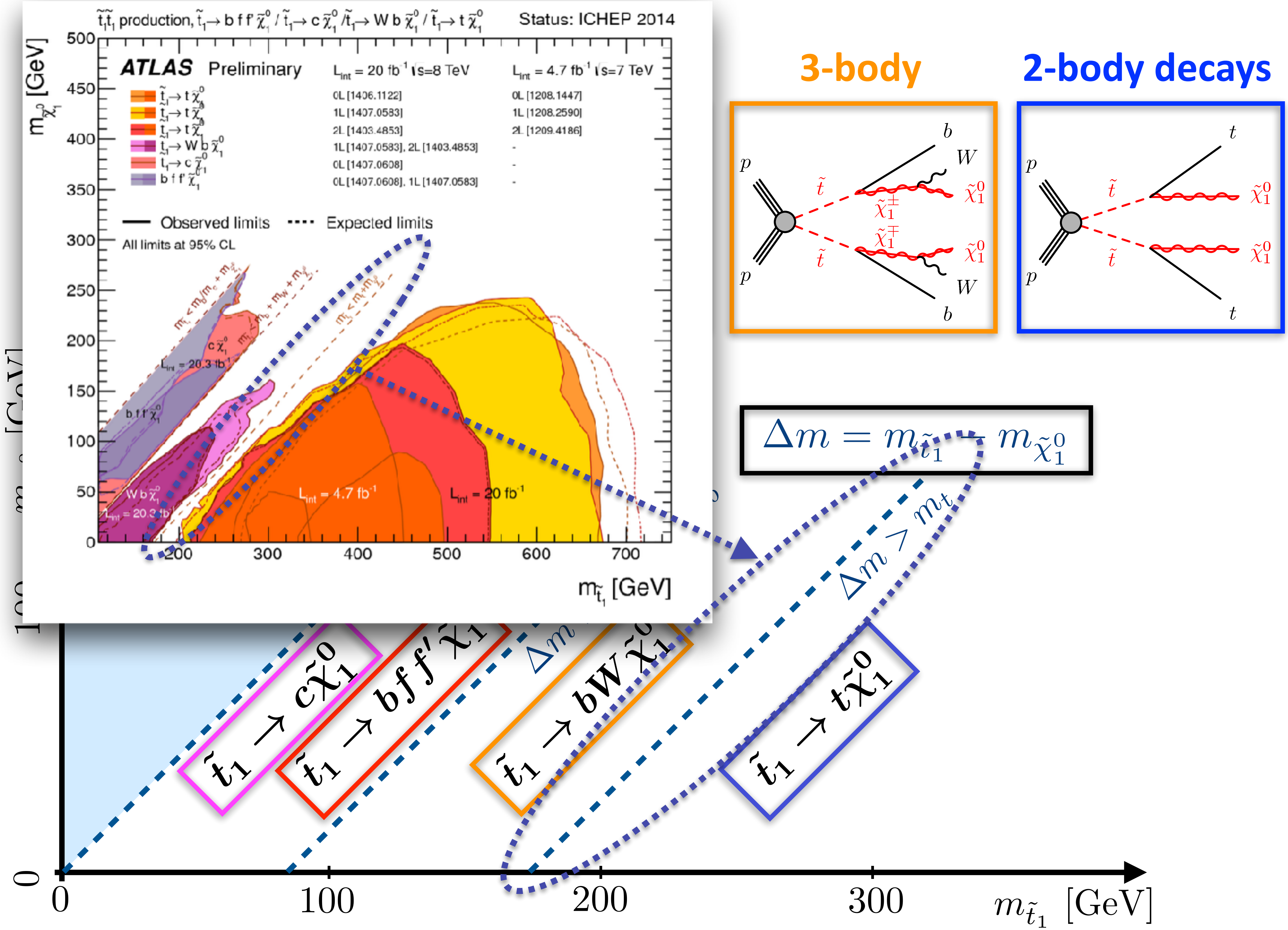
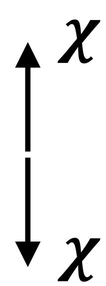
Hunting Stops: Decays



Hunting Diagonal Stops

$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \approx m_t : \tilde{t}\tilde{t}$ **kinematics close to $t\bar{t}$**

need ISR activity
to "misalign" $\chi\chi$
and get tangible
contribution to E_T^{miss}



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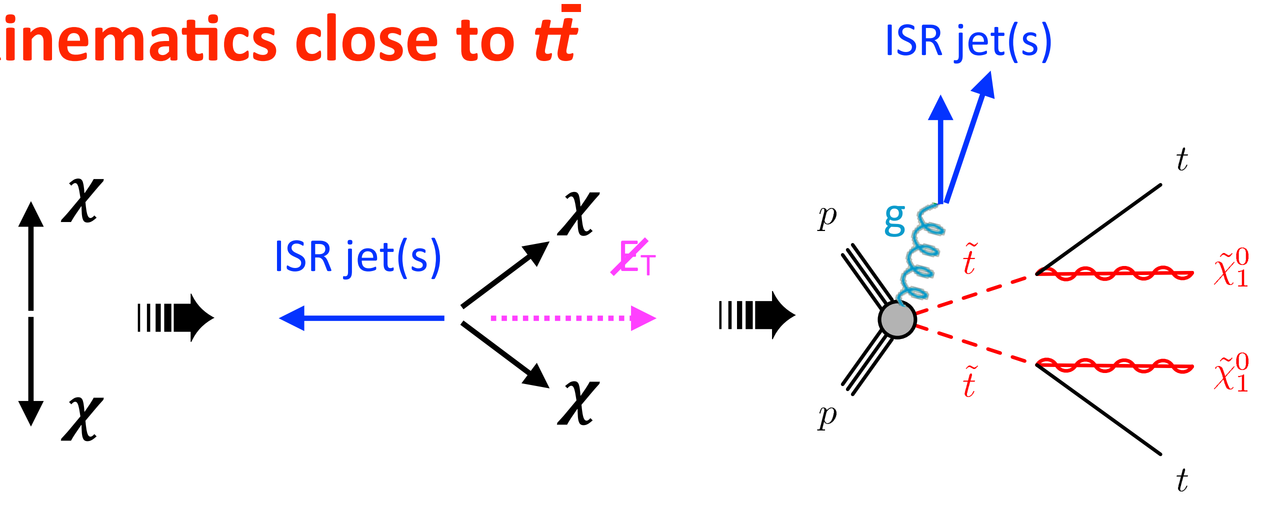

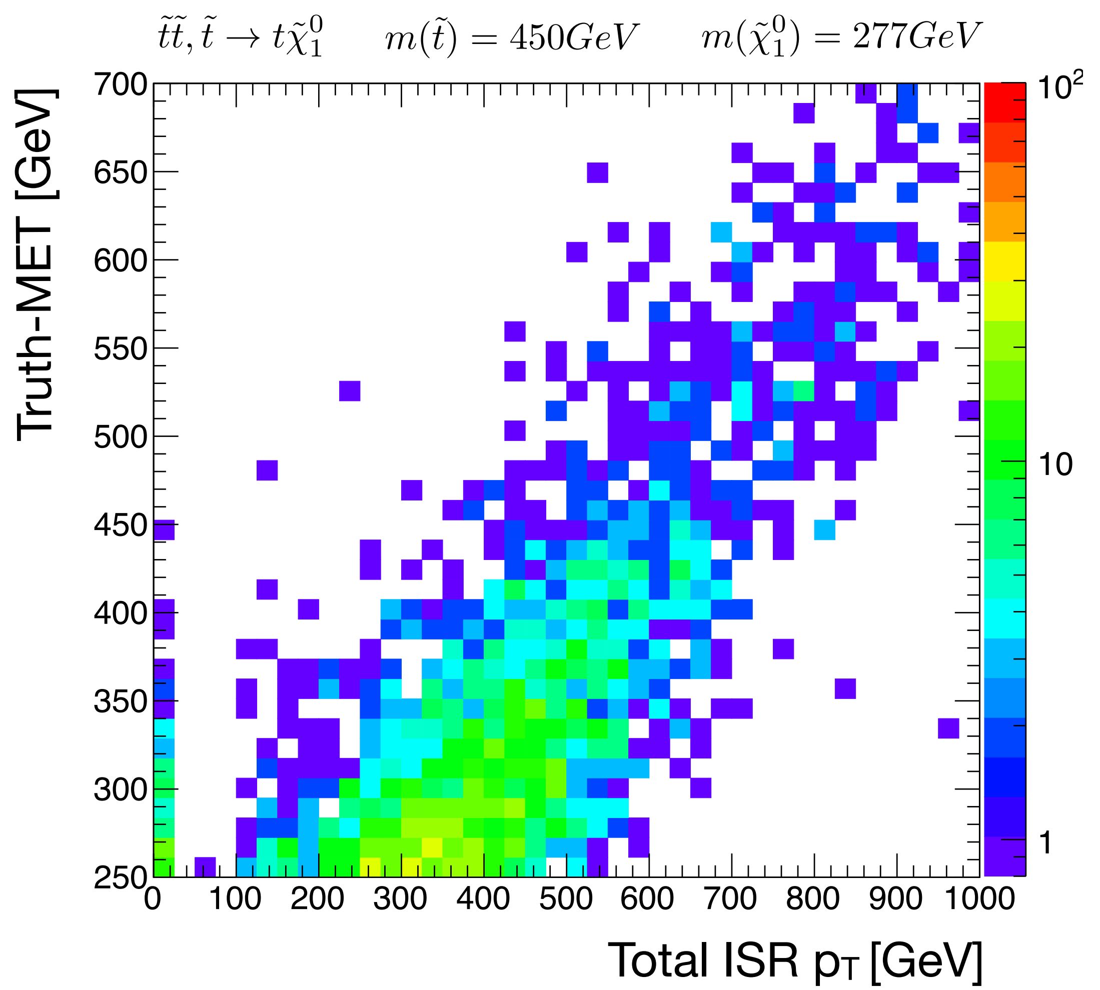

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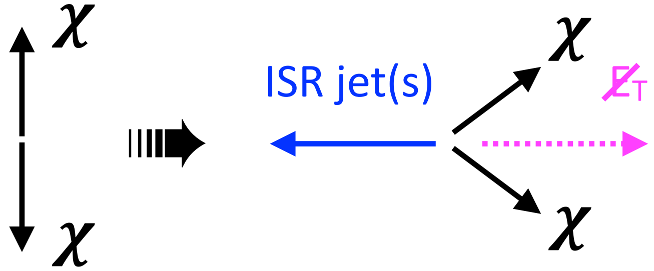
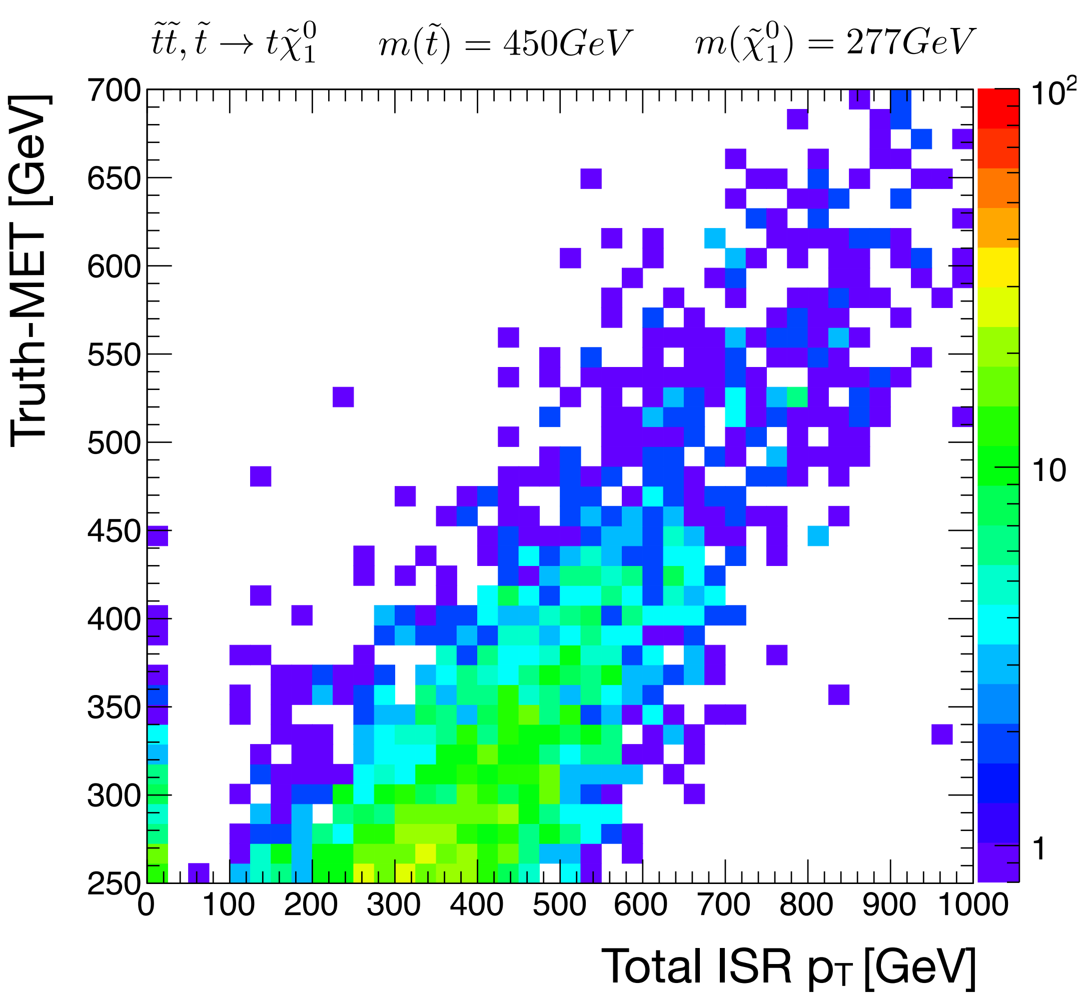




plethora of pheno. papers:

$$p_{T,ISR} \approx -(p_T(\tilde{t}_1) + p_T(\tilde{t}_2))$$

$$\frac{\not{E}_T}{p_{T,ISR}} \approx \frac{m(\tilde{\chi}_1^0)}{m(\tilde{t})}$$

K. Hagiwara et al, 2015: arXiv:1307.1553v3

H. An et al, 2015: arXiv:1506.00653v2

S. Macaluso et al, 2015: arXiv:1506.07885.

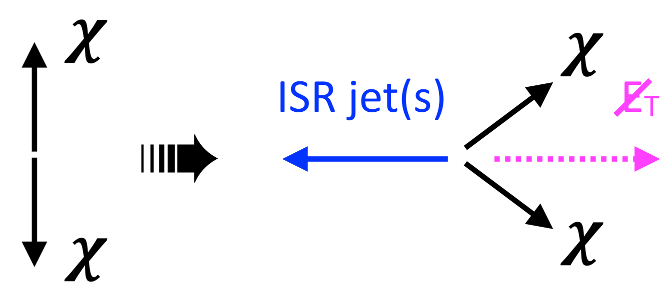
H. Cheng et al, 2016: arXiv:1604.00007v1

etc…

Hunting Diagonal Stops

$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \approx m_t$: $\tilde{t}\tilde{t}$ **kinematics close to** $t\bar{t}$

need ISR activity to “misalign” $\chi\chi$ and get tangible contribution to $\not{E}_T$



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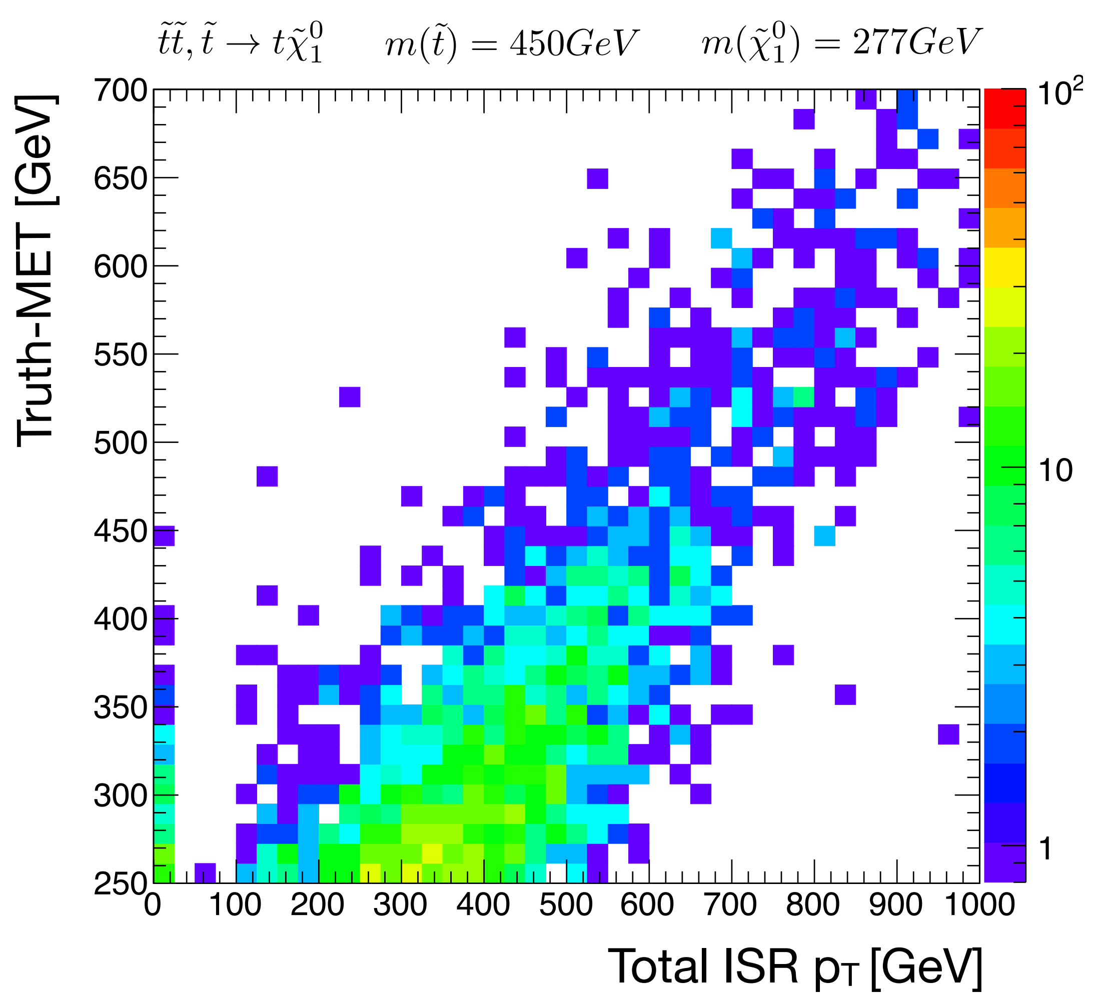

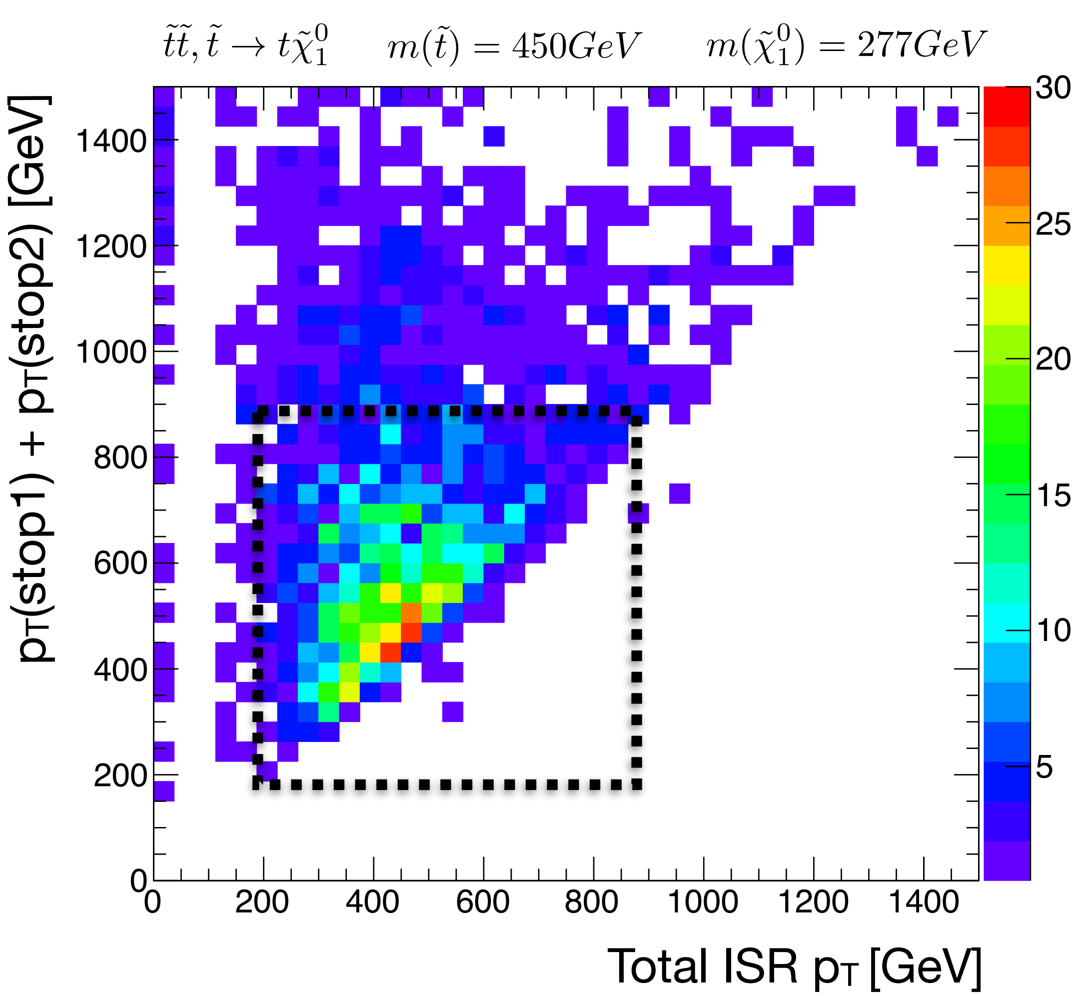

Hunting Diagonal Stops

easier said than done… among the many jets, which ones are from ISR?

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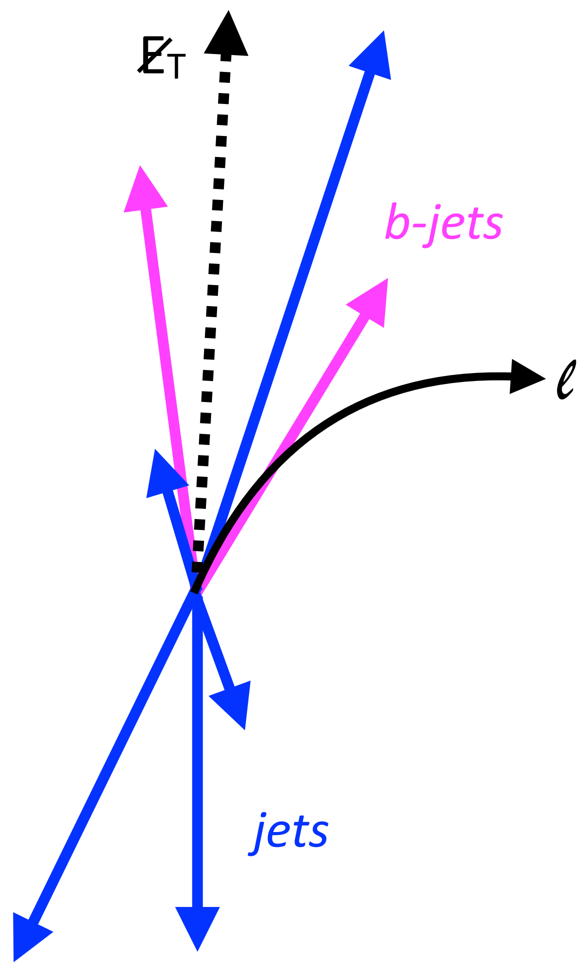
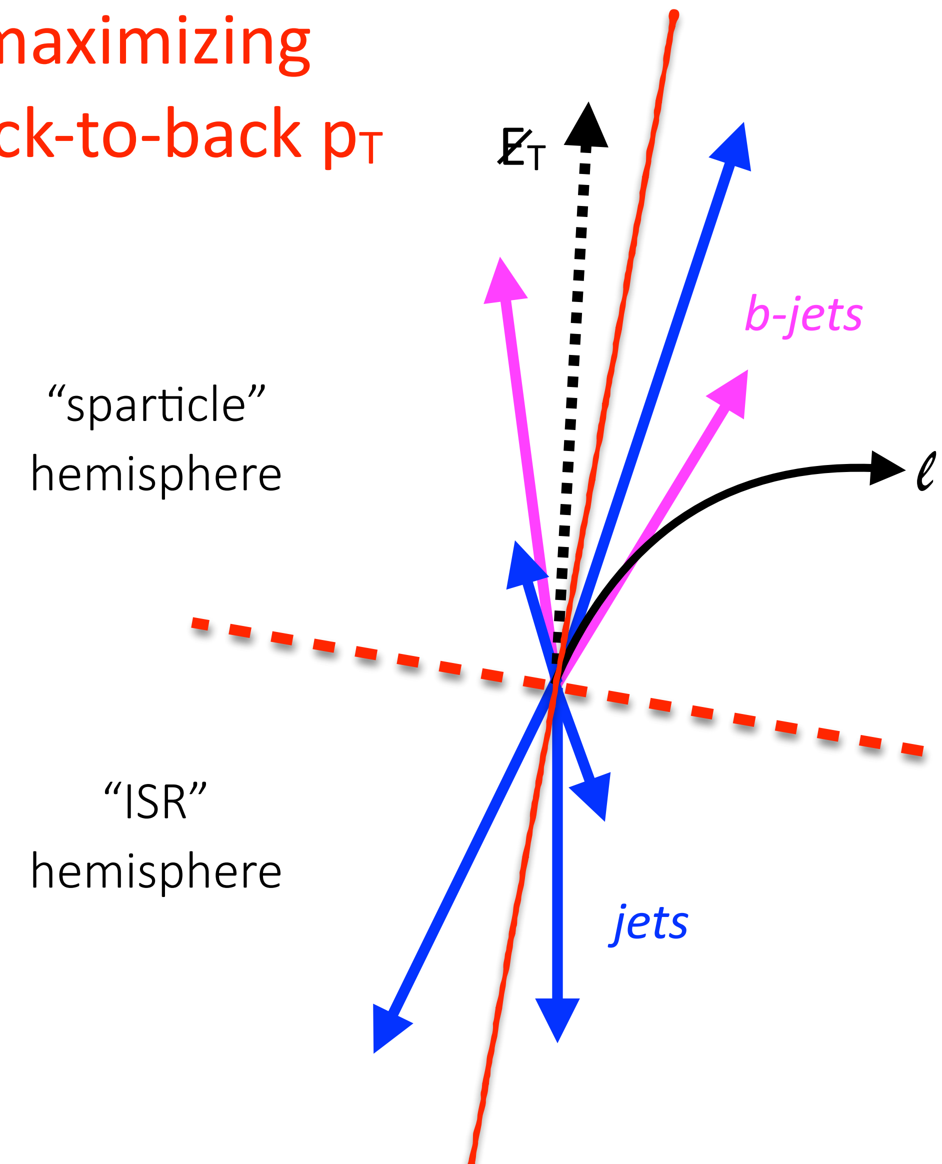


Thrust-Based ISR Identification

easier said than done… among the many jets, which ones are from ISR?

thrust axis: direction maximizing back-to-back p_T



plethora of pheno. papers:

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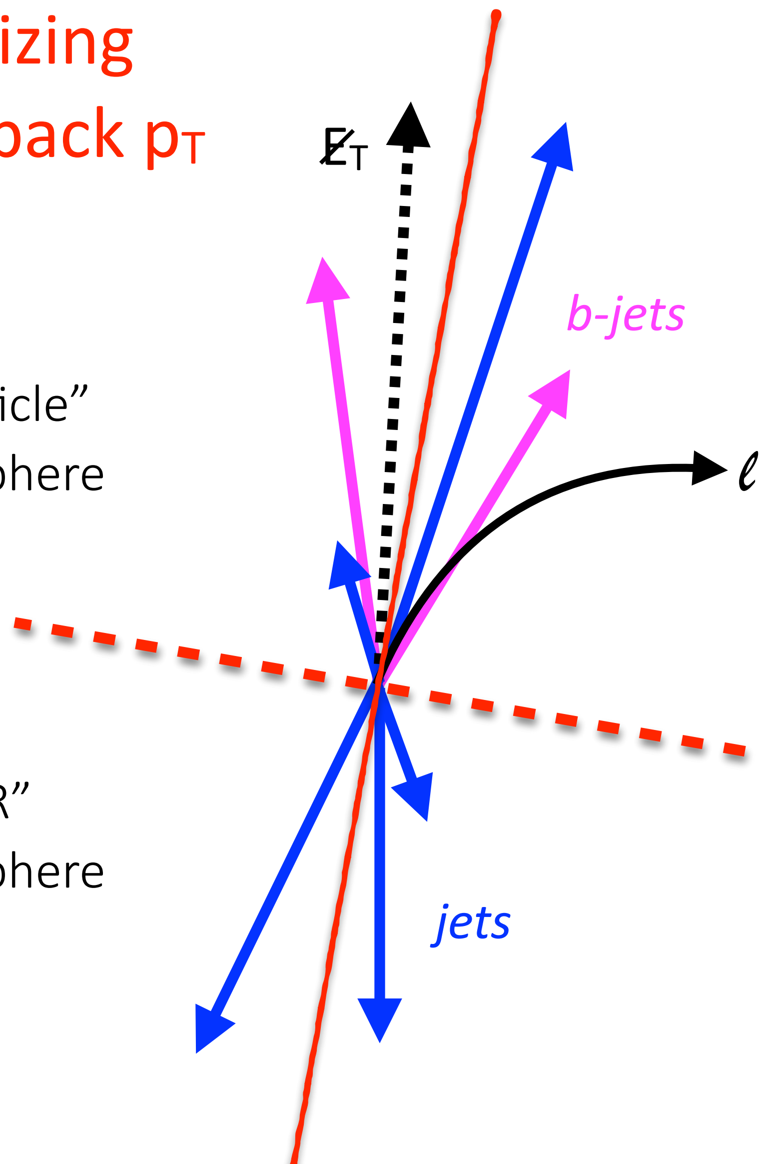

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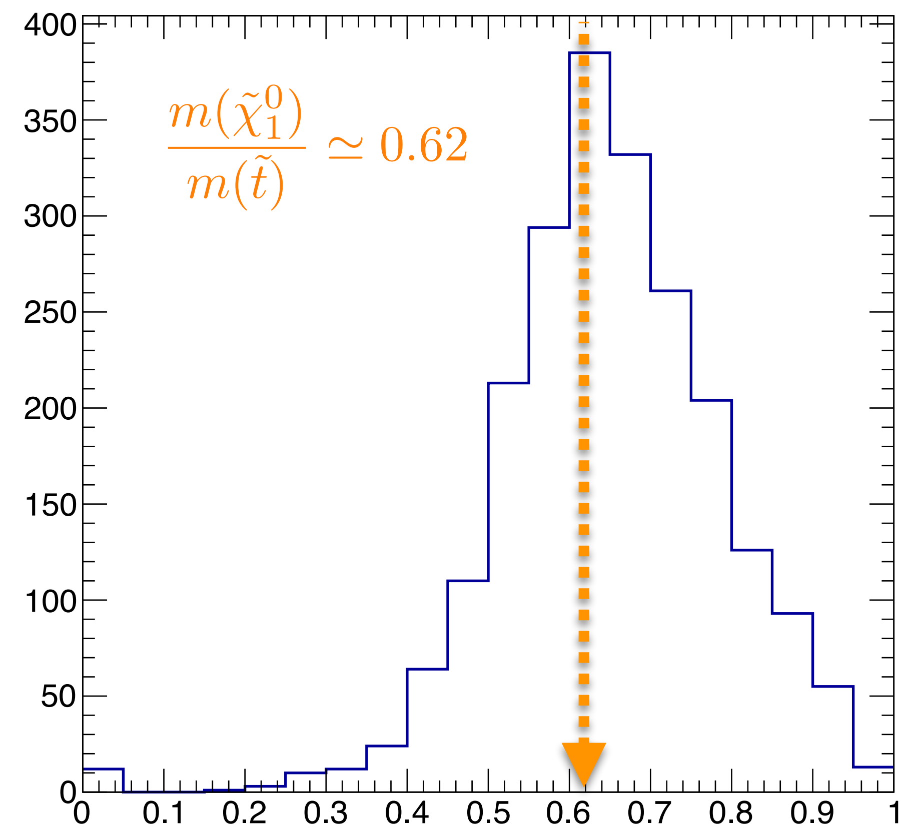
$$p_{T,ISR} \approx -(p_T(\tilde{t}_1) + p_T(\tilde{t}_2))$$

$$\frac{\not{E}_T}{p_{T,ISR}} \approx \frac{m(\tilde{\chi}_1^0)}{m(\tilde{t})}$$

$\tilde{t}\tilde{t}, \tilde{t} \to t\tilde{\chi}_1^0 \quad m(\tilde{t}) = 450GeV \quad m(\tilde{\chi}_1^0) = 277GeV$

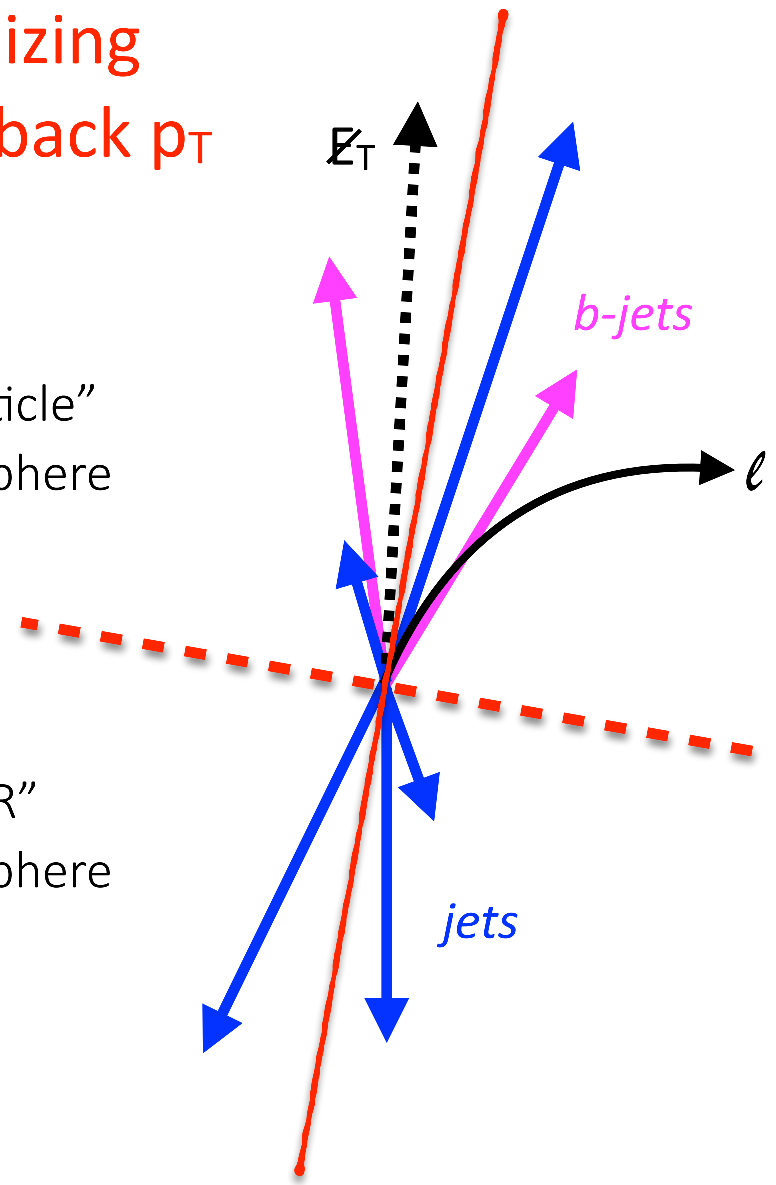


$R_{ISR} = \not{E}_T / p_{T,ISR}$ (thrust-based)

Thrust-Based ISR Identification

easier said than done... among the many jets, which ones are from ISR?

thrust axis: direction maximizing back-to-back p_T



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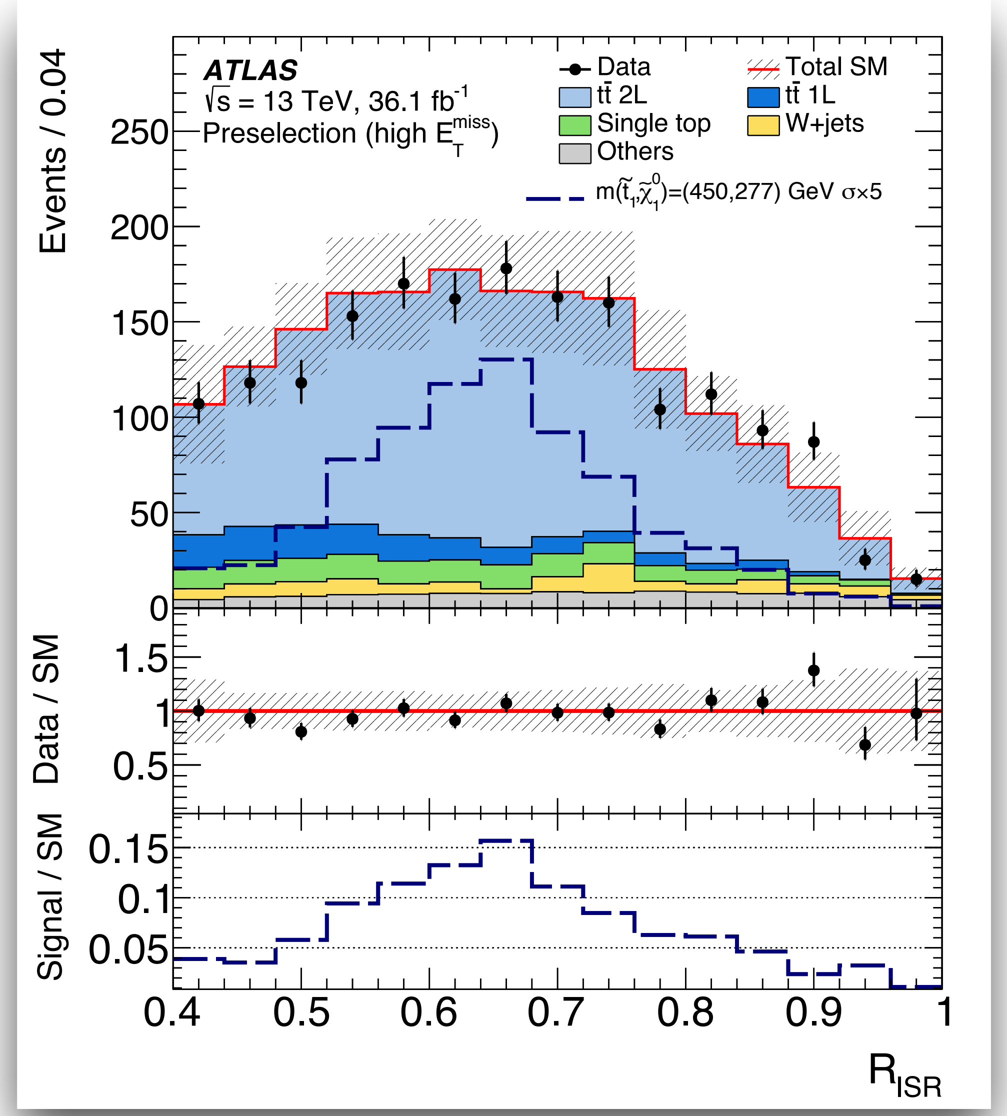


Signal Selection: Boosted Decision Tree (BDT)

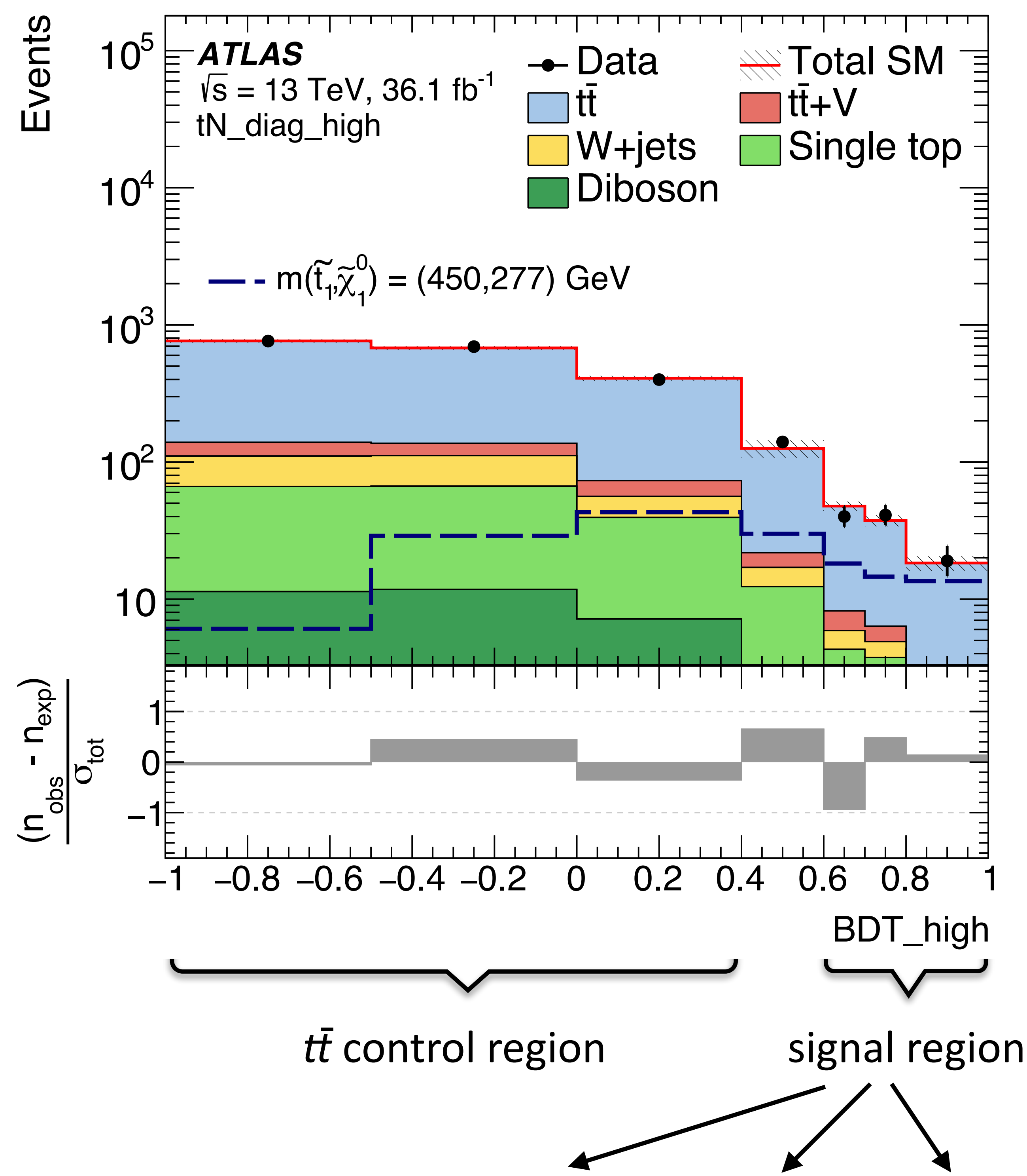
SR based on BDT discriminant

trained to select stop and reject $t\bar{t}$

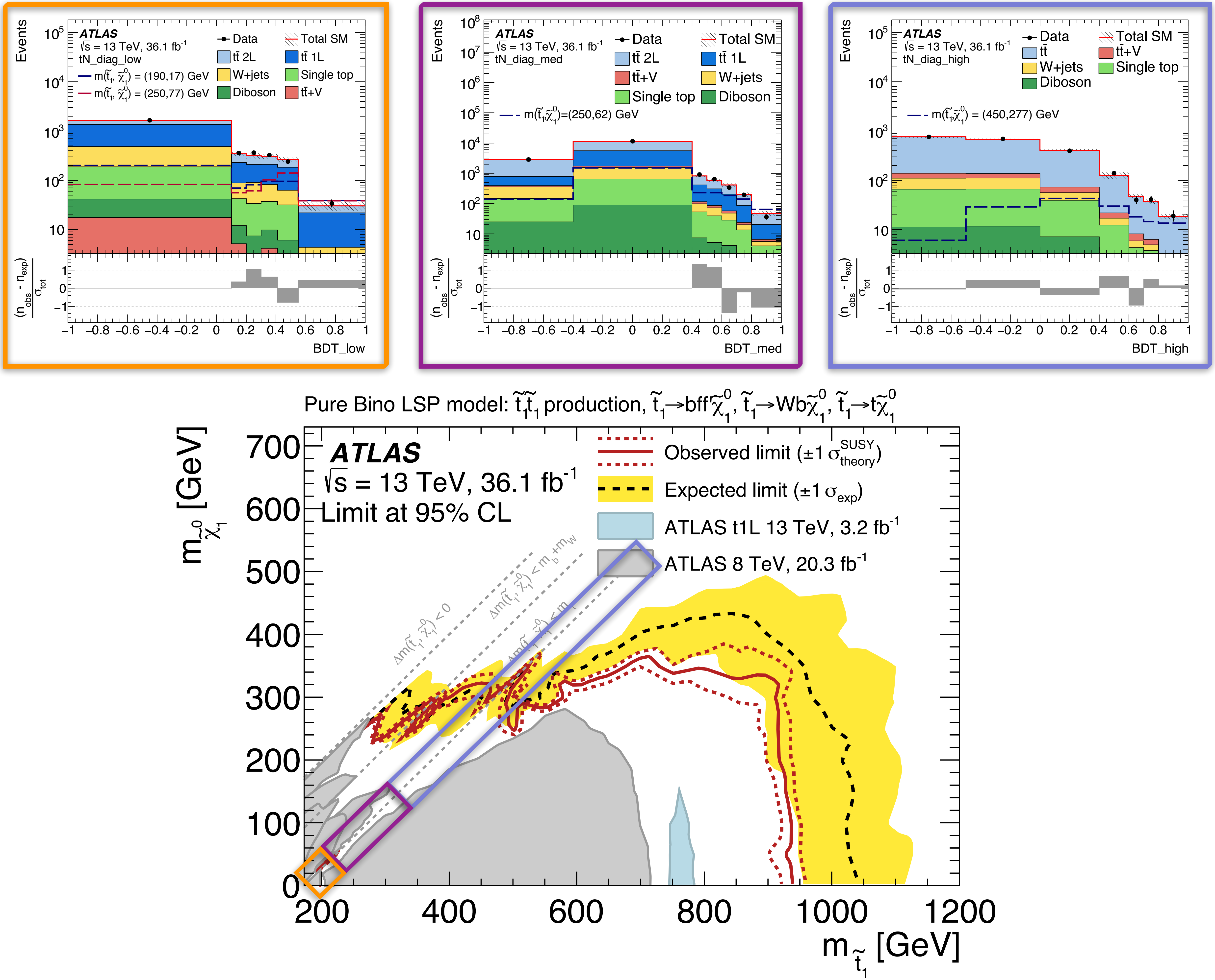
10 variables, some computed using thrust-based ISR reconstruction

only well-modeled and understood variables enter the BDT

lots of validation performed to make sure the exploited correlations are understood



Observed	40	41	19
Total background	47.3 ± 3.6	37.5 ± 3.5	18.3 ± 2.2

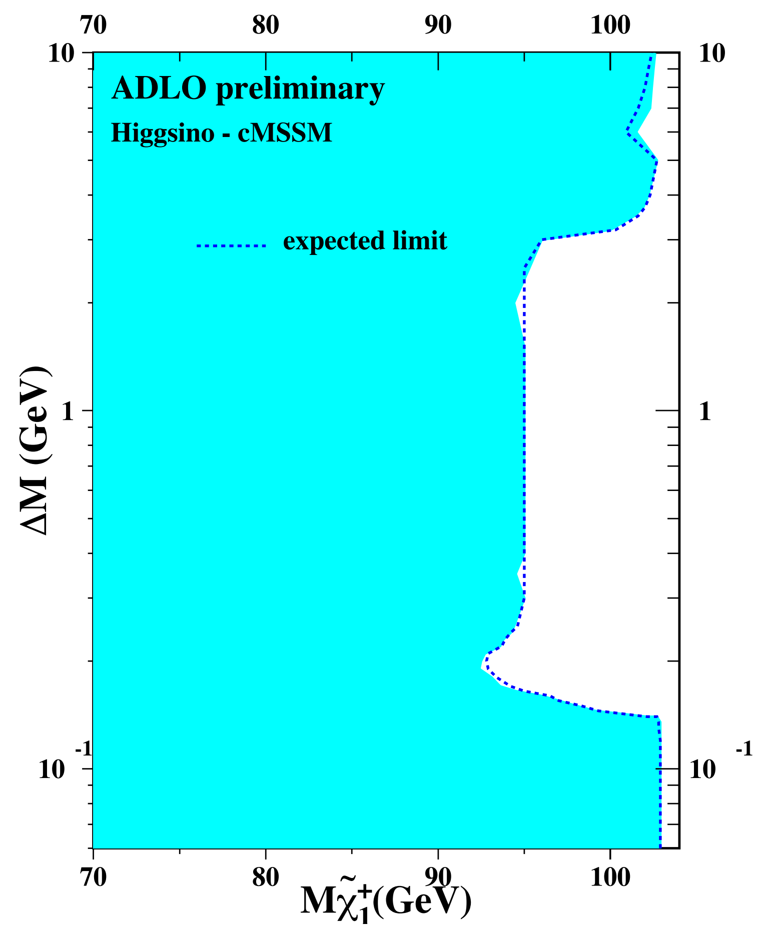


ATLAS
√s = 13 TeV, 36.1 fb-1
tN_diag_low
Data
Total SM
tt̄ 2L
tt̄ 1L
W+jets
Single top
Diboson
tt̄+V
m(t̃1, χ̃01) = (190,17) GeV
m(t̃1, χ̃01) = (250,77) GeV
BDT_low
tN_diag_med
m(t̃1,χ̃01)=(250,62) GeV
BDT_med
tN_diag_high
tt̄
m(t̃1,χ̃01) = (450,277) GeV
BDT_high
Events
(n_obs - n_exp)/σ_tot
Pure Bino LSP model: t̃1t̃1 production, t̃1→bff'χ̃01, t̃1→Wbχ̃01, t̃1→tχ̃01
ATLAS
√s = 13 TeV, 36.1 fb-1
Limit at 95% CL
Observed limit (±1 σ^SUSY_theory)
Expected limit (±1 σ_exp)
ATLAS t1L 13 TeV, 3.2 fb-1
ATLAS 8 TeV, 20.3 fb-1
Δm(t̃1,χ̃01) < 0
Δm(t̃1,χ̃01) < m_b+m_W
Δm(t̃1,χ̃01) < m_t
m_χ̃01 [GeV]
m_t̃1 [GeV]

Hunting for Natural SUSY at the LHC

Part III - The Higgsinos

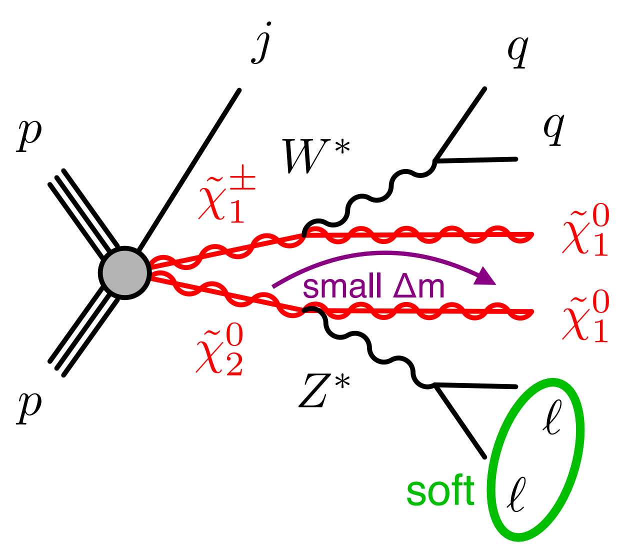
Excluded up to 110 GeV at LEP

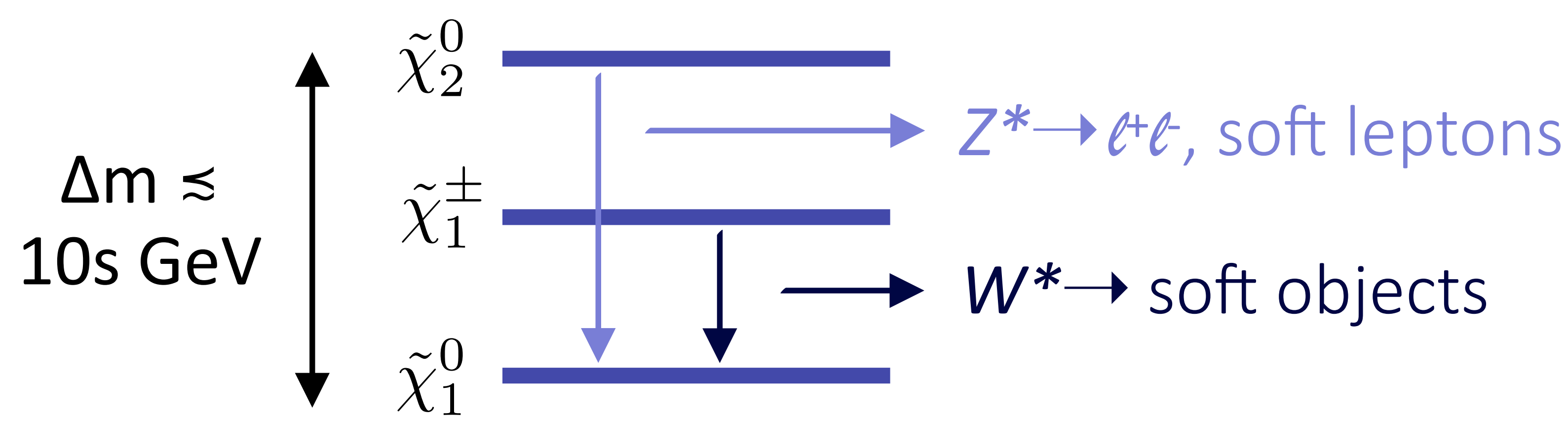


Hunting Higgsinos

As for "diagonal" stop, sensitivity driven by ISR-induced MET

Higgsinos mix with other EWKinos:
multiplets of neutralinos and charginos



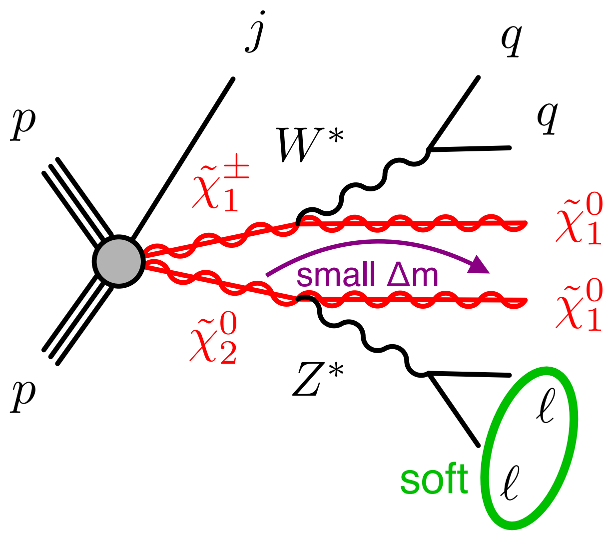


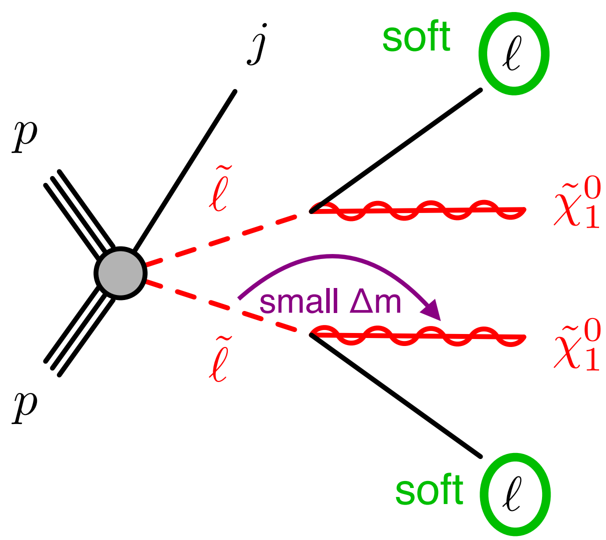
Main analysis challenge: soft leptons
intra-higgsinos decay products often too soft to be reconstructed

S. Zambito | *Harvard University*

Hunting Higgsinos

As for "diagonal" stop, sensitivity driven by ISR-induced MET





Higgsinos mix with other EWKinos:
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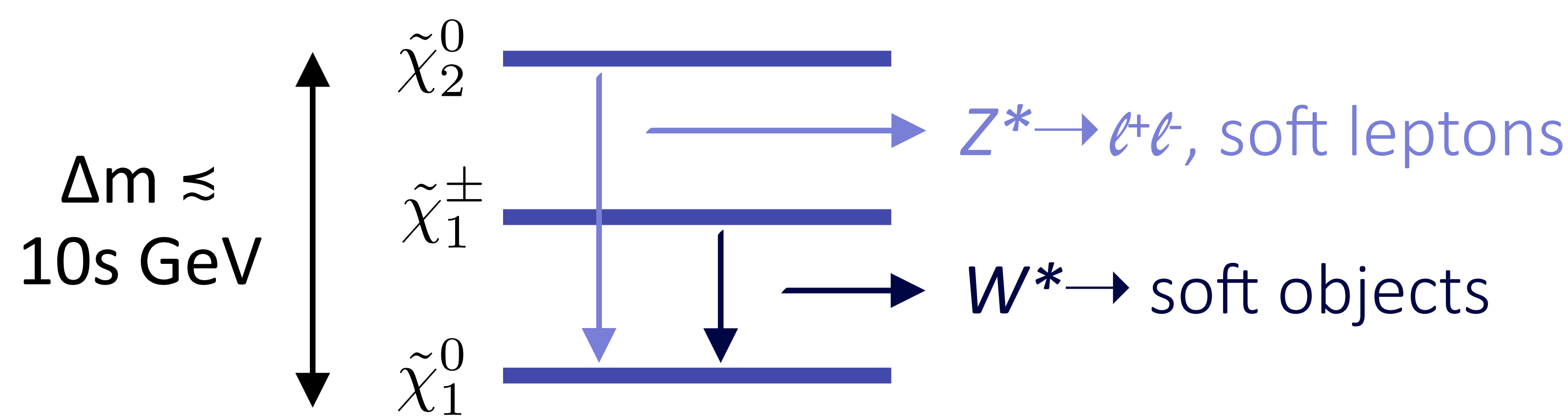

Main analysis challenge: soft leptons
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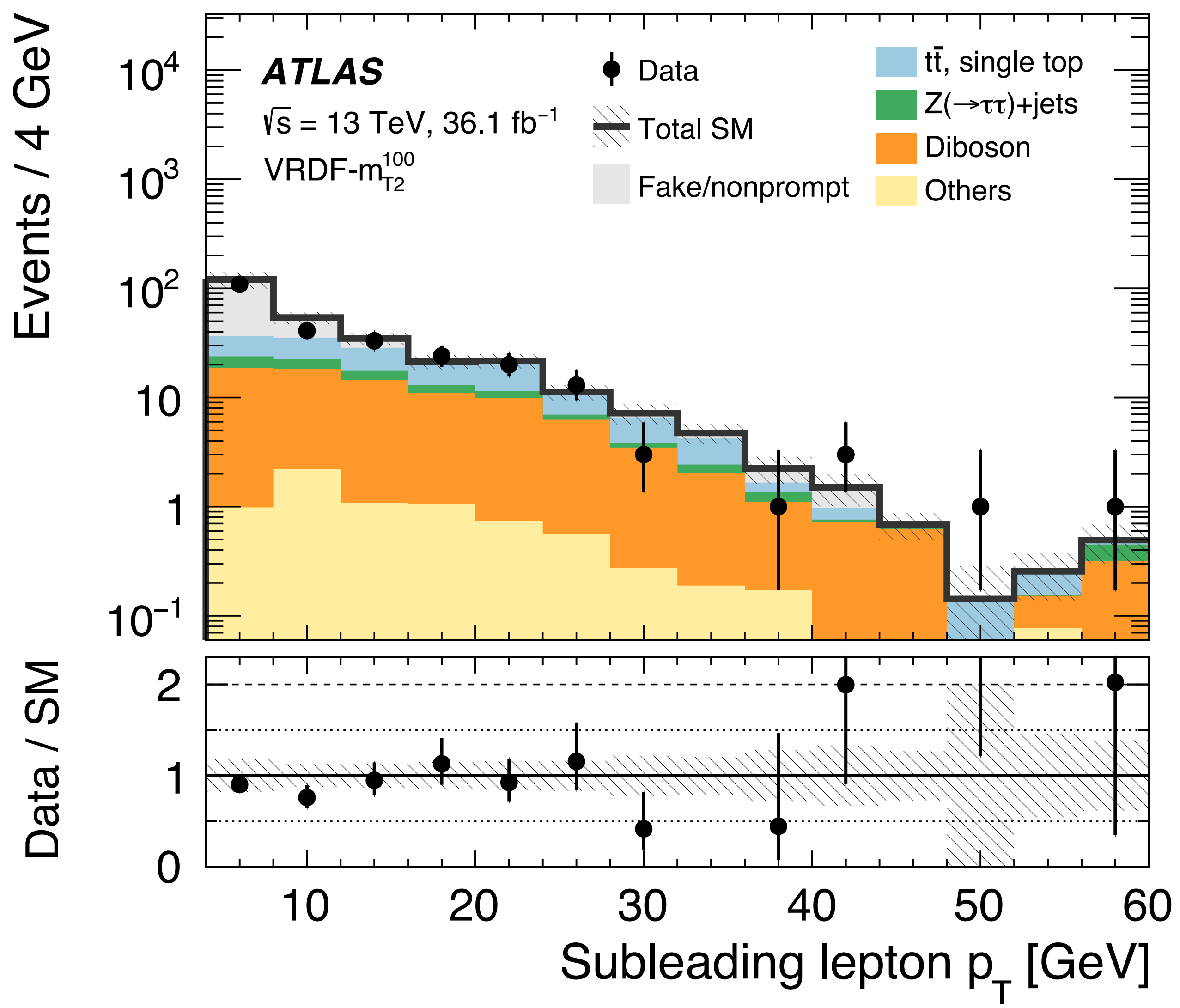
Low-p_T Leptons: Performance

Sensitivity impacted by soft ℓ performance

key to signal acceptance, background rejection (lepton mis-ID)



also connected to largest uncertainty!

Low-p_T Leptons: Performance

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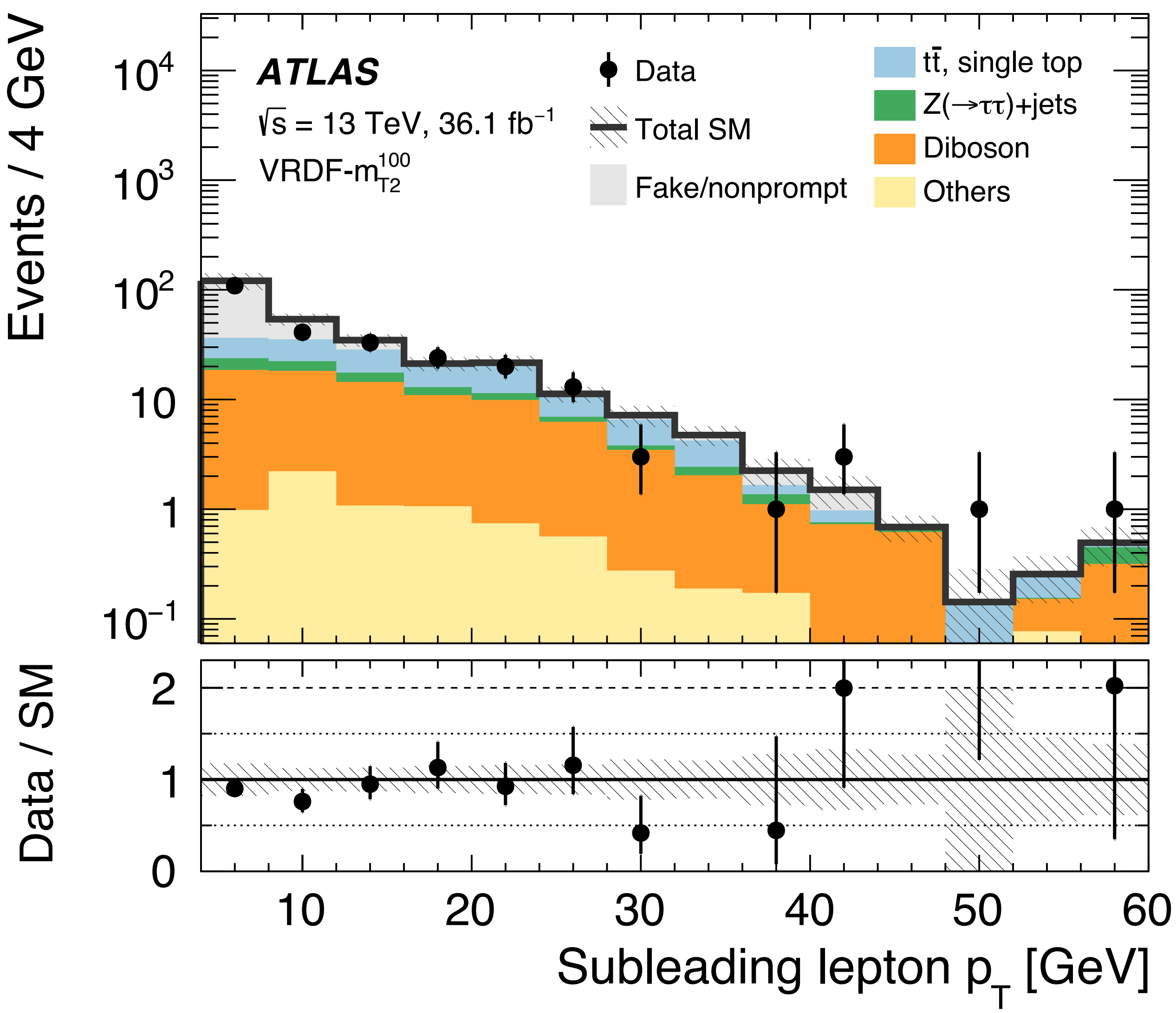

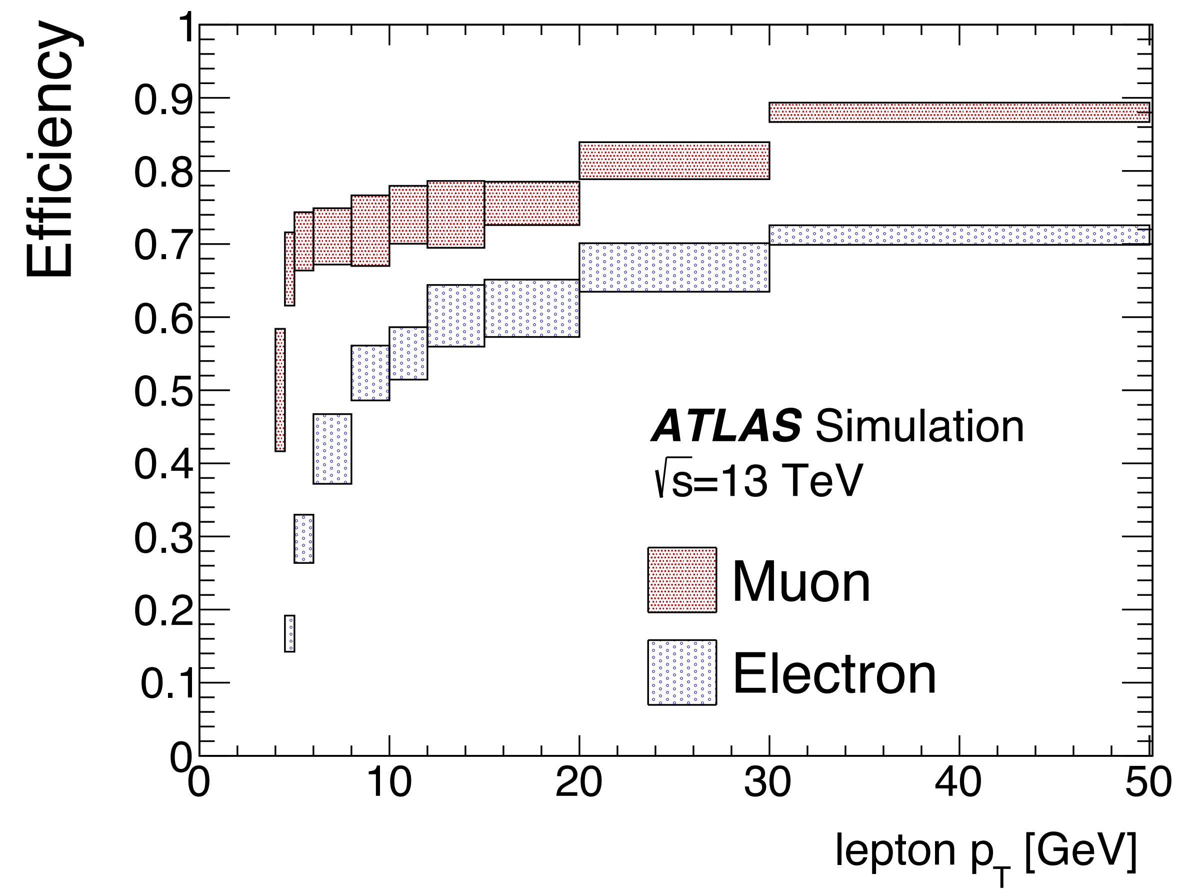

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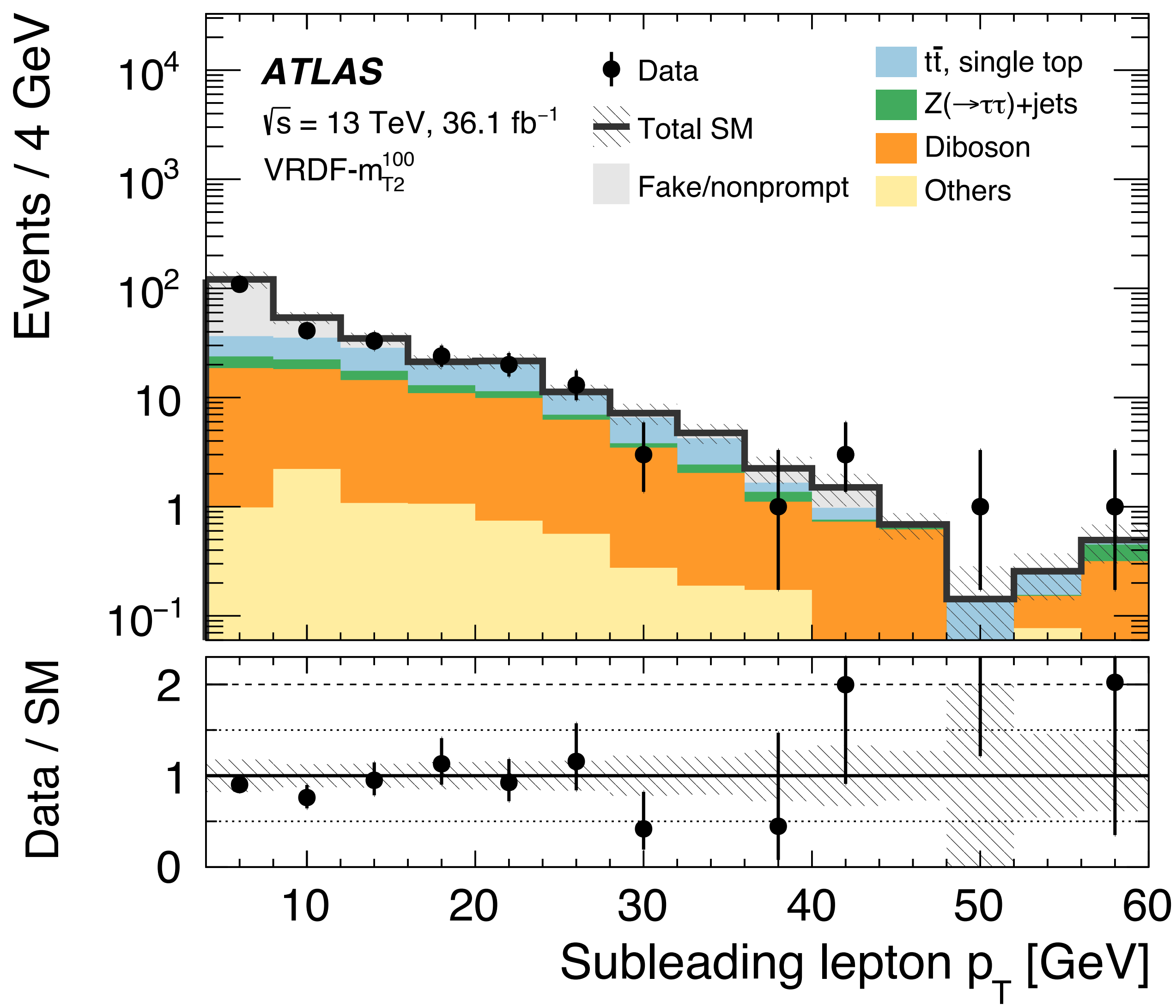

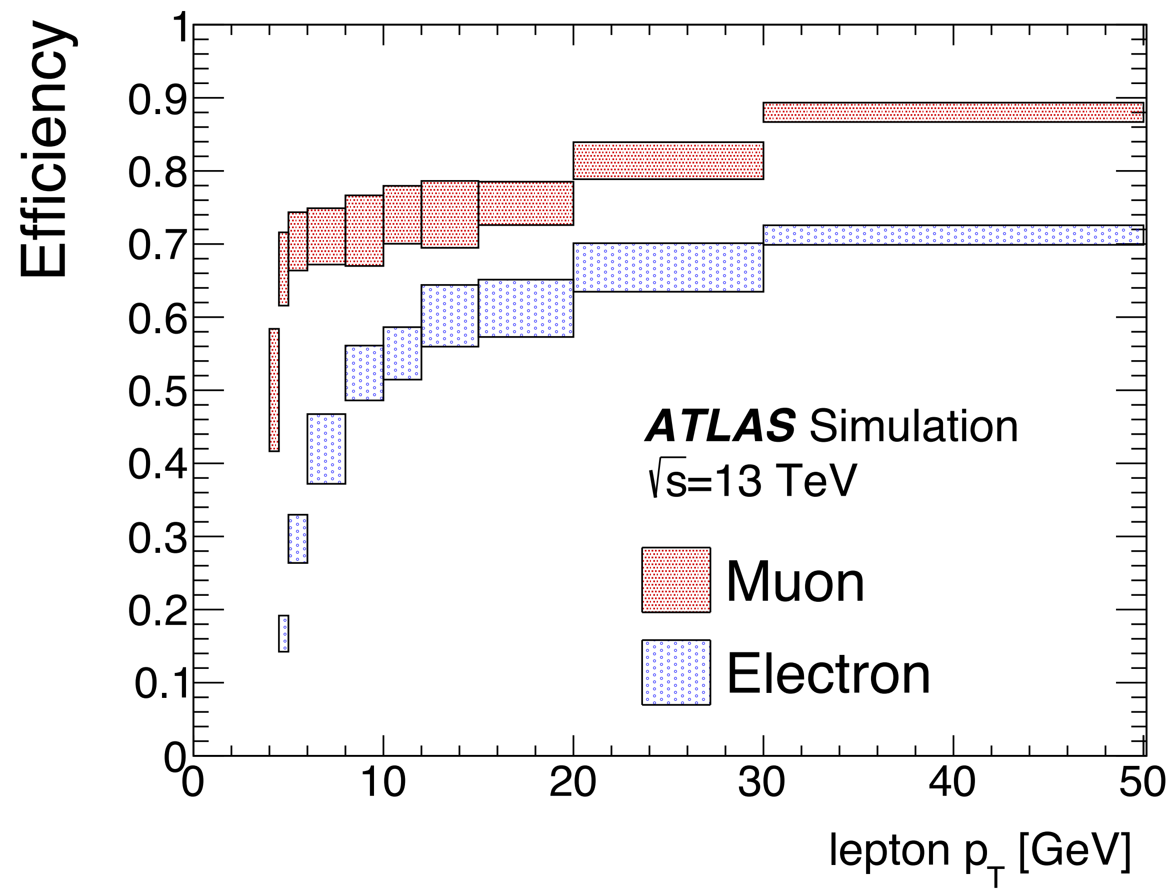

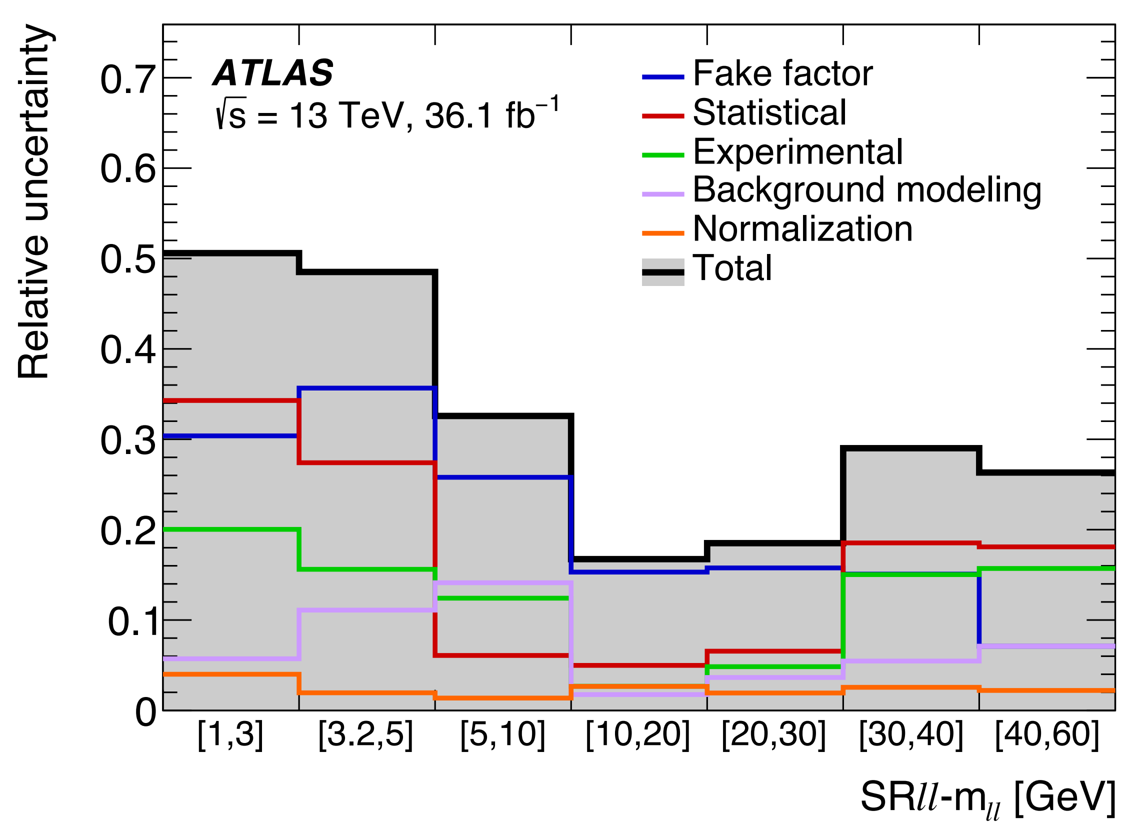

also connected to largest uncertainty!

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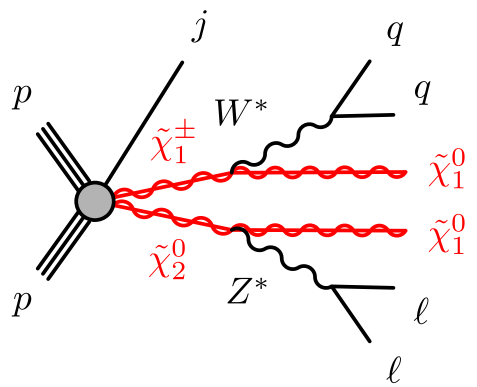
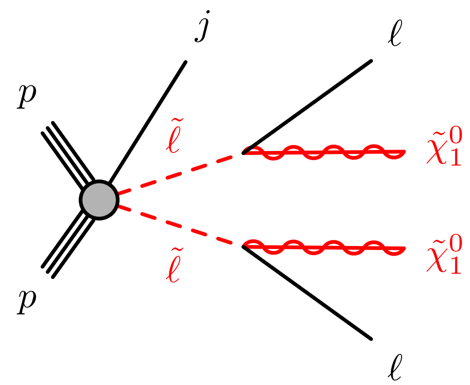
Signal Selection

Key variables: $m_{\ell\ell}$ (higgsinos) or m_{T2} (sleptons) and $E\!\!\!/_T/H_{T,lep}$

Backgrounds tend to have lower $E\!\!\!/_T$ and harder leptons ➠ smaller $E\!\!\!/_T/H_{T,lep}$



expect kinematic edge in $m_{\ell\ell}$ at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

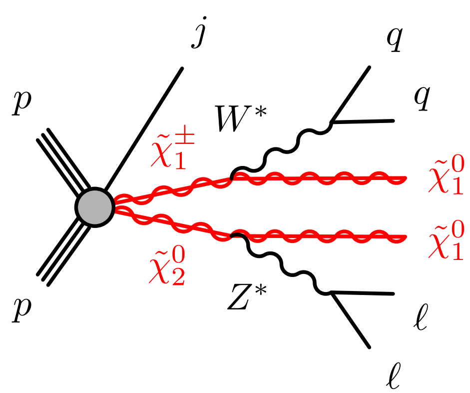


expect kinematic edge in m_{T2} at $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$

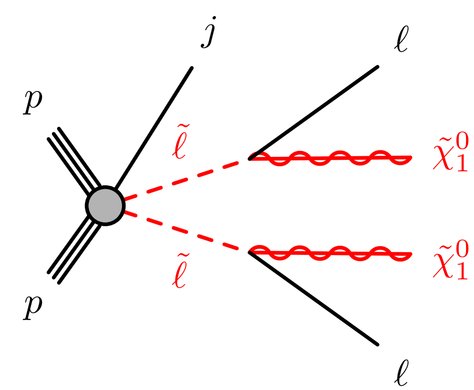
Signal Selection

Key variables: $m_{\ell\ell}$ (higgsinos) or m_{T2} (sleptons) and $\not\!\!E_T/H_{T,lep}$

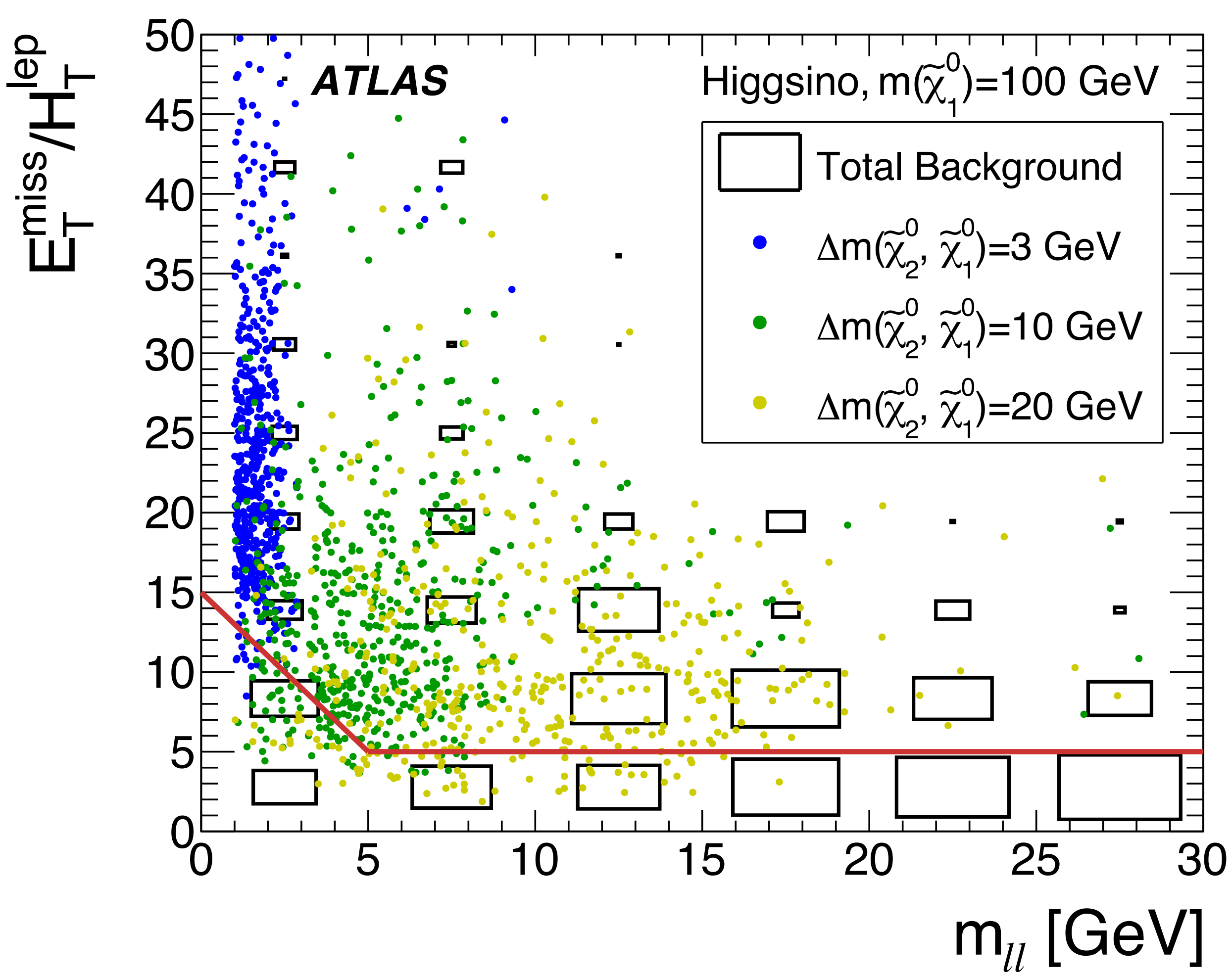
Backgrounds tend to have lower $\not\!\!E_T$ and harder leptons ➠ smaller $\not\!\!E_T/H_{T,lep}$

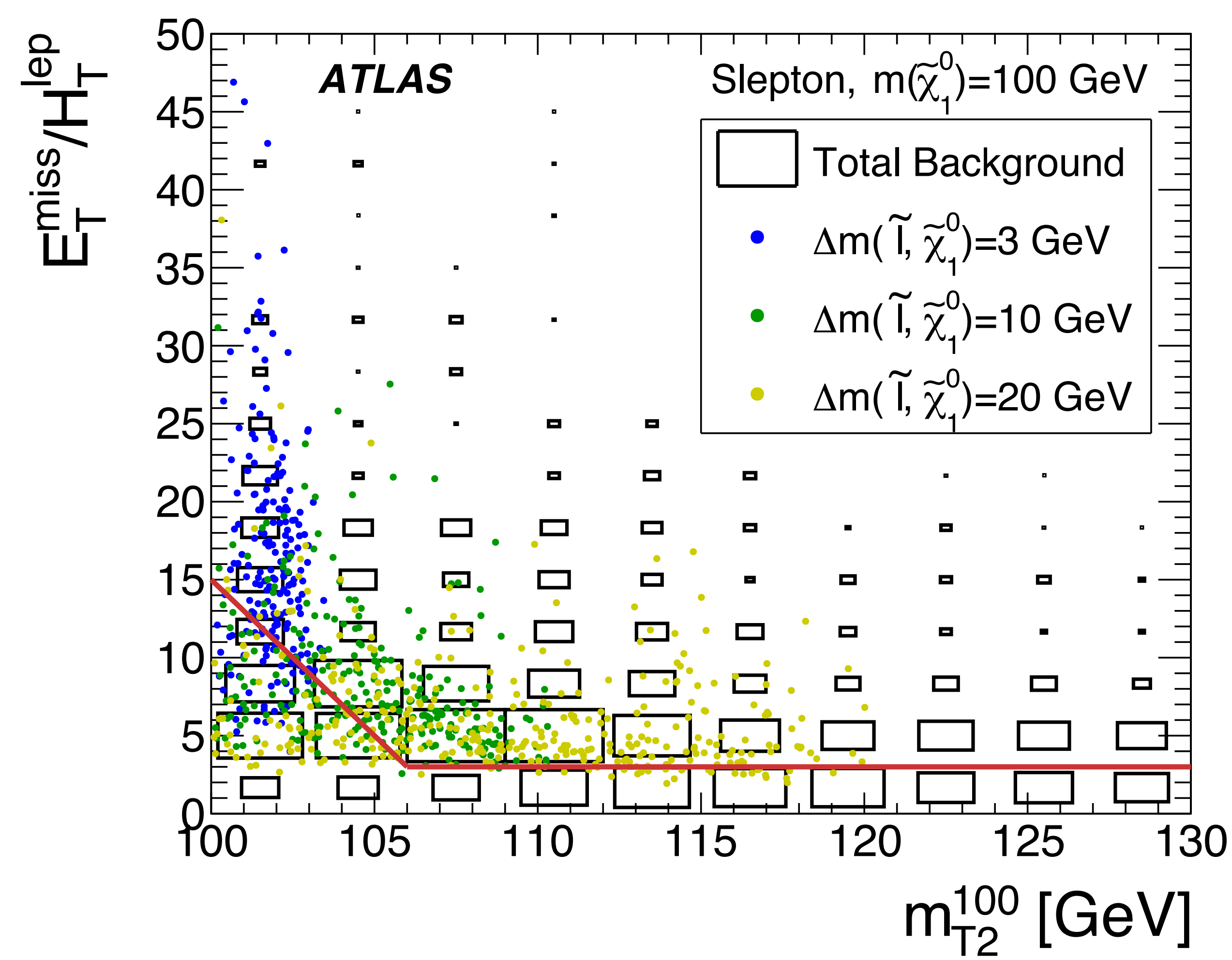


expect kinematic edge in $m_{\ell\ell}$ at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

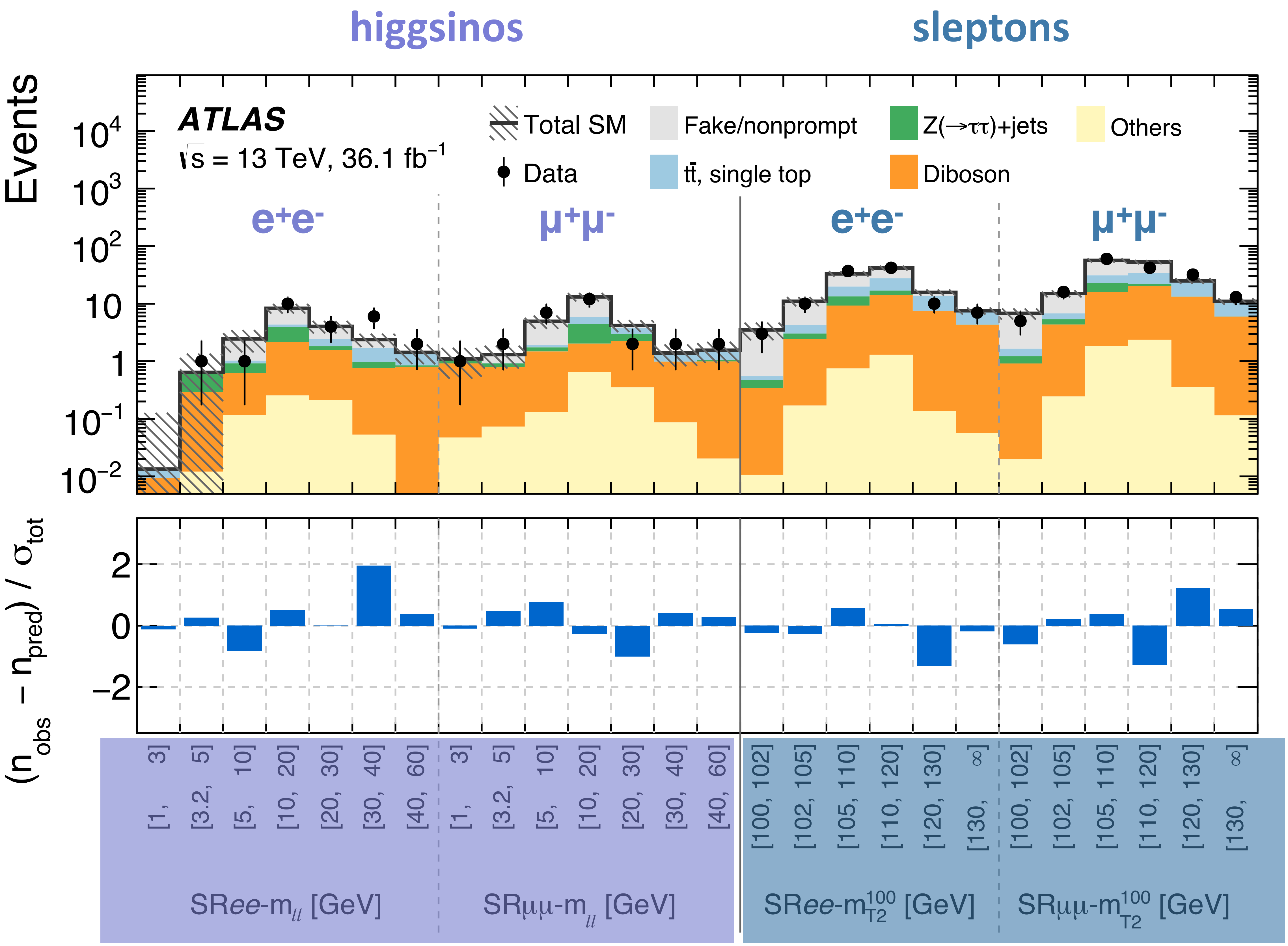


expect kinematic edge in m_{T2} at $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$



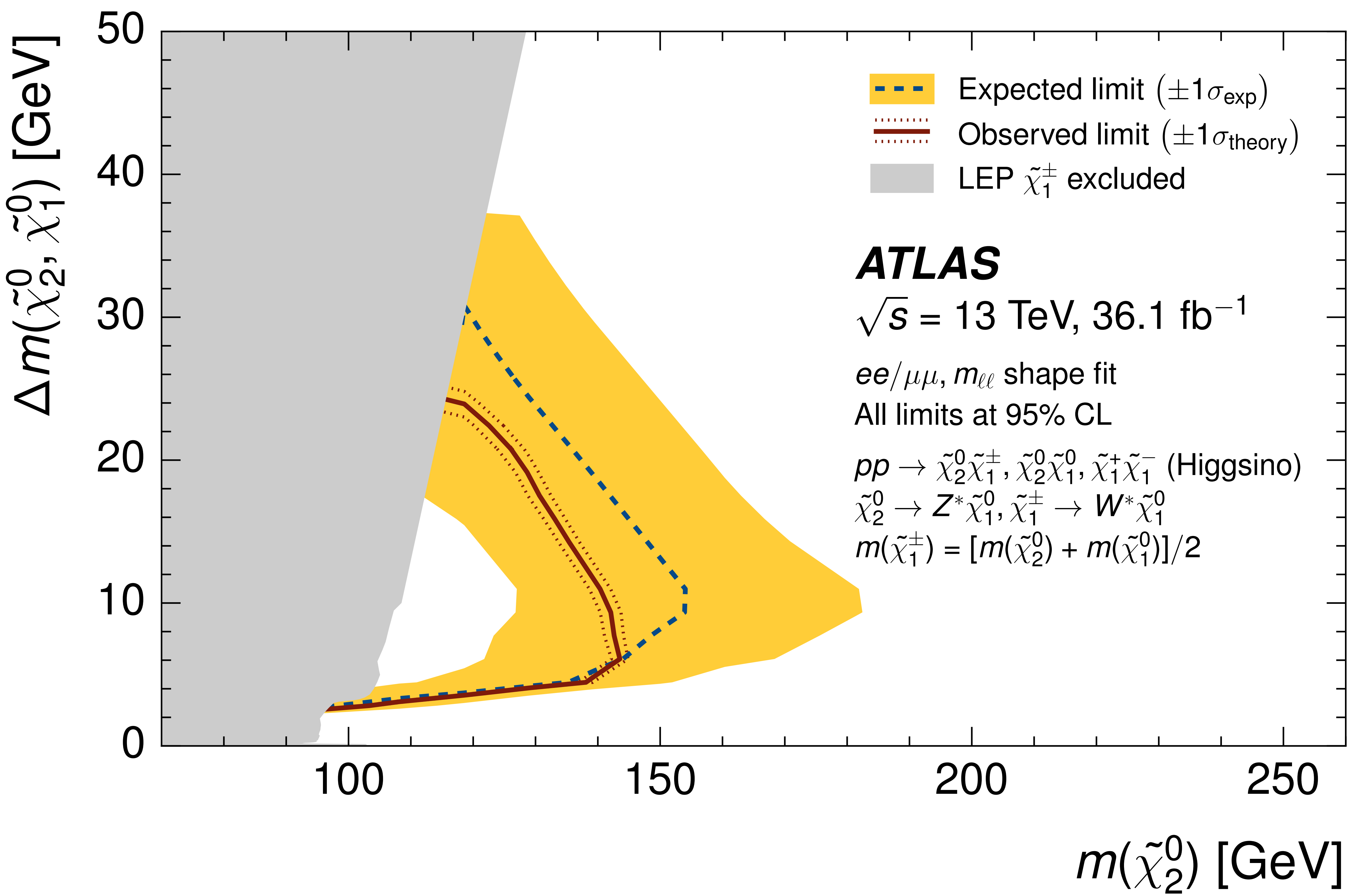


Results: Observed Event Yields



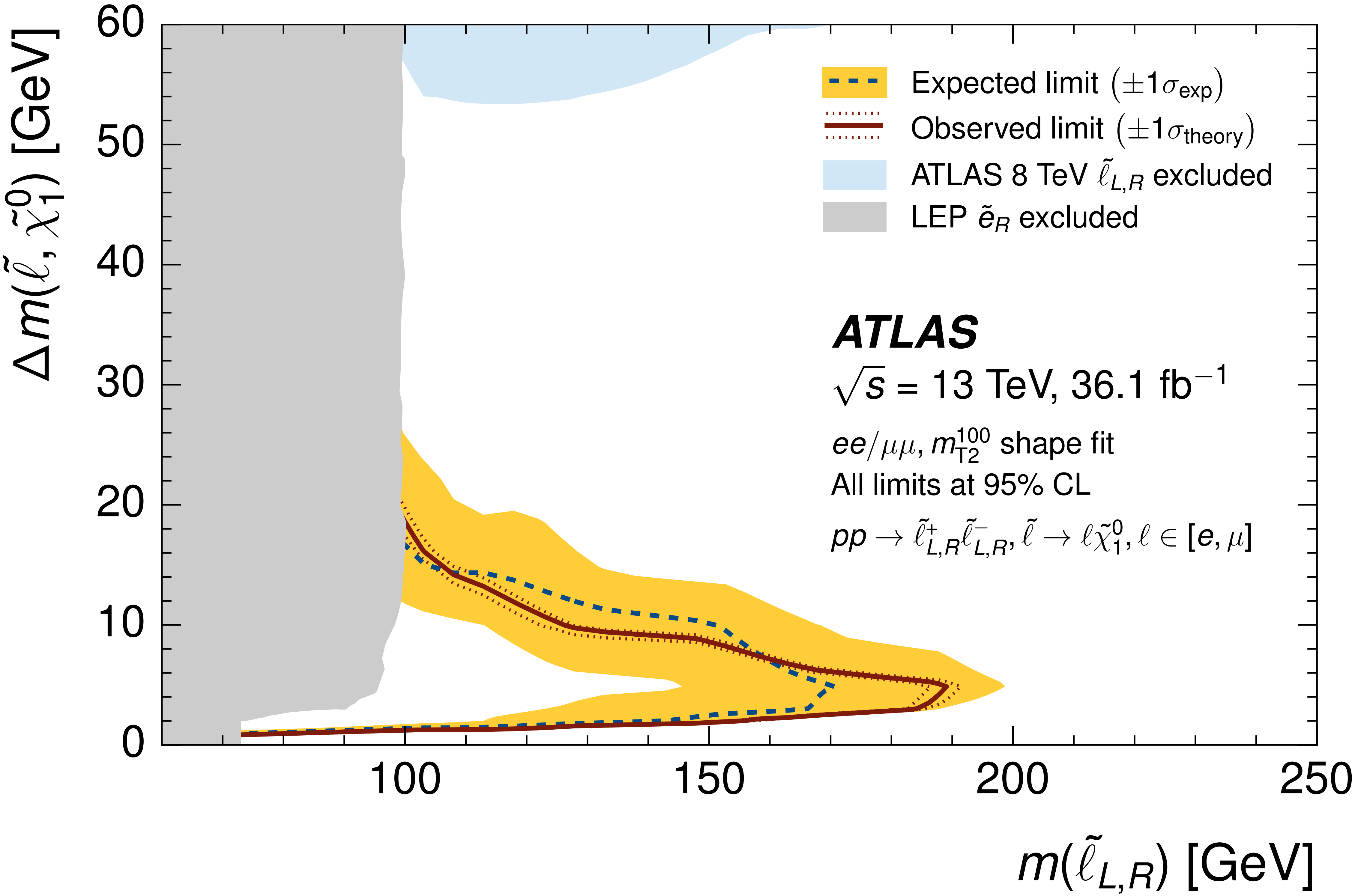
Results: 95% CL Limits

Exclusion limits on higgsinos exploiting multi-bin fit on $m_{\ell\ell}$



Results: 95% CL Limits

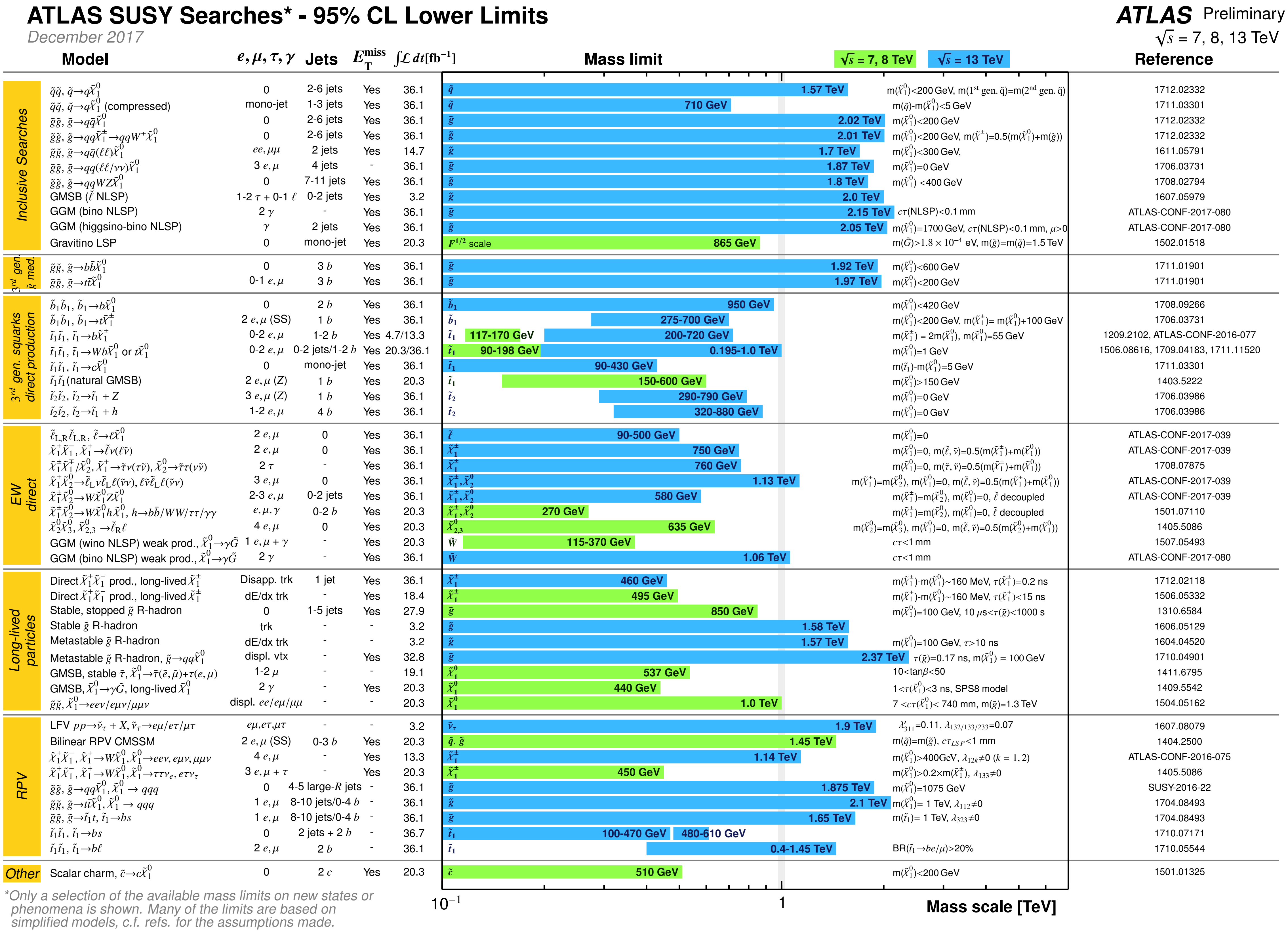
Exclusion limits on sleptons exploiting multi-bin fit on m_{T2}



A Bit Of Fortune-Telling…

Part IV - What next?

LHC: Stringent Limits, No New Physics…



La Gazzetta dello Sport

Tutto il rosa della vita

VIOLINO TEVEZ JUVE A UN PUNTO DALLO SCUDETTO

Doppietta Apache (ora a quota 20): 3-2 alla Fiorentina
Bianconeri campioni sabato col pareggio in casa Samp

CHAMPIONS (E NON SOLO)
Lazio e Roma un euroderby con 7 gol in due
E Toni fa... 18

IL GENOA VINCE 3-1, SAN SIRO CONTESTA: IL TECNICO VERSO L'ESONERO

CAPOLINEA

Dopo Run-2, per la panchina pronto Brocchi SUSY?

Anche Gasperini domina con i rossoneri. Inzaghi appare ormai fuori gioco e rassegnato: «Ho dato tutto, ma non è bastato. Vado a testa alta, questa squadra resterà comunque nel mio cuore»

IL COMMENTO di Sebastiano Vernazza

E' UN INGLORIOSO FINALE DI UNA FANTASTICA EPOPEA

IL ROMPIPALLONE di Gene Gnocchi

SUSY

MR. BEE
TRATTA CON SILVIO OFFRE 500 MILIONI ED E' OTTIMISTA OGGI LA RISPOSTA

Ad Arcore quattro ore di vertice, il thailandese punta al 60% del club. Sullo sfondo restano i cinesi

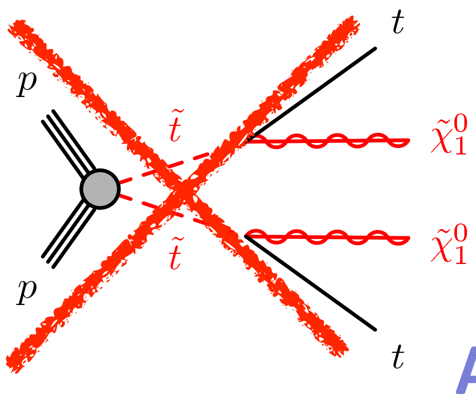
L'INTERVISTA
Mayweather «Aggancio Marciano e mi fermo»

IL POSTICIPO
De Laurentiis: «Caro Benitez ti prendo 3 big Ma sabato dimmi se resti a Napoli»

DA NON PERDERE

FATTURE ELETTRONICHE ALLA PA?
Le Facciamo Noi Per Te!
CompEd Servizi

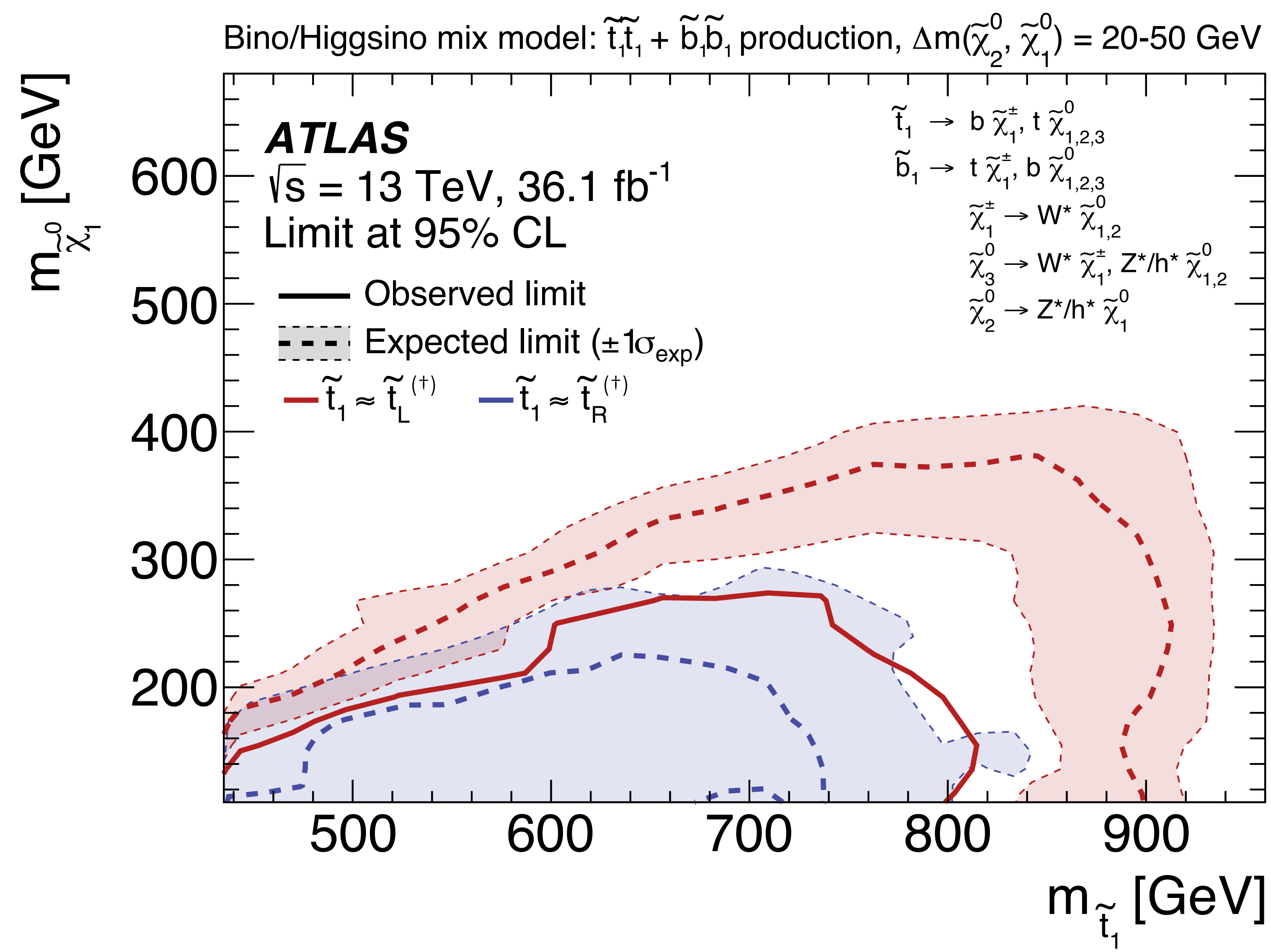
Hunting For ~~Vanilla~~ realistic? Stops

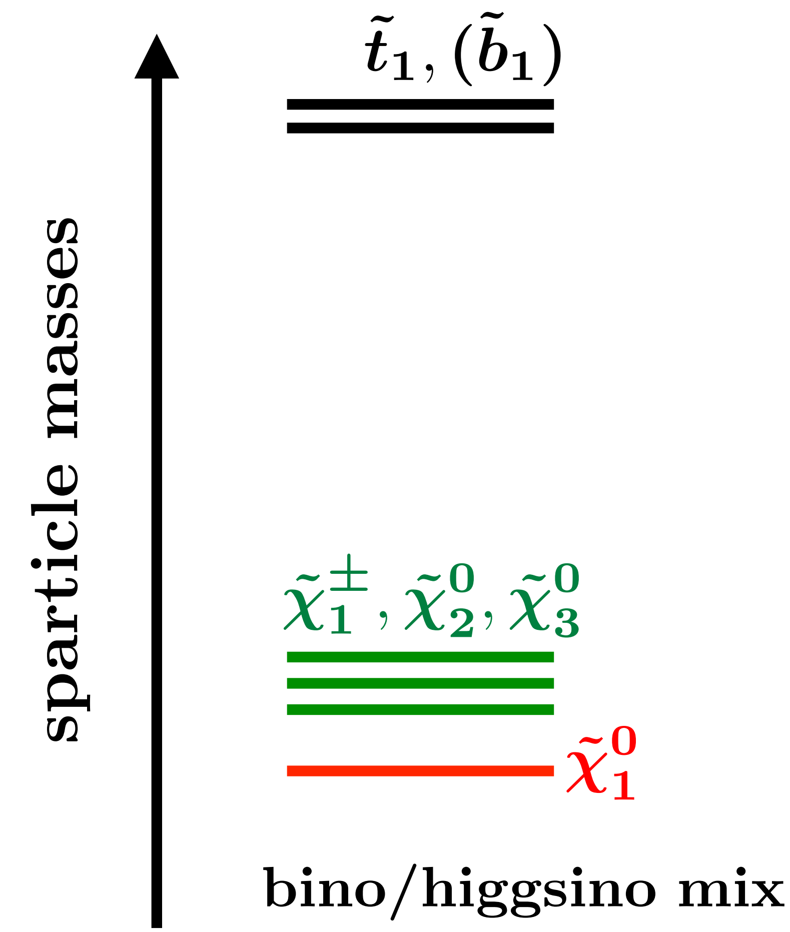


Stop search reinterpreted in terms of a pMSSM-inspired model:

- ➙ correct dark matter relic abundance: $0.10<\Omega h^2<0.12$
- ➙ natural, compressed EWKinos mass spectrum

A light stop with a light higgsino-like LSP might still be allowed





(†) "handiness" of scalar top comes from couplings (SM partner, top, is a fermion)

LHC Long-Term Schedule

LHC

HiLumi HL-LHC PROJECT

Run 1		Run 2		Run 3	Run 4, 5, ...
7-8 TeV		13 TeV		14 TeV	14 TeV

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2037

30 fb^{-1}	shutdown: LS1	*150 fb^{-1}*	shutdown: LS2	*300 fb^{-1}*	shutdown: LS3	*3000 fb^{-1}*

current analyses:
36 fb^{-1}

today:
x2.5 more data

in 5 years:
x10 more data

HL-LHC Prospects For SUSY

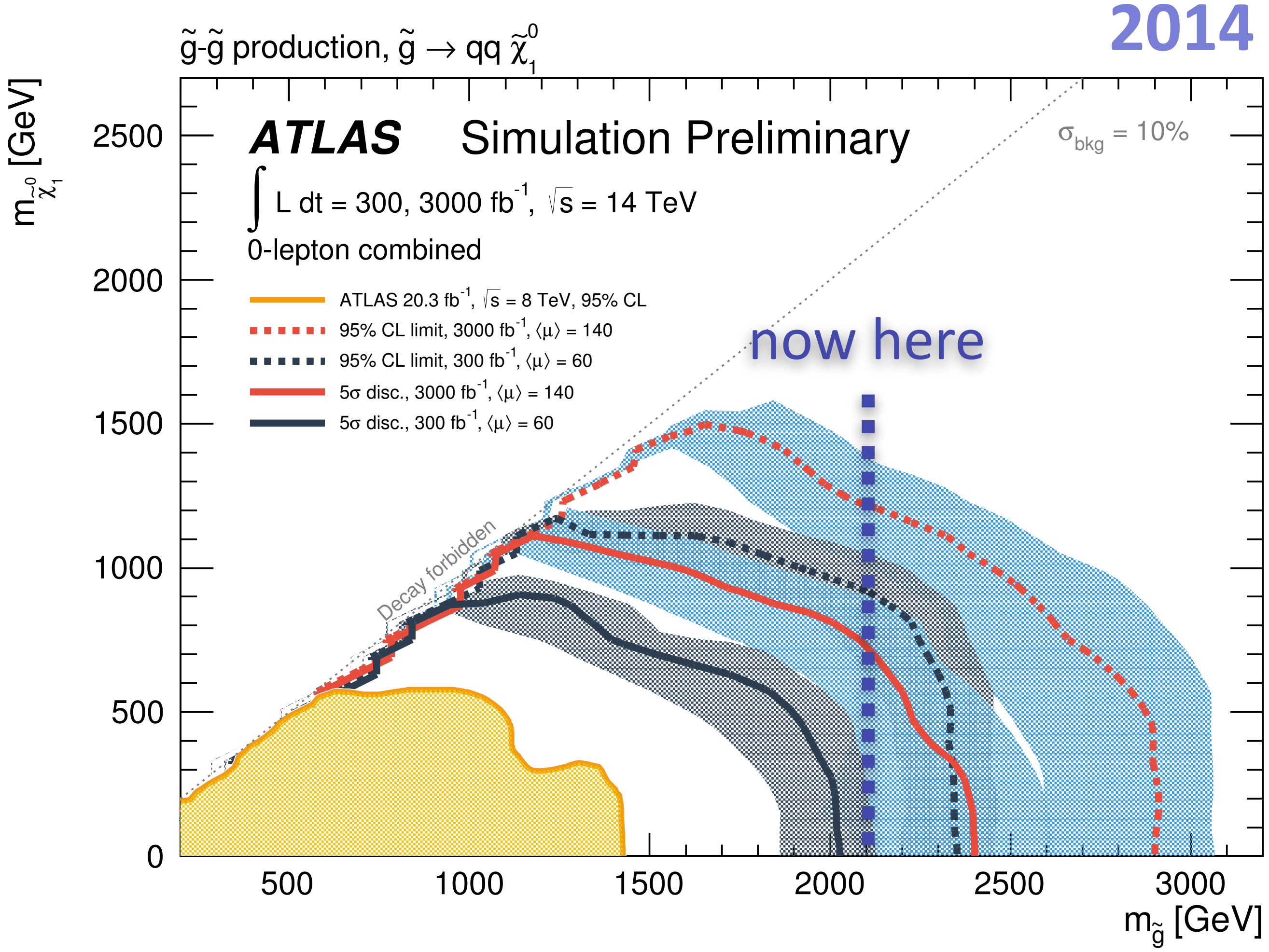
100x data expected to bring <50% improvements in mass reach

extrapolations based on simple analyses → probably over-conservative…

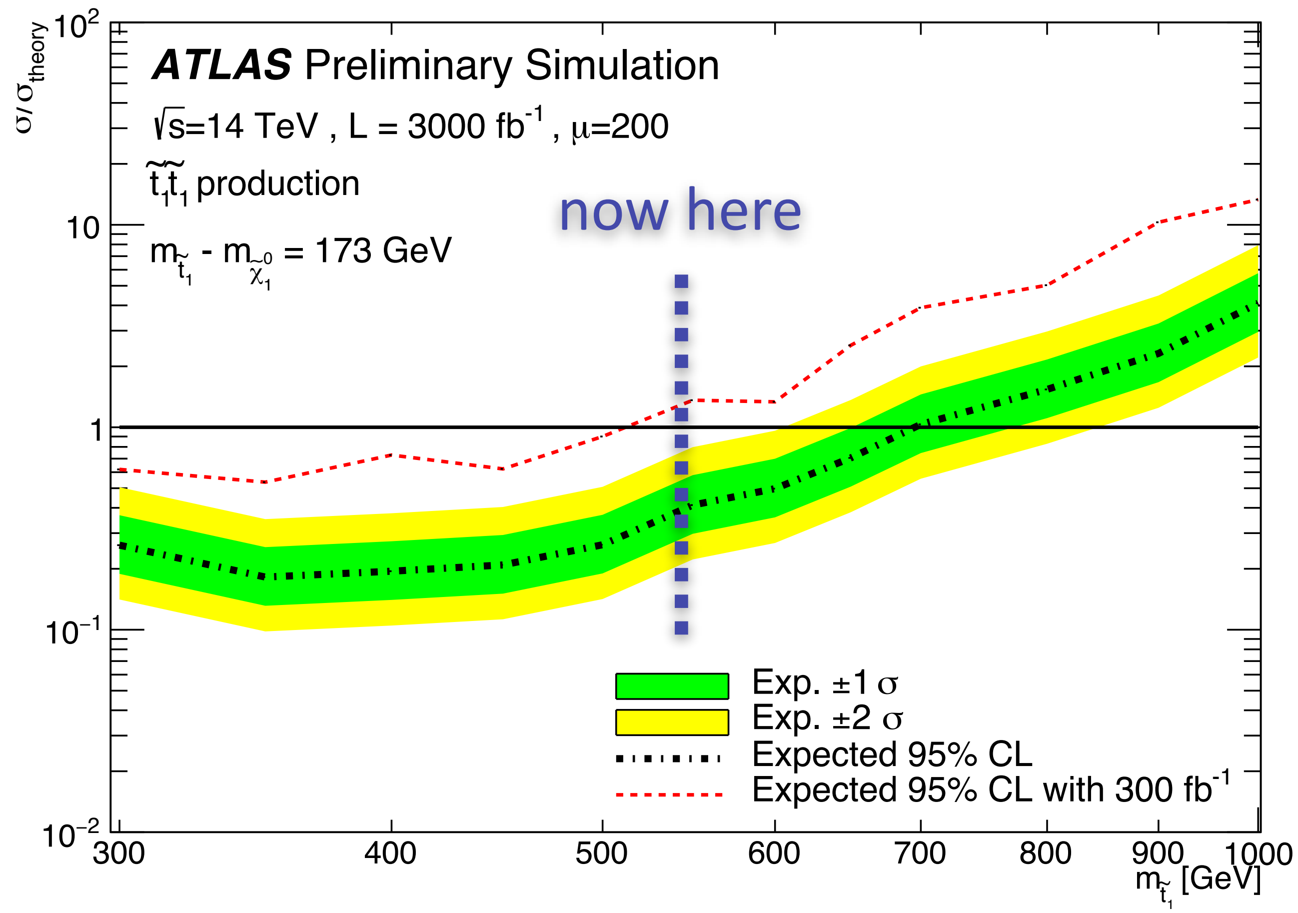
…however, the main message stands!

searches will move toward more sophisticated analysis techniques and more complex signatures

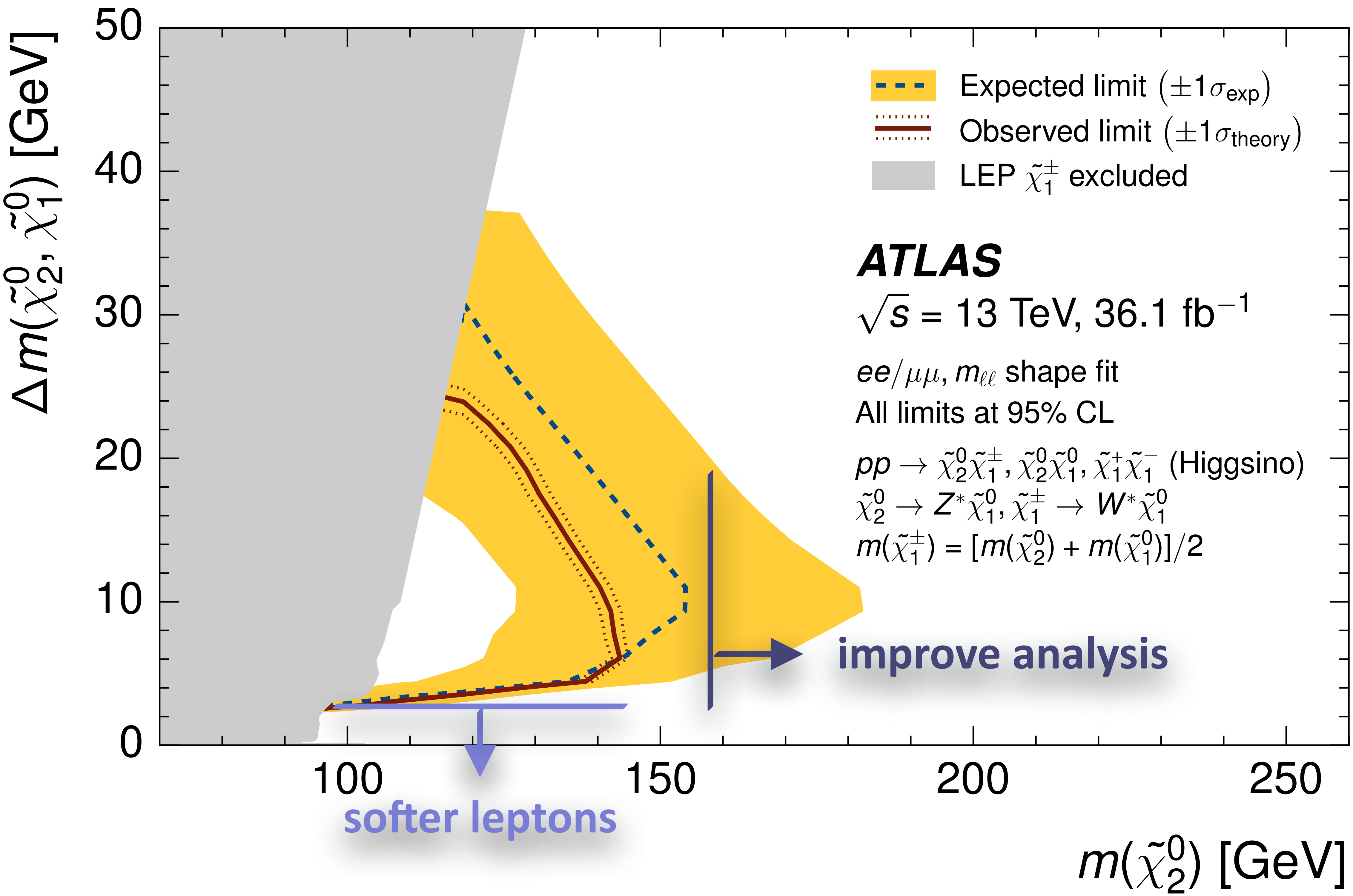
2014



2016



We Need To Get Smarter!

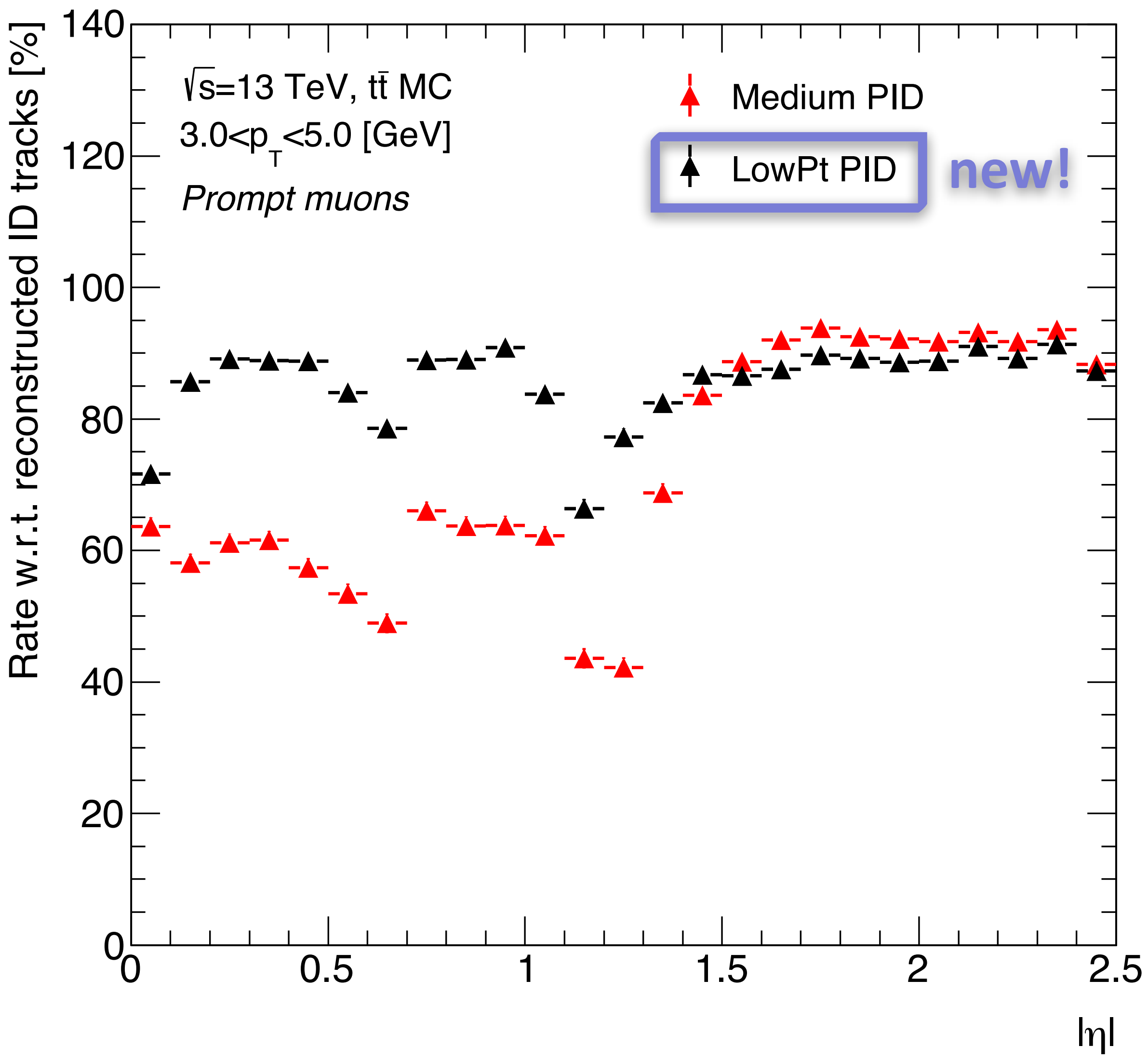


Improving Reach Of Higgsino Analysis

Softer leptons → lower Δm

designed new PID level for soft muons

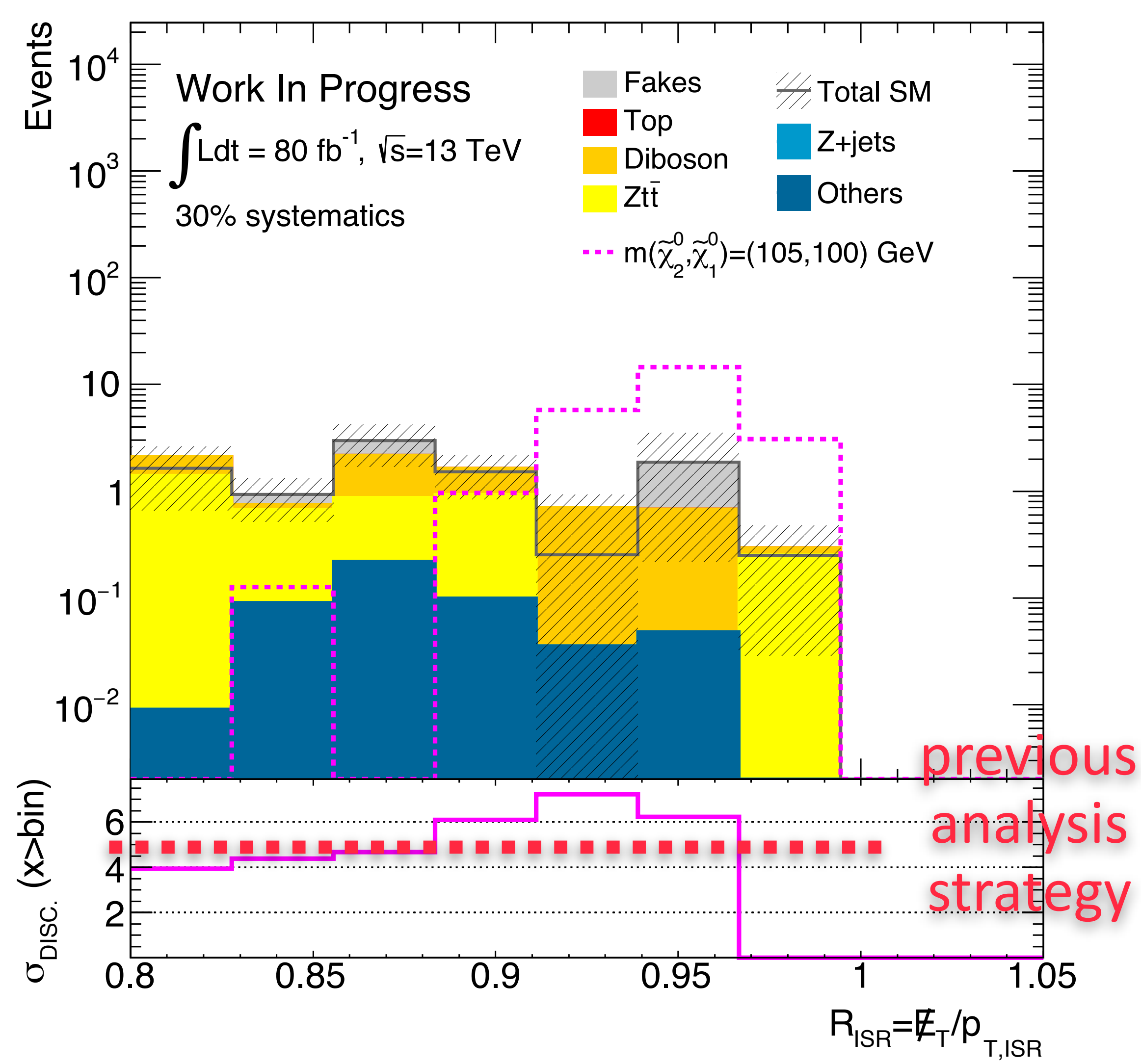
recovers efficiency for p_T<6 GeV tracks, improves π/K rejection for p_T>6 GeV



Improve analysis → larger m reach

adopt thrust-based ISR identification

very similar to the diagonal stop case, large improvements for small mass splittings

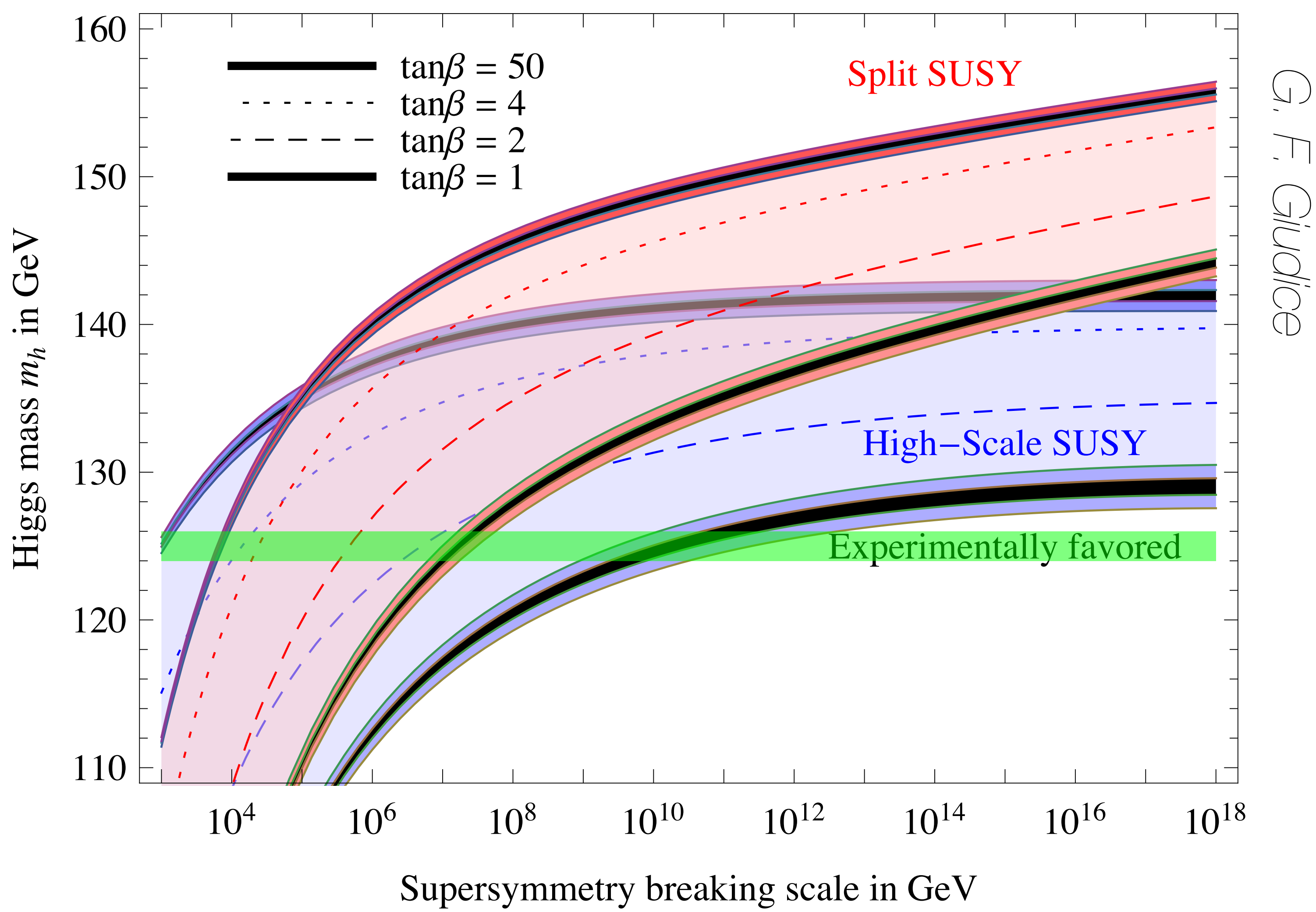


Long-Lived And/Or Highly-Ionizing Particles

Long-lived and/or highly-ionizing particles ("R-hadrons") well motivated

Hideyuki Oide (Genova) and Larry L. Lee (Harvard) leading current efforts in ATLAS

Interest can only rise if we will progressively abandon natural SUSY!



"Flavor Anomalies"

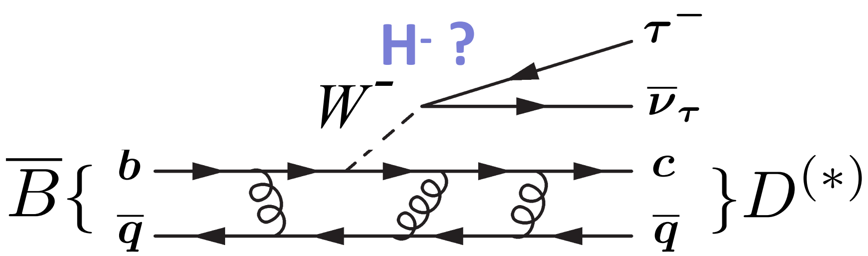
New physics can show up first from indirect constraints (LHCb - intensity frontier)

first evidences of lepton flavor universality violation in b→c and b→s transitions?

Charged current

NP at tree level?

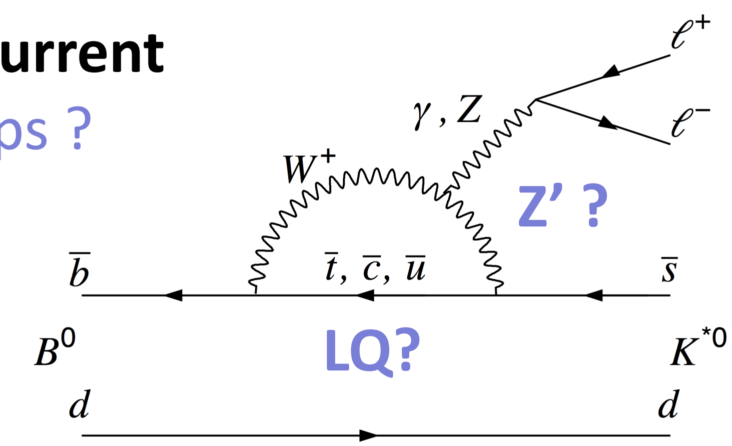
R→ $\frac{\tau\nu_\tau}{\mu\nu_\mu}$

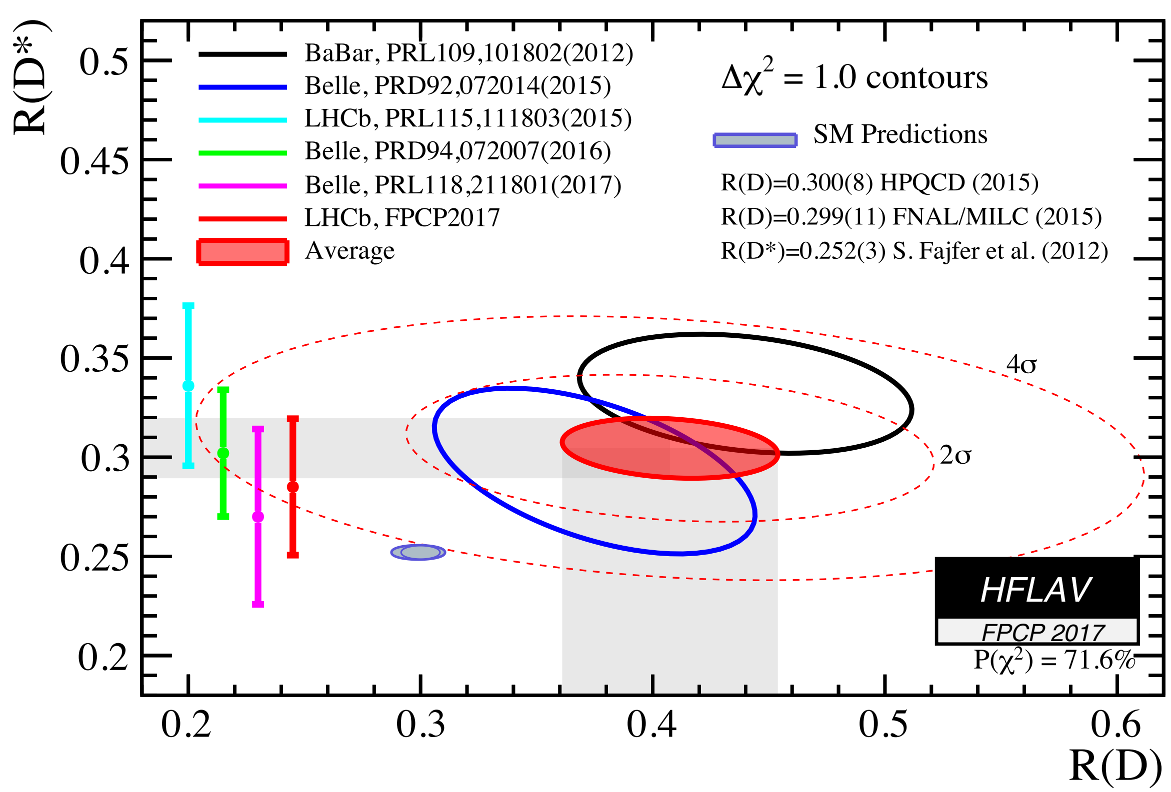


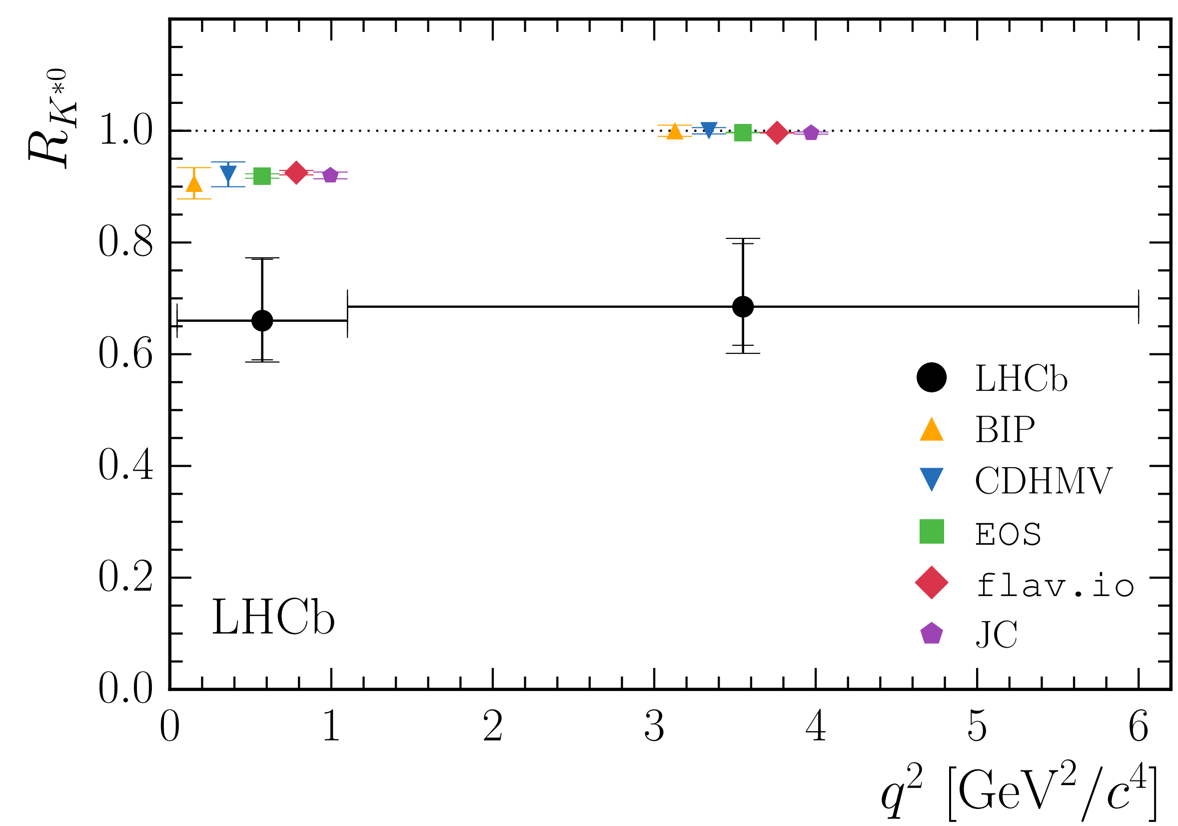
Neutral current

NP in loops ?

R→ $\frac{\mu\mu}{ee}$

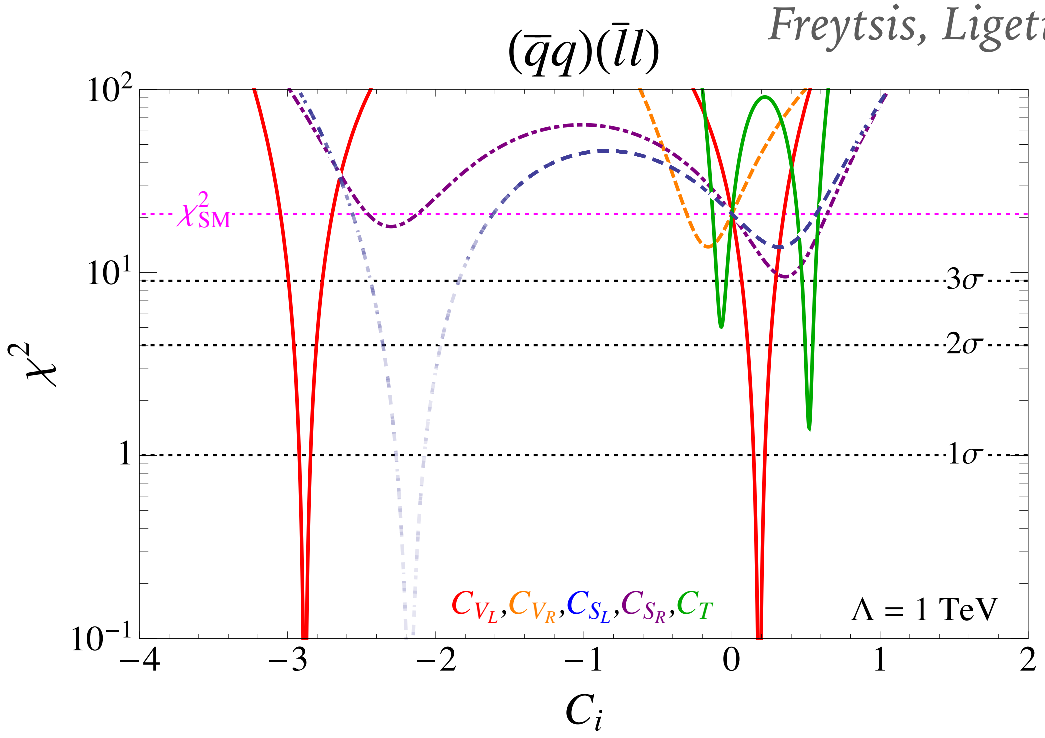


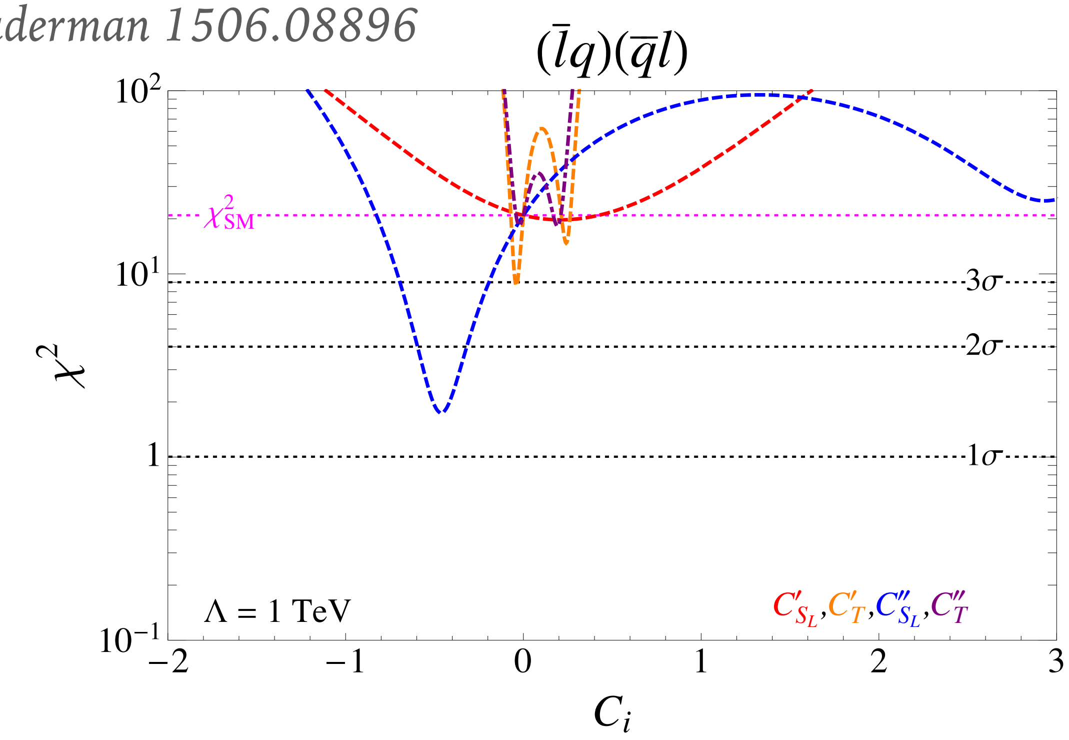




"Flavor Anomalies"

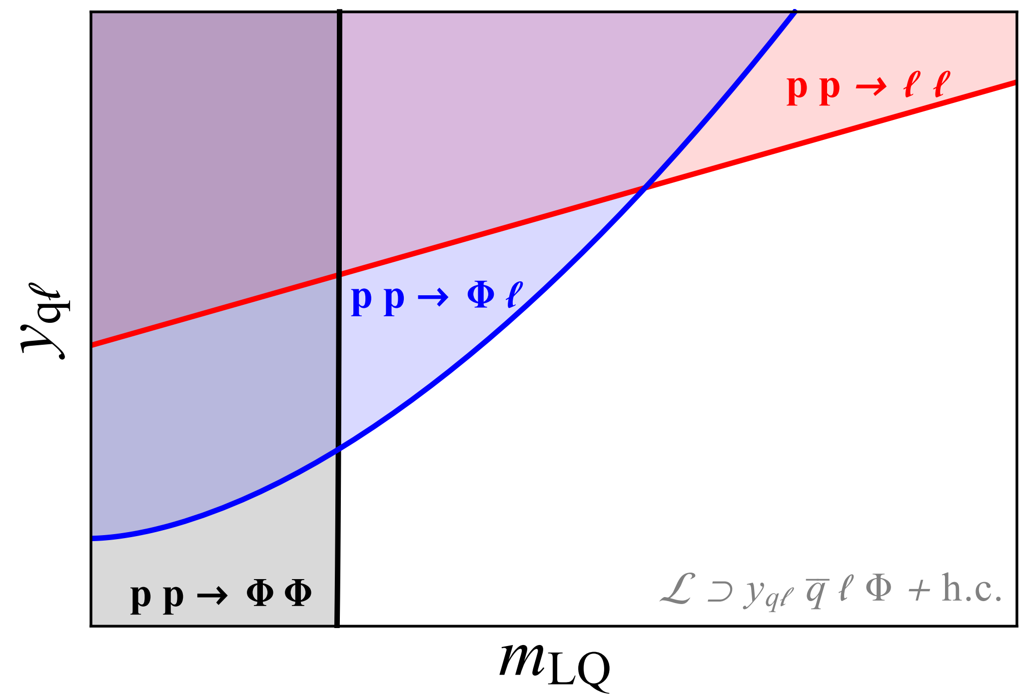
Freytsis, Ligeti, Ruderman 1506.08896





Favored interpretation: ***leptoquark?***

If real, though for SUSY but great for SUSY searches!



E.g. colored scalar, decaying into:

c,b,t + MET

c,b,t + **τ**,μ

Conclusions

Colombo left Genova with an idea: he sailed to India… and found America!

We also left for a long journey seeking new physics, but no land at the horizon yet…

Will we find SUSY? Will we find our Americas?

Conclusions

Colombo left Genova with an idea: he sailed to India… and found America!

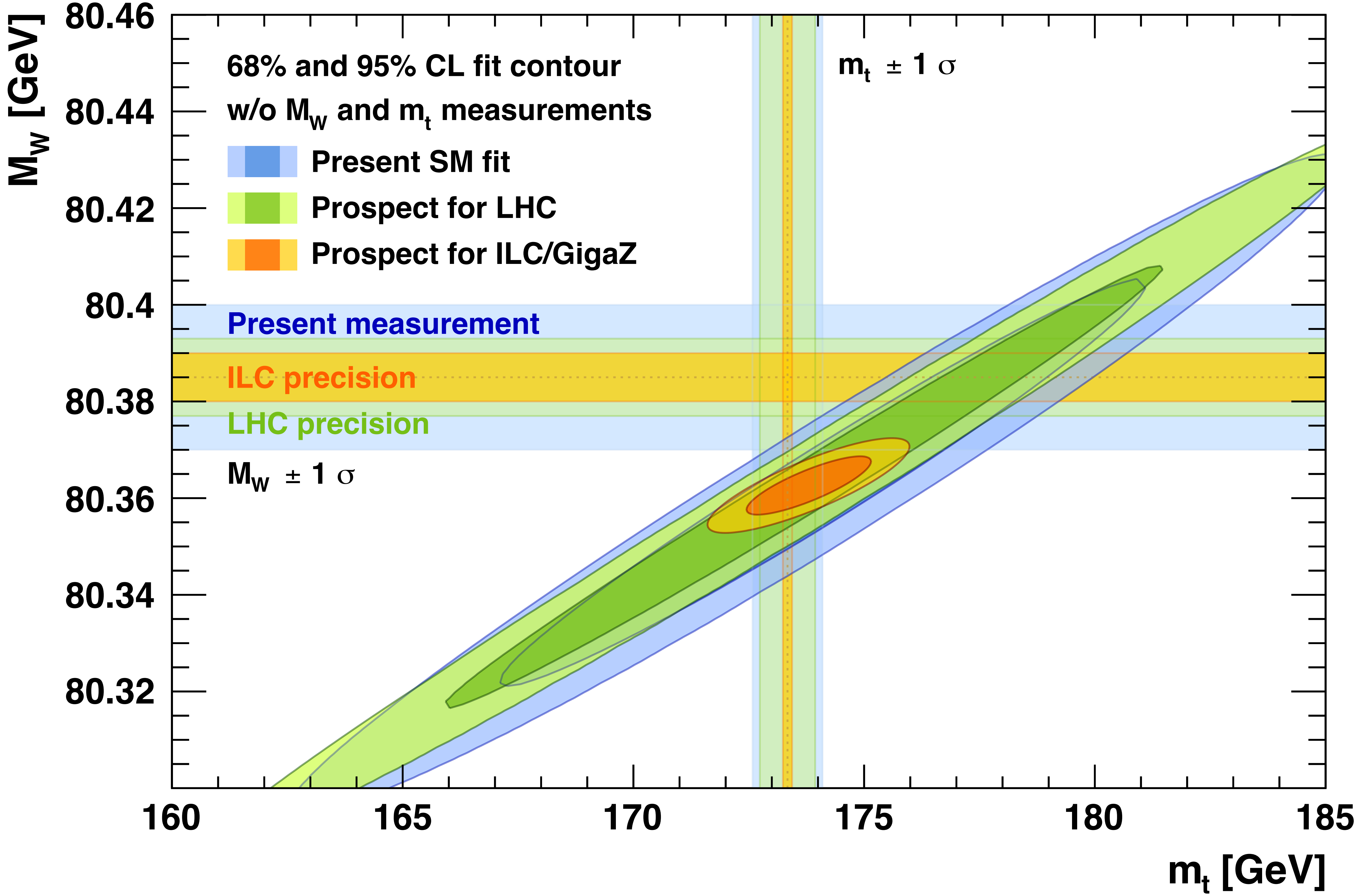
We also left for a long journey seeking new physics, but no land at the horizon yet…

Will we find SUSY? Will we find our Americas?

One thing is for sure: no matter what, we will have a much richer cartography, which will dictate the direction of next generation of HEP experiments

Spares

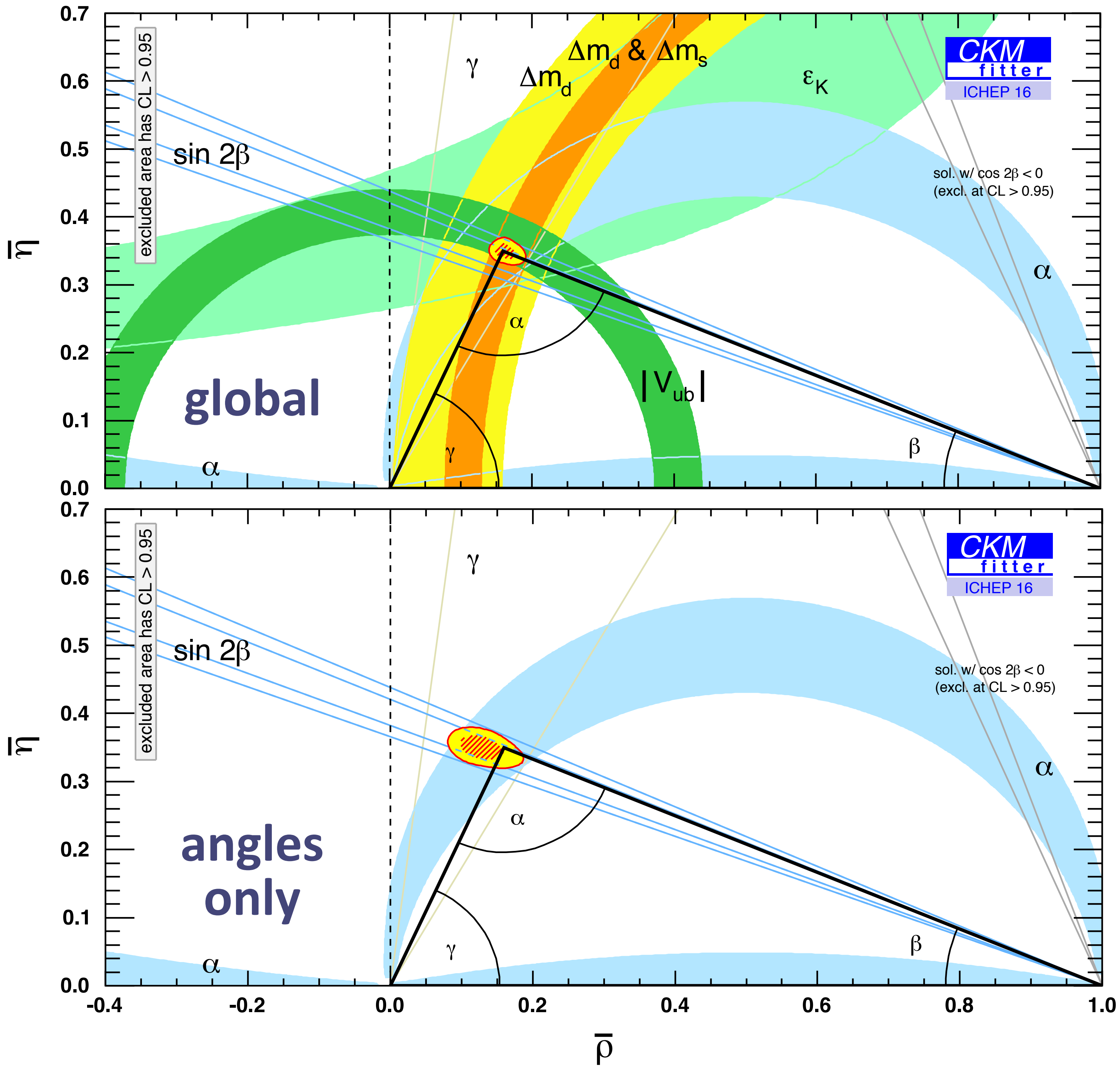
Precision Measurements Of SM Parameters



CKM Matrix: Measuring γ

near future | intensity: LHCb

γ: least constrained angle of unitary triangle!



Insensitive to "pollution" from BSM physics: perfect reference to seek for SM deviations using global fits

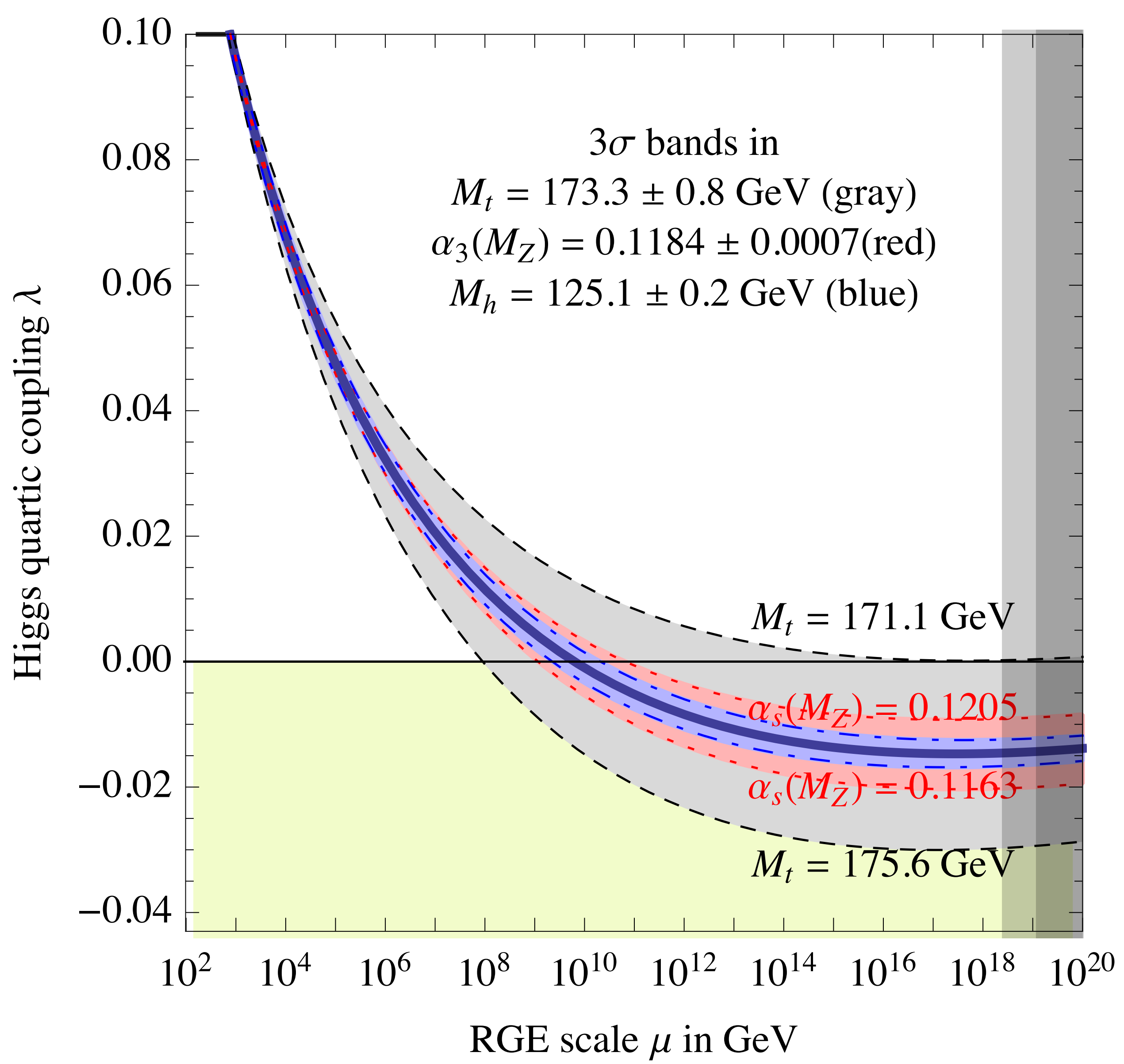
Accessible in B→DK decays involving tree-level processes with ≈ no hadronic uncertainties

Currently knows within a ≈5° accuracy: beating the 1° barrier is one of LHCb goals

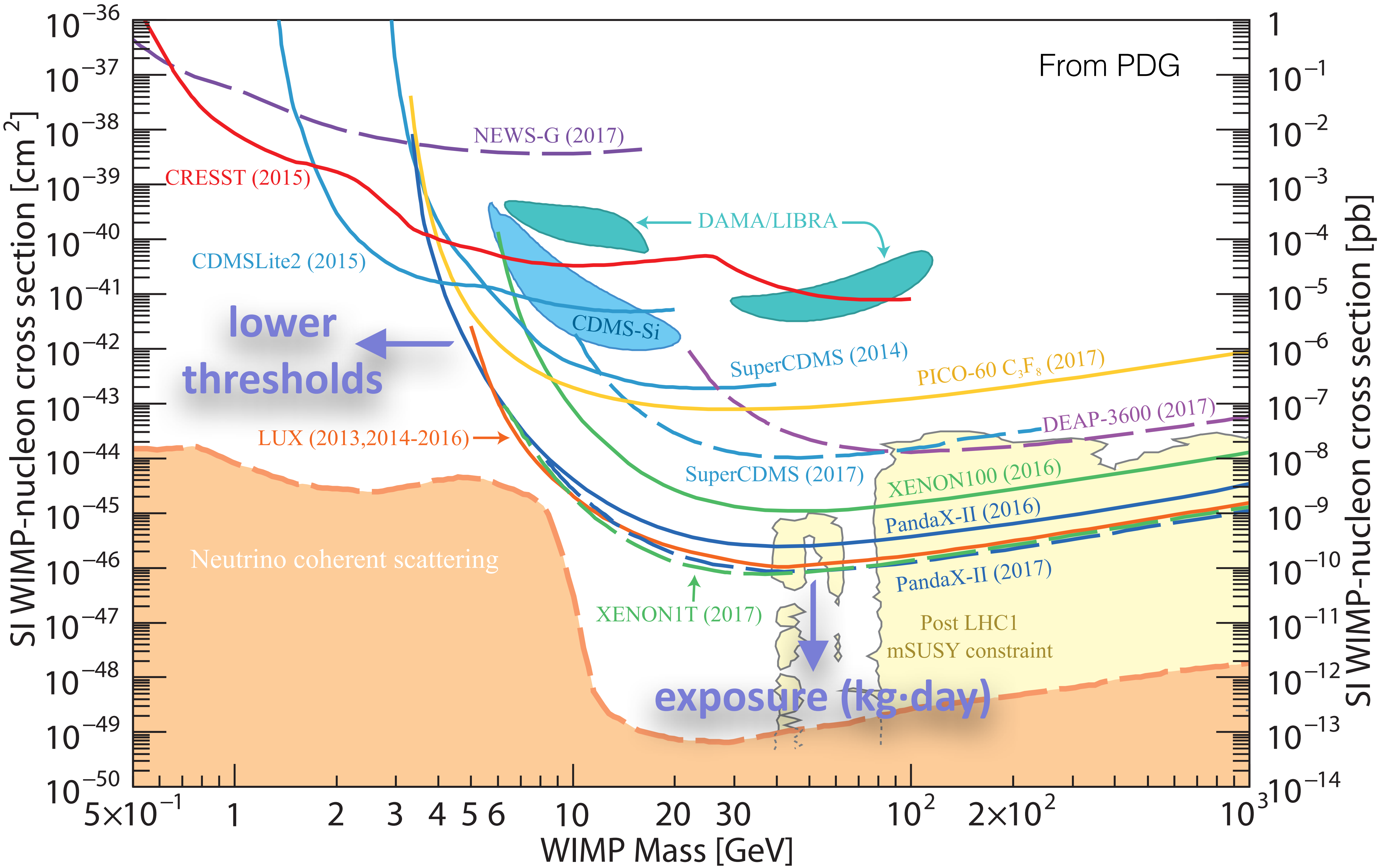
Running Of Higgs Self-Couplings

Investigating the near-criticality of the Higgs boson

Dario Buttazzo[a,b], Giuseppe Degrassi[c], Pier Paolo Giardino[a,d], Gian F. Giudice[a], Filippo Sala[b,e], Alberto Salvio[b,f], Alessandro Strumia[d]



Dark Matter: Direct Detection

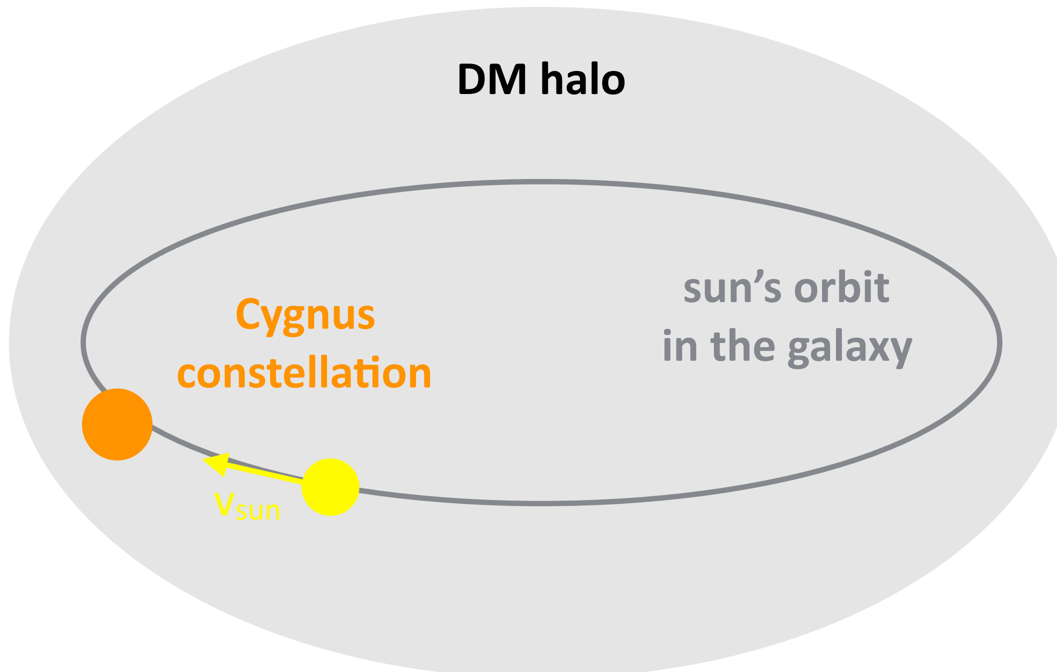


Dark Matter: Directional Direct Detection

near future | intensity: LHCb | cosmic/neutrino frontier

Anisotropic signal

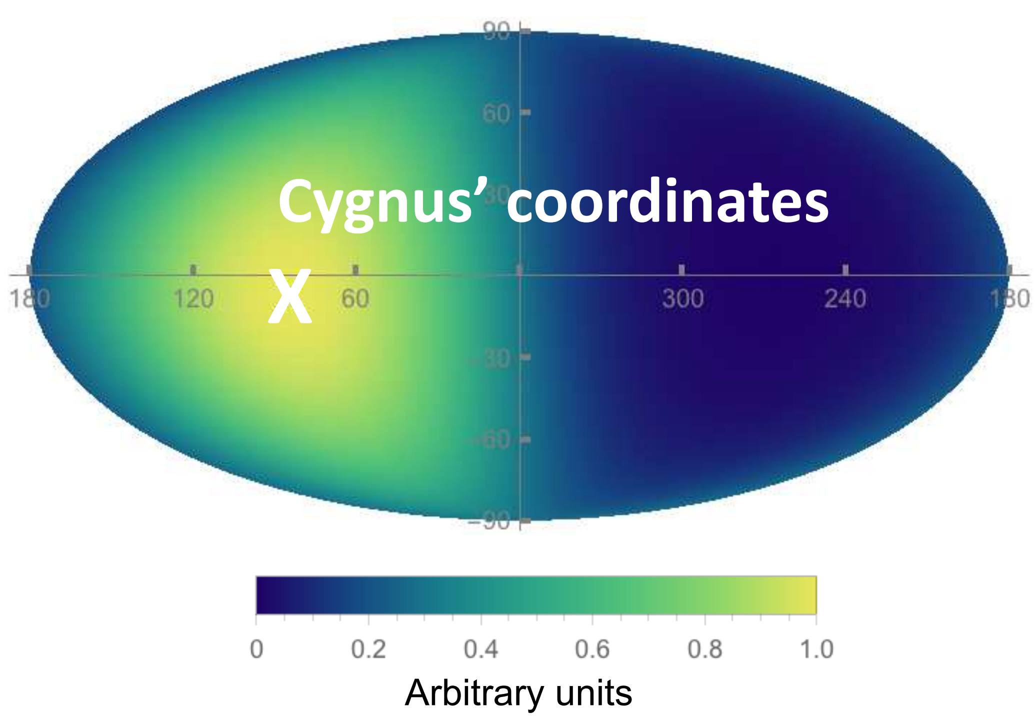
"wind" of WIMPs in the direction of sun's motion (≈Cygnus)



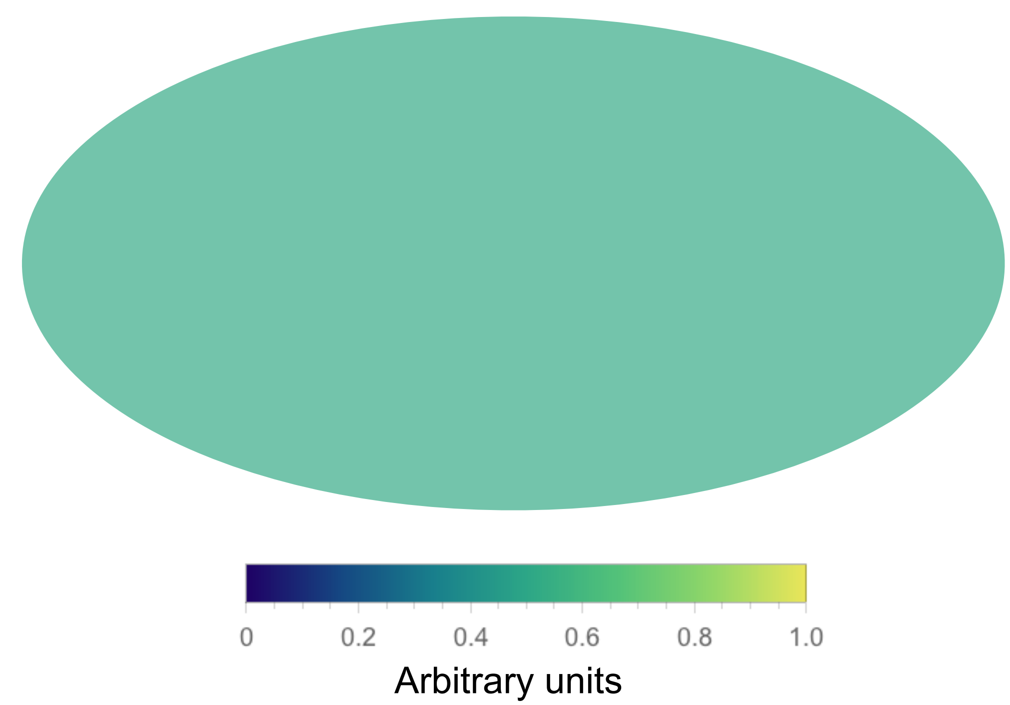
Annual modulation

Earth's motion induces (small) annual modulation

Expected WIMP signal distribution



Expected background distribution



arXiv:1602.03781

Neutrinoless Double-β Decay

Are neutrinos Dirac or Majorana particles?

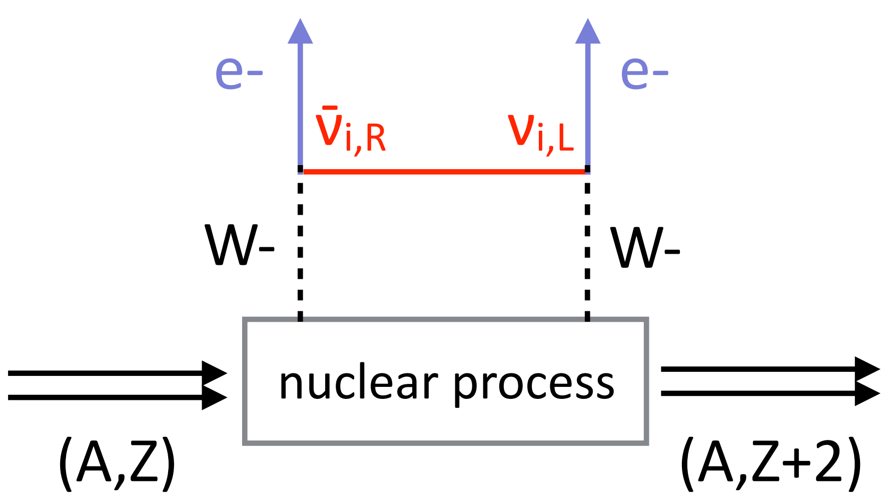
0νββ aim to address this question, measure ν mass scale, test lepton number conservation
can probe new physics contributions: need multi-isotope comparative analysis!

phase space integral

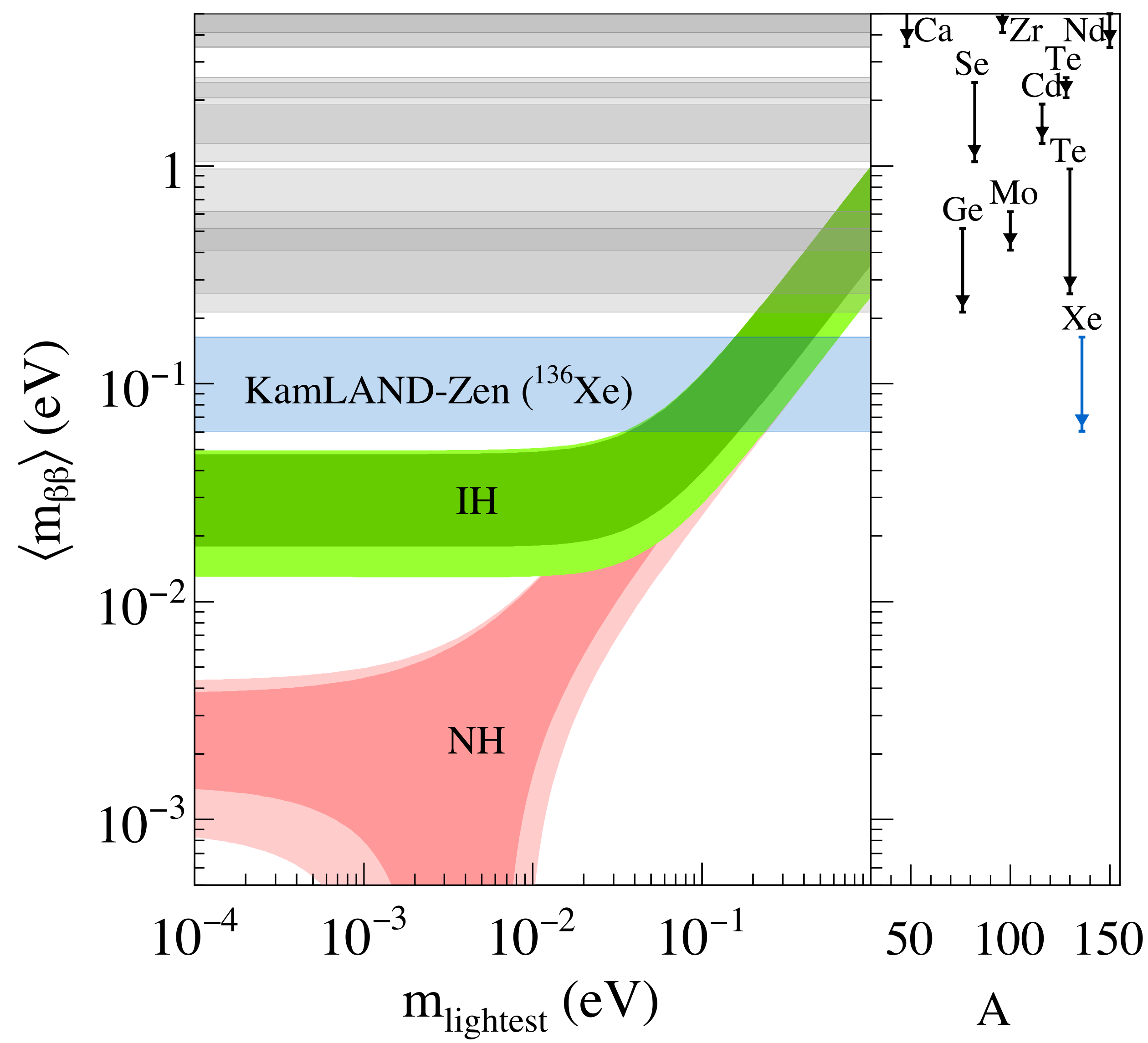
<$m_{\beta\beta}$>

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |\sum_i U^2_{ei} m_i|^2$$

nuclear matrix element *PMNS matrix*



As of July '16 - arXiv:1605.02889



LHC Long-Term Schedule

LHC

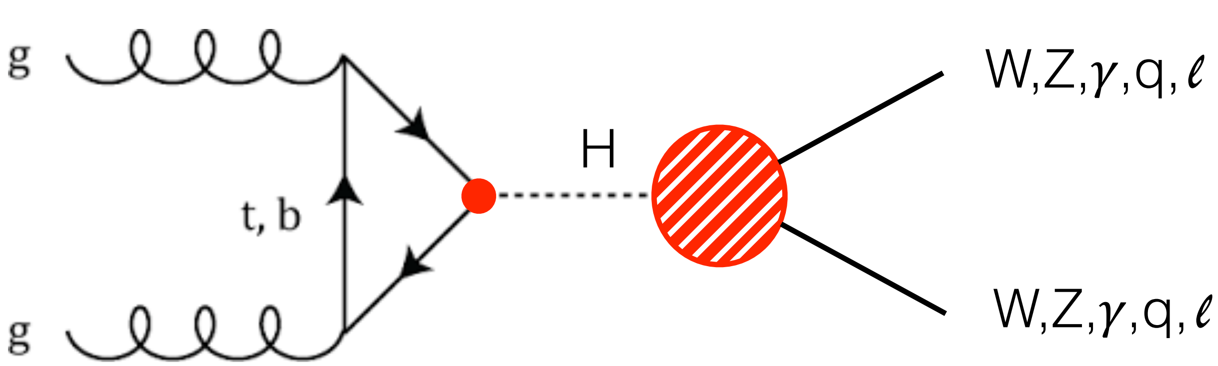
HiLumi HL-LHC PROJECT

Run 1		Run 2		Run 3	Run 4, 5, ...
7-8 TeV		13 TeV		14 TeV	14 TeV
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020	2021 2022 2023	2024 2025 2026 … 2037
30 fb^{-1}	shutdown: LS1	*150 fb^{-1}*	shutdown: LS2	*300 fb^{-1}*	shutdown: LS3 *3000 fb^{-1}*

High intensity @ HL-LHC: shifting toward precision physics

e.g. fingerprinting Higgs sector

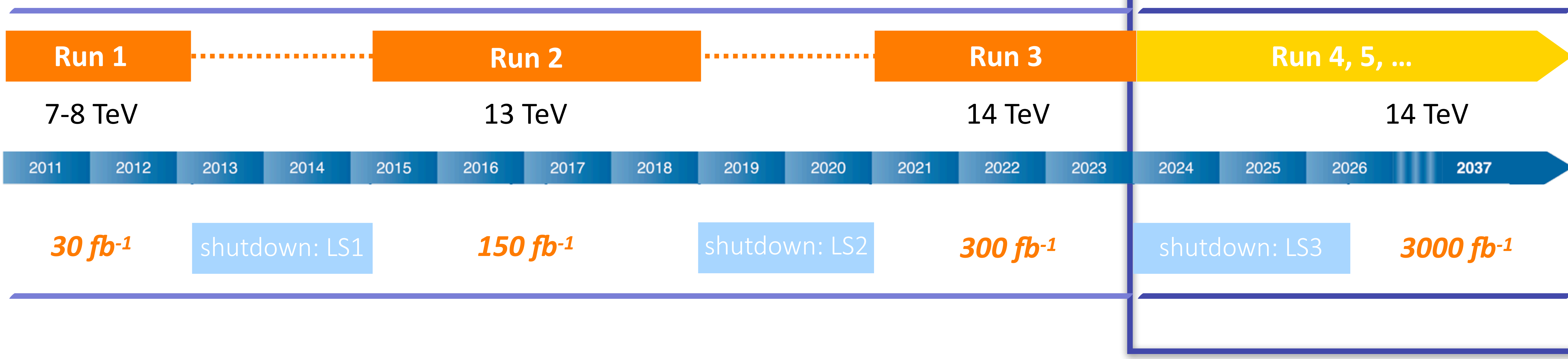
In 20 years…



≈5% precision on Higgs couplings: SM-like or not?

LHC Long-Term Schedule

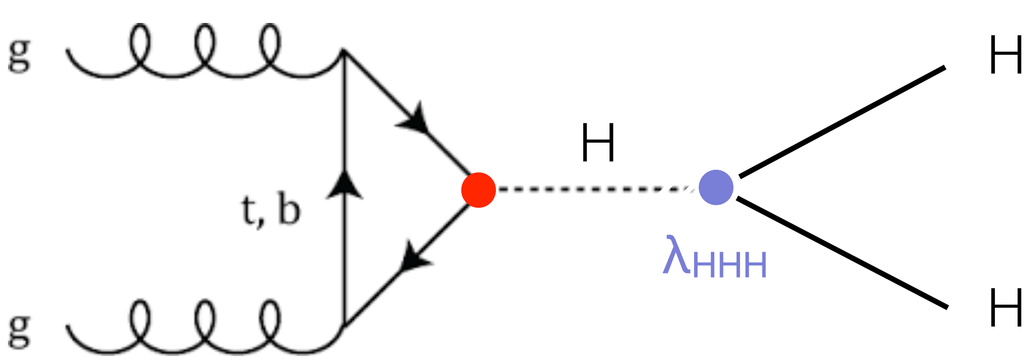
LHC



High intensity @ HL-LHC: shifting toward precision physics

e.g. fingerprinting Higgs sector

In 20 years...



≈5% precision on Higgs couplings: SM-like or not?

$1 \lesssim \lambda/\lambda_{SM} \lesssim 9$ at 95% CL: not enough to resolve details of Higgs potential

LHC Long-Term Schedule + Future Colliders?

LHC

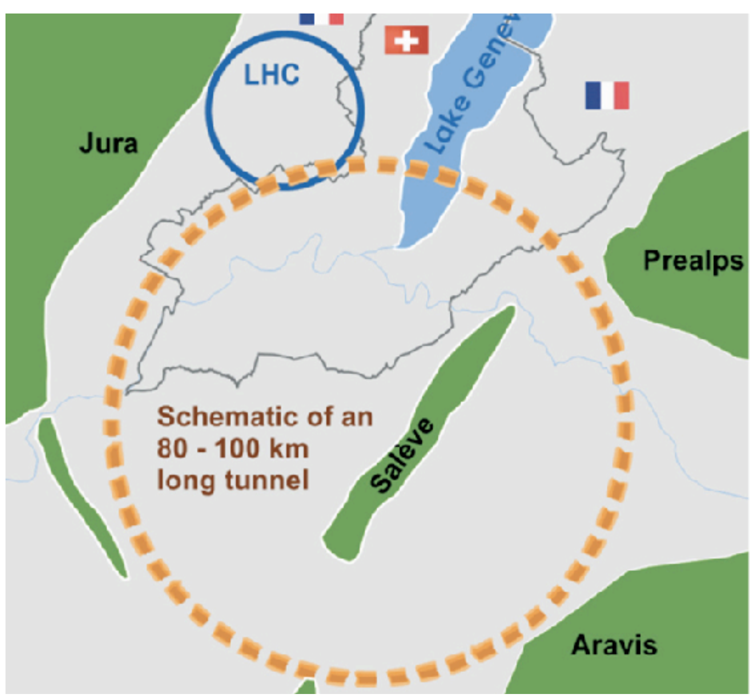
HiLumi HL-LHC PROJECT

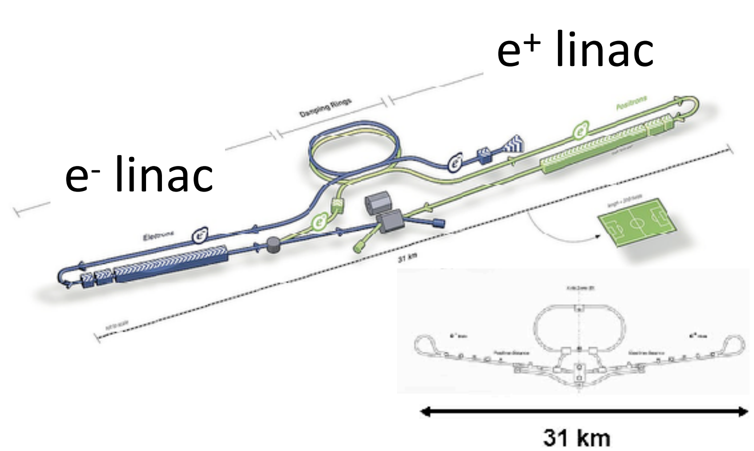
Run 1	....	Run 2	....	Run 3	Run 4, 5, ...
7-8 TeV		13 TeV		14 TeV	14 TeV
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020	2021 2022 2023	2024 2025 2026 ... 2037
30 fb^{-1}	shutdown: LS1	150 fb^{-1}	shutdown: LS2	300 fb^{-1}	shutdown: LS3 / 3000 fb^{-1}

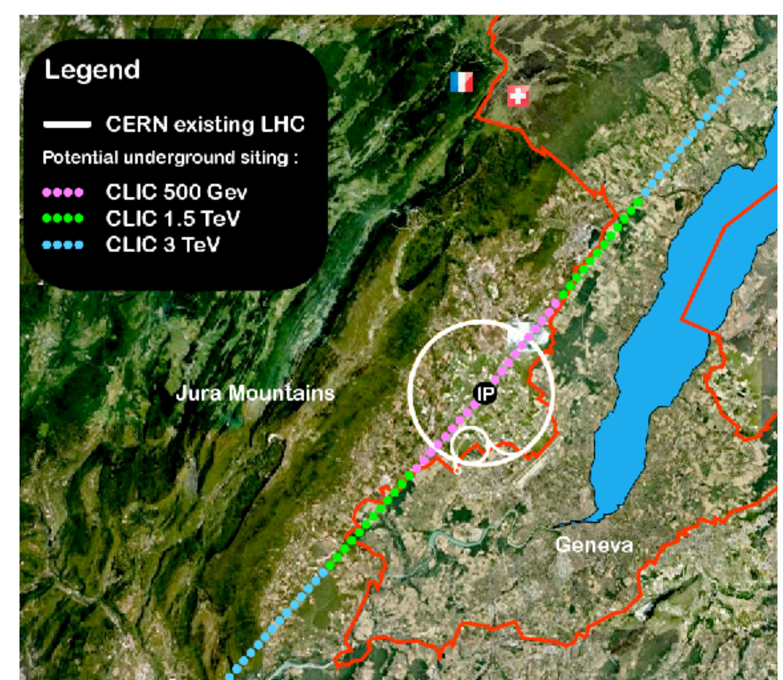
FCC - reach √s=100 TeV
search/study new physics

ILC - mature technology
characterize the Higgs

CLIC - new technology
Higgs and new physics?

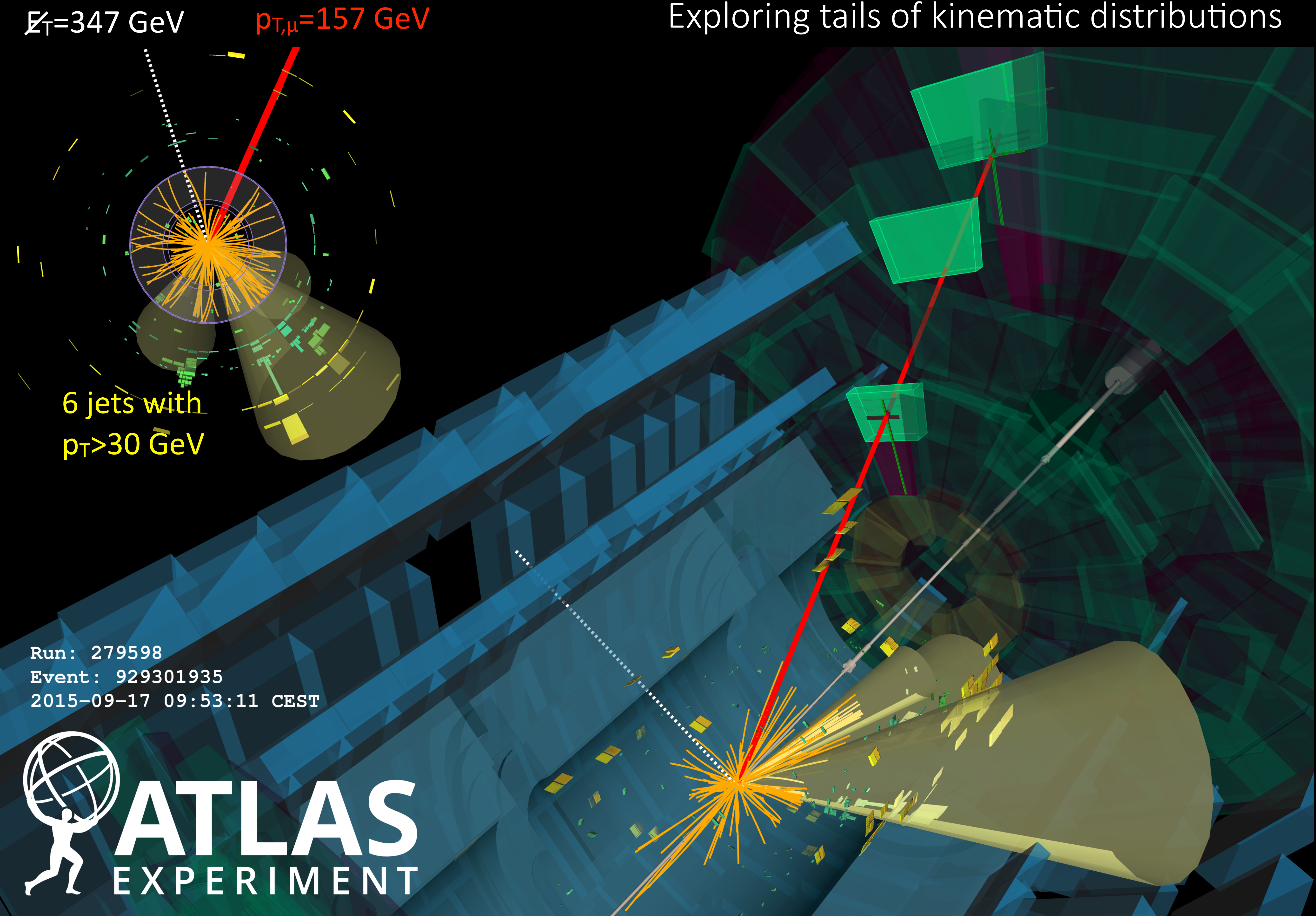






Selecting **spectacular** events!

Exploring tails of kinematic distributions



Gluinos: Background Estimation

Two *well-understood* and *well-modeled* variables define CR/VR/SR plane

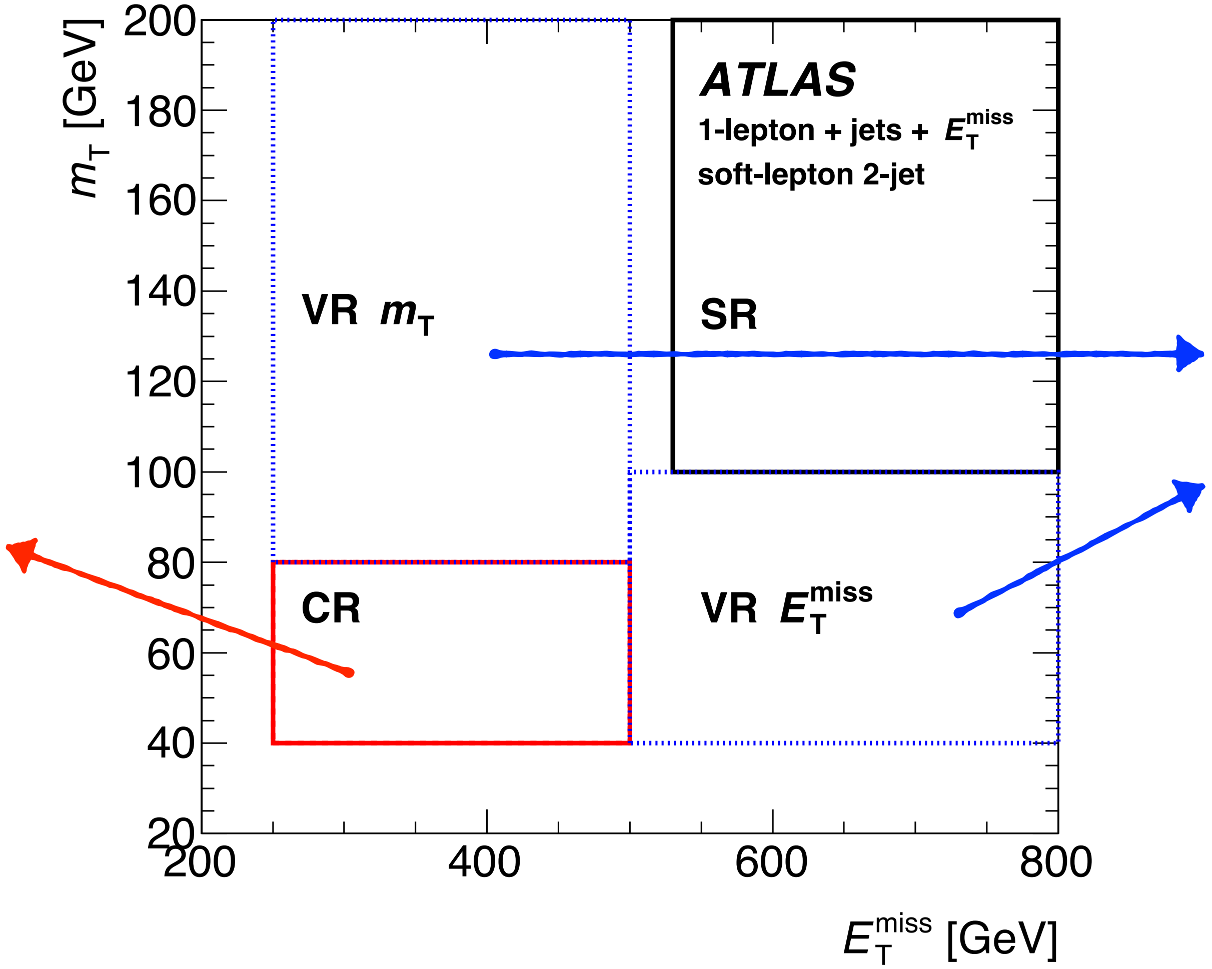
Control Regions (CR) ➙ normalize simulated backgrounds to data

↳ select or veto b-jets to enrich in $t\bar{t}$ or *W+jets*

↳ extrapolate to SR using MC-based transfer factors

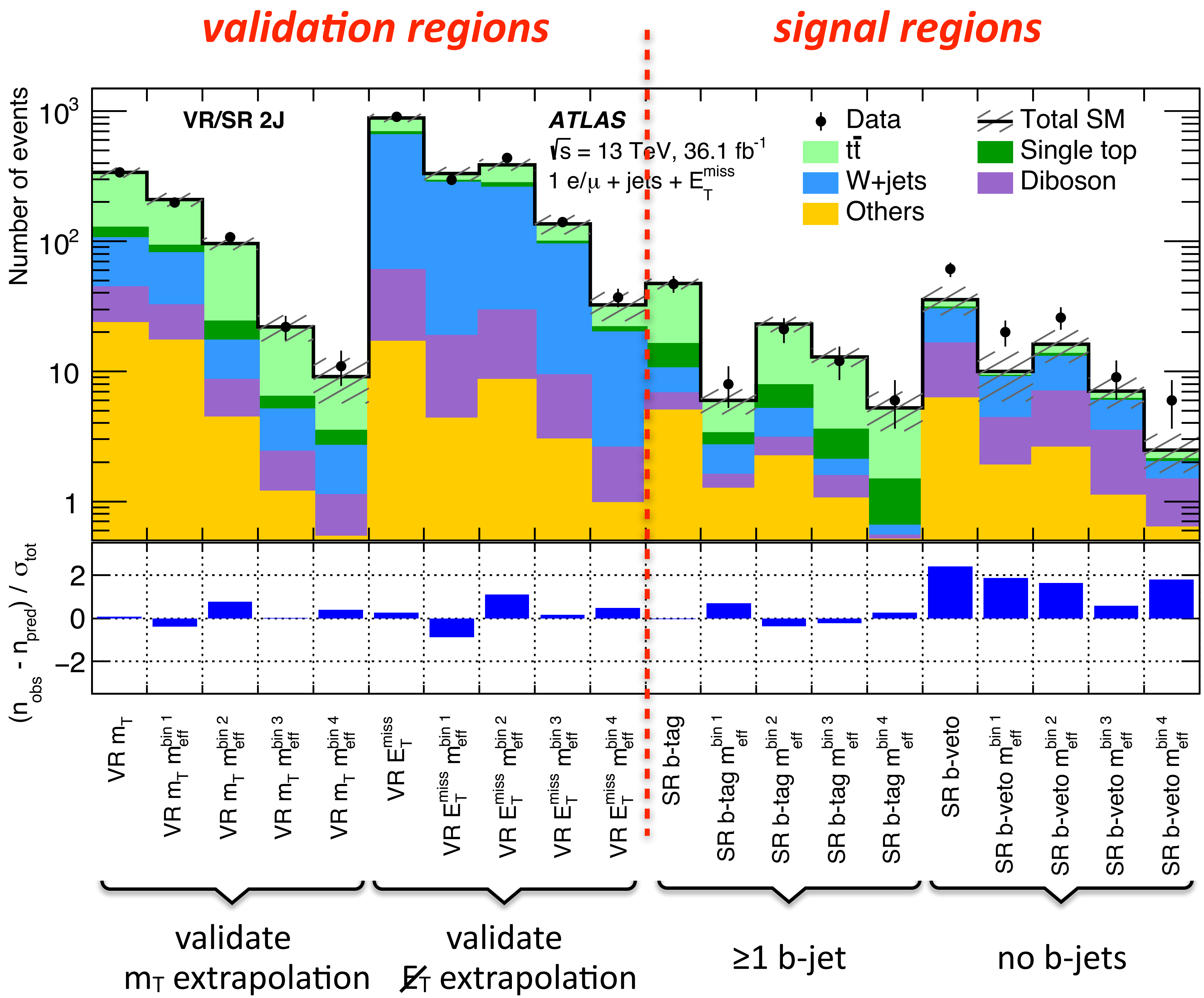
Validation Regions (VR) ➙ validate background estimates against data

kinematic region close to SR, with negligible signal contamination



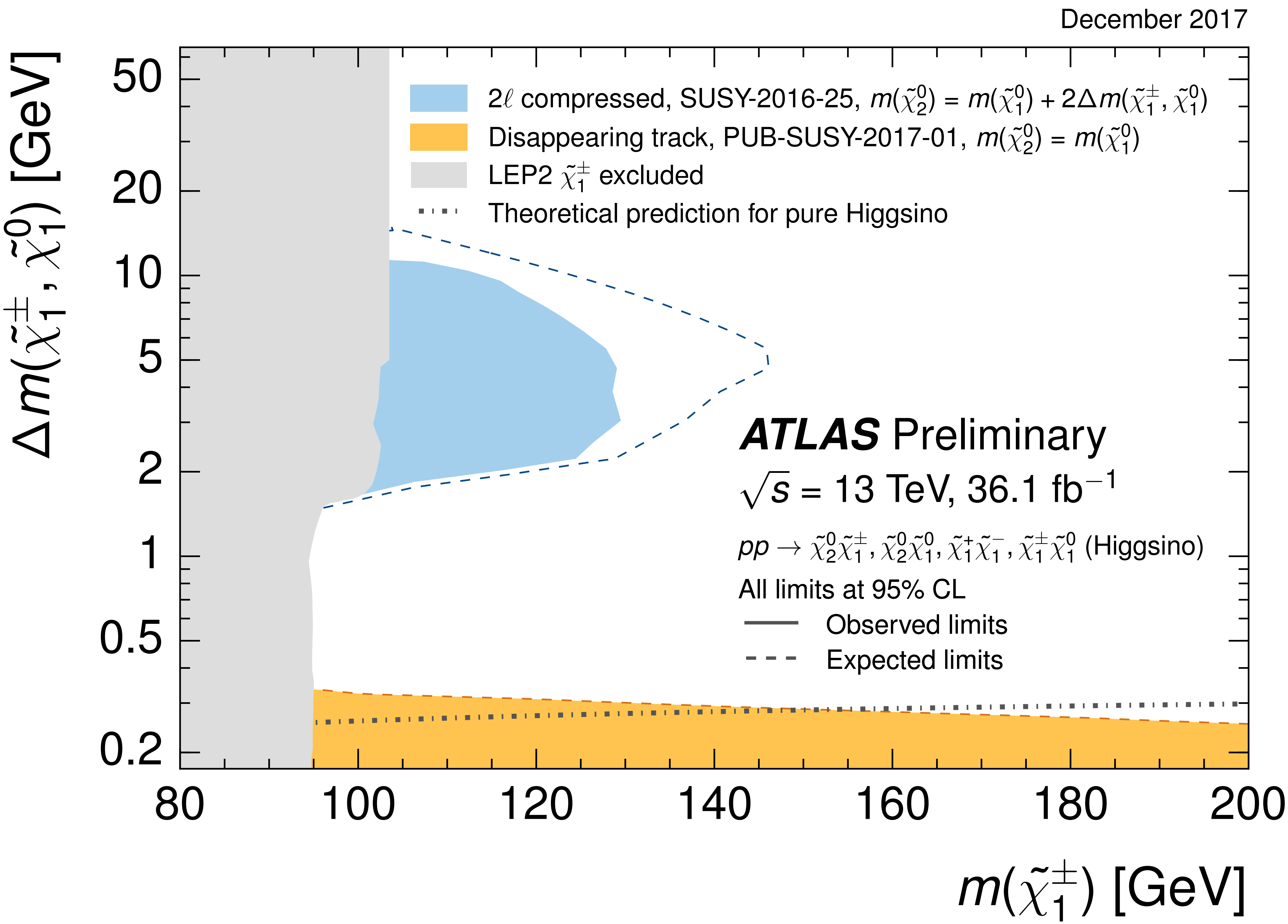
validate CR → SR extrapolation along each variable, separately

Observed Event Yields

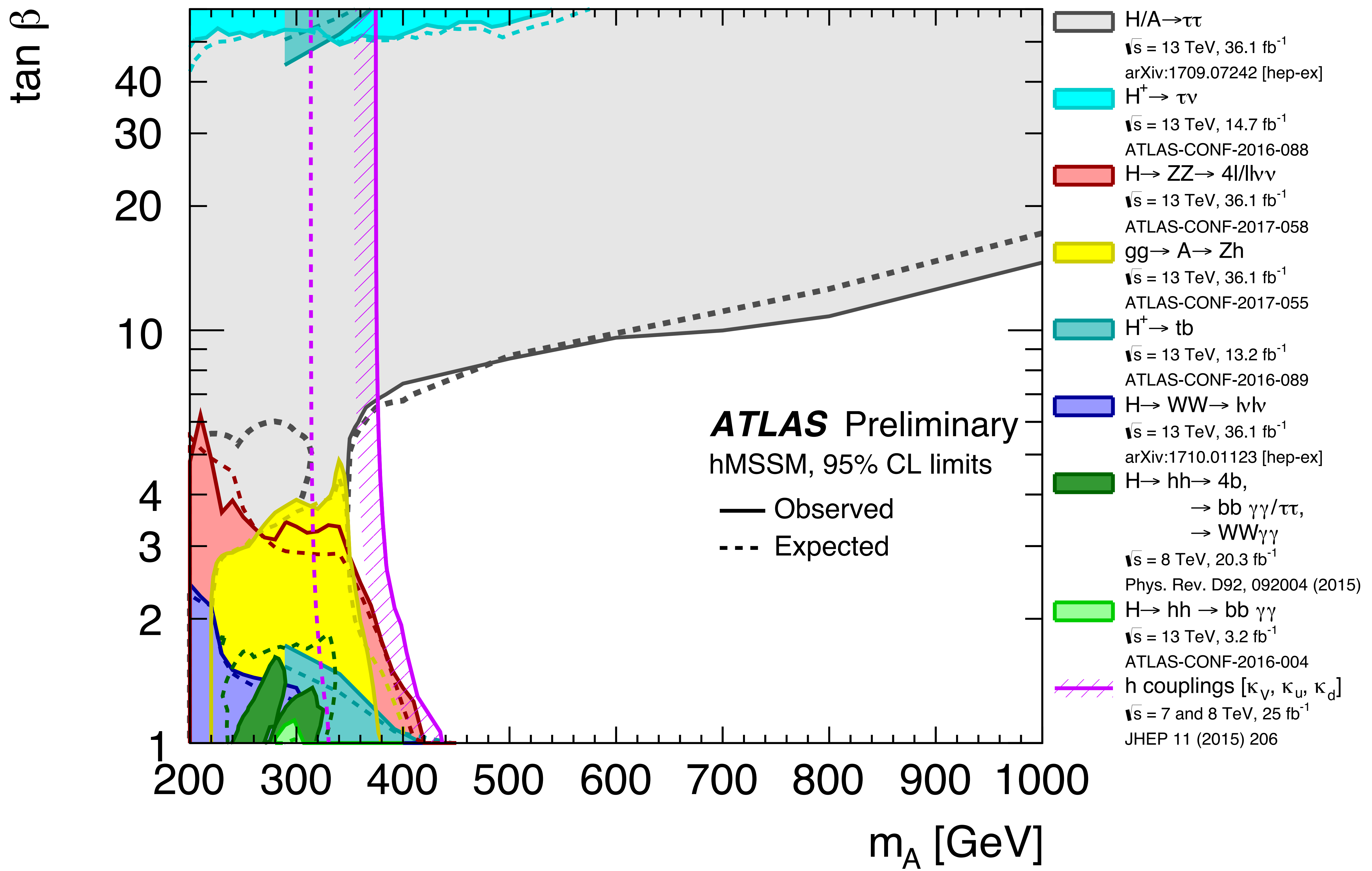


We Need To Get Smarter!

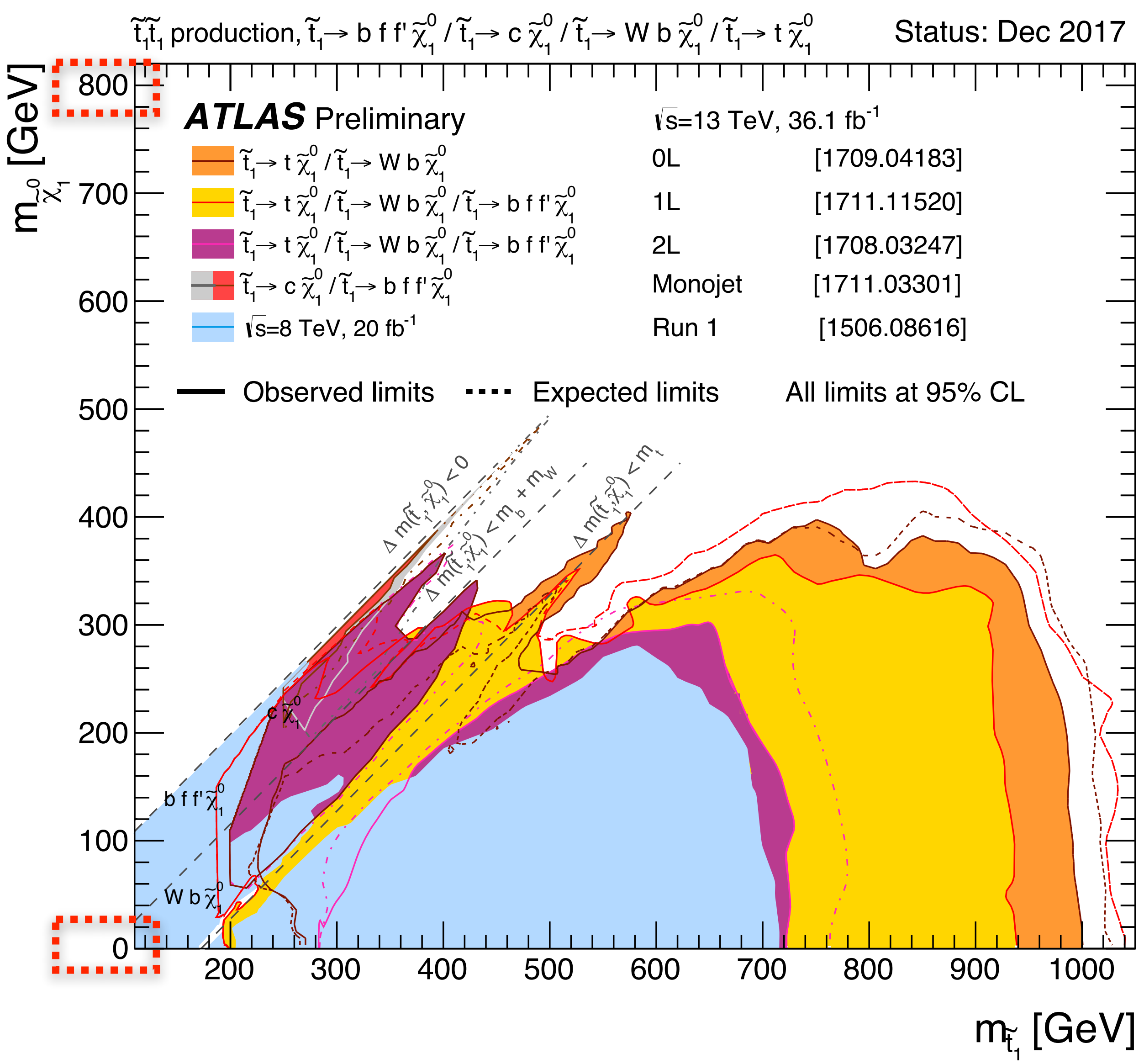
near future

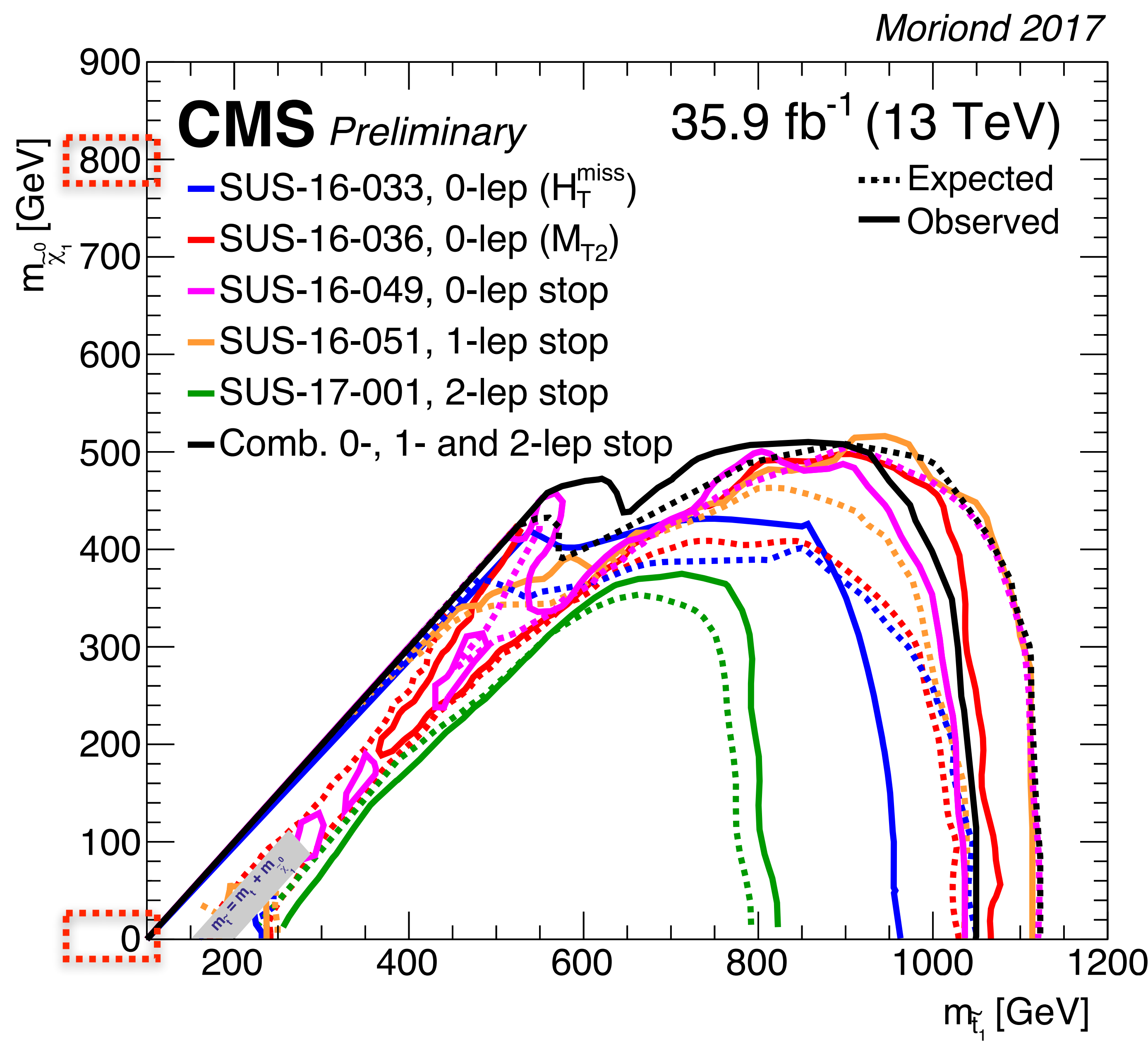


hMSSH - Higgs Sector

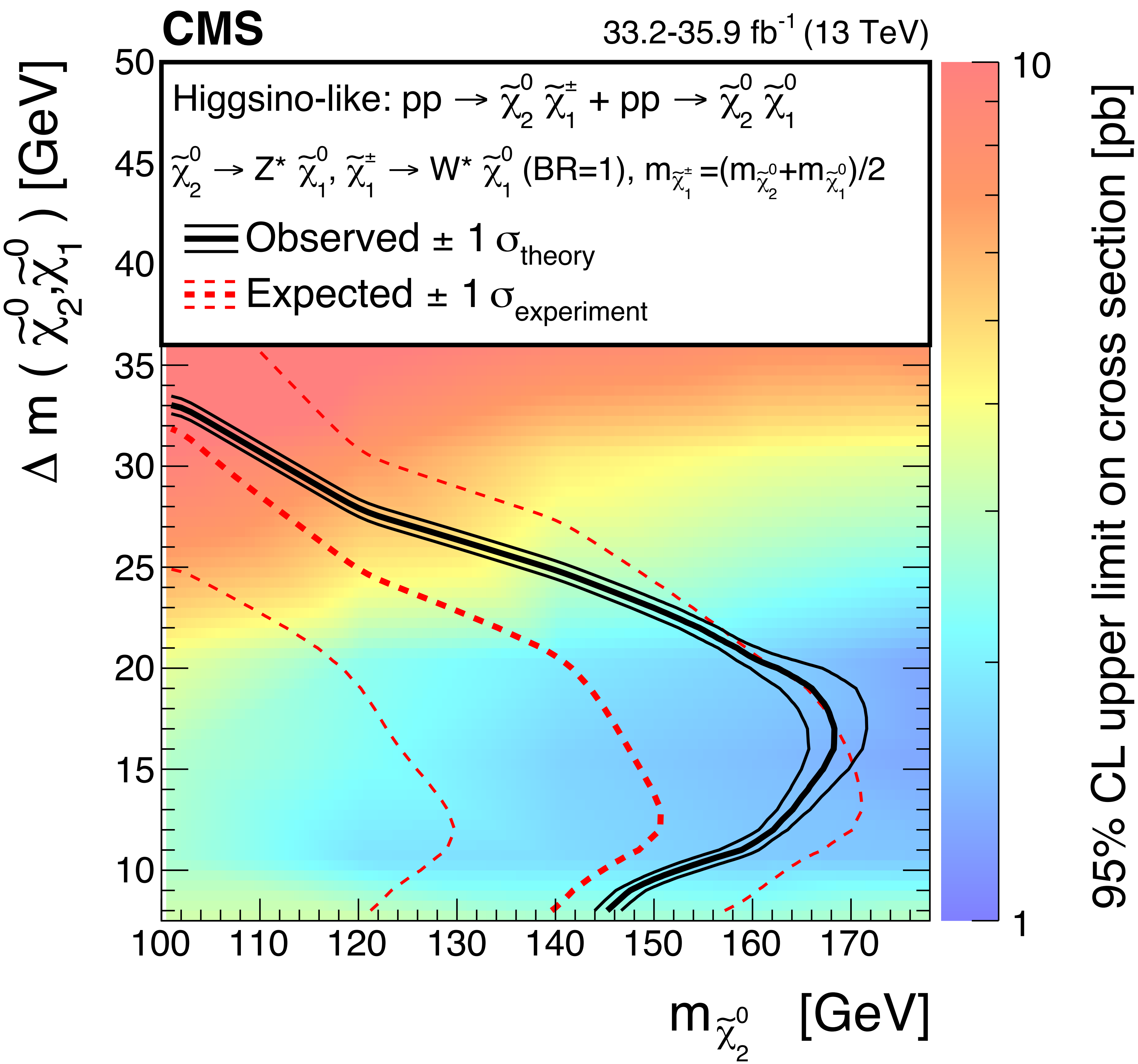


Stop Searches - Atlas Vs CMS

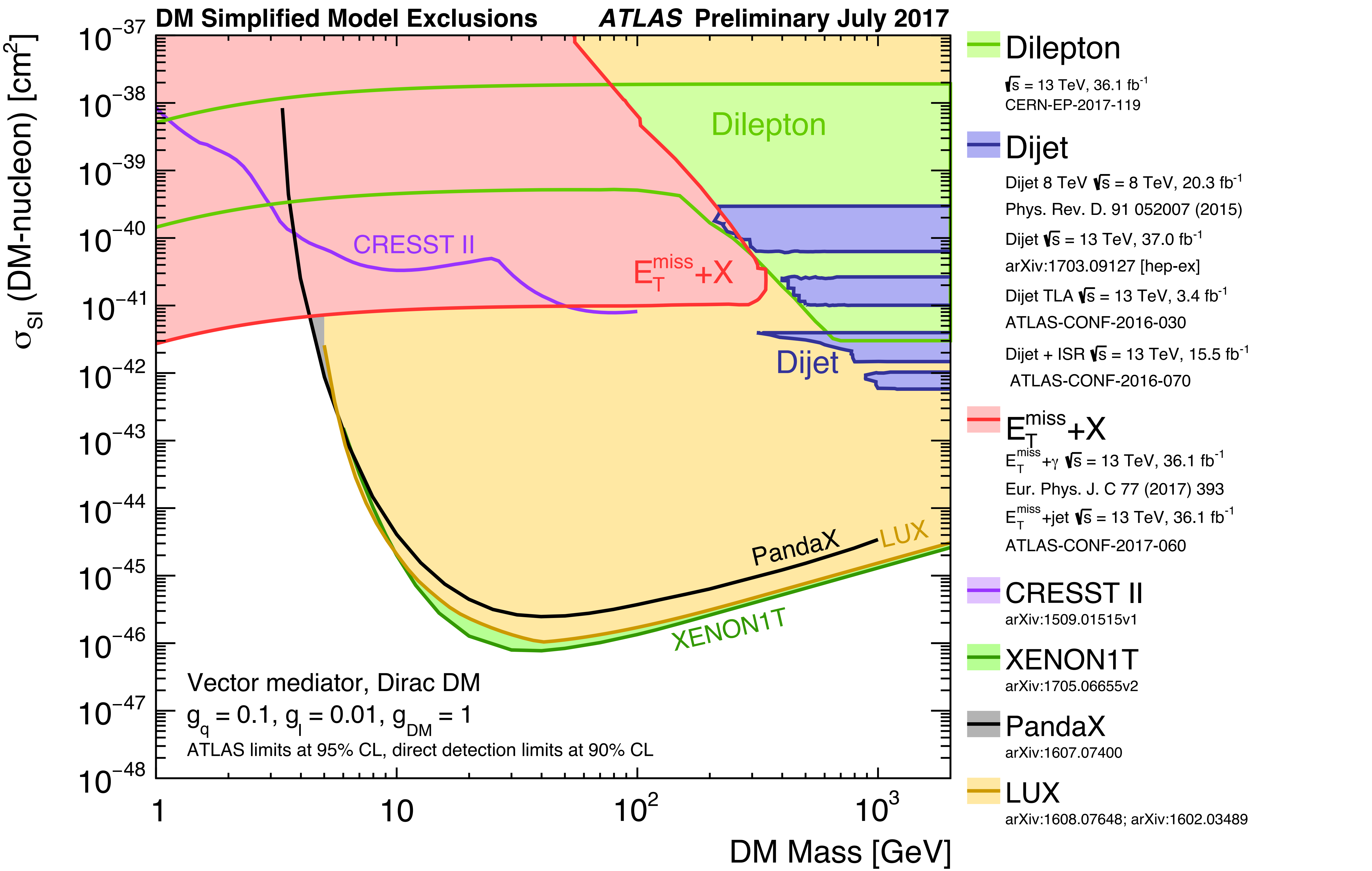




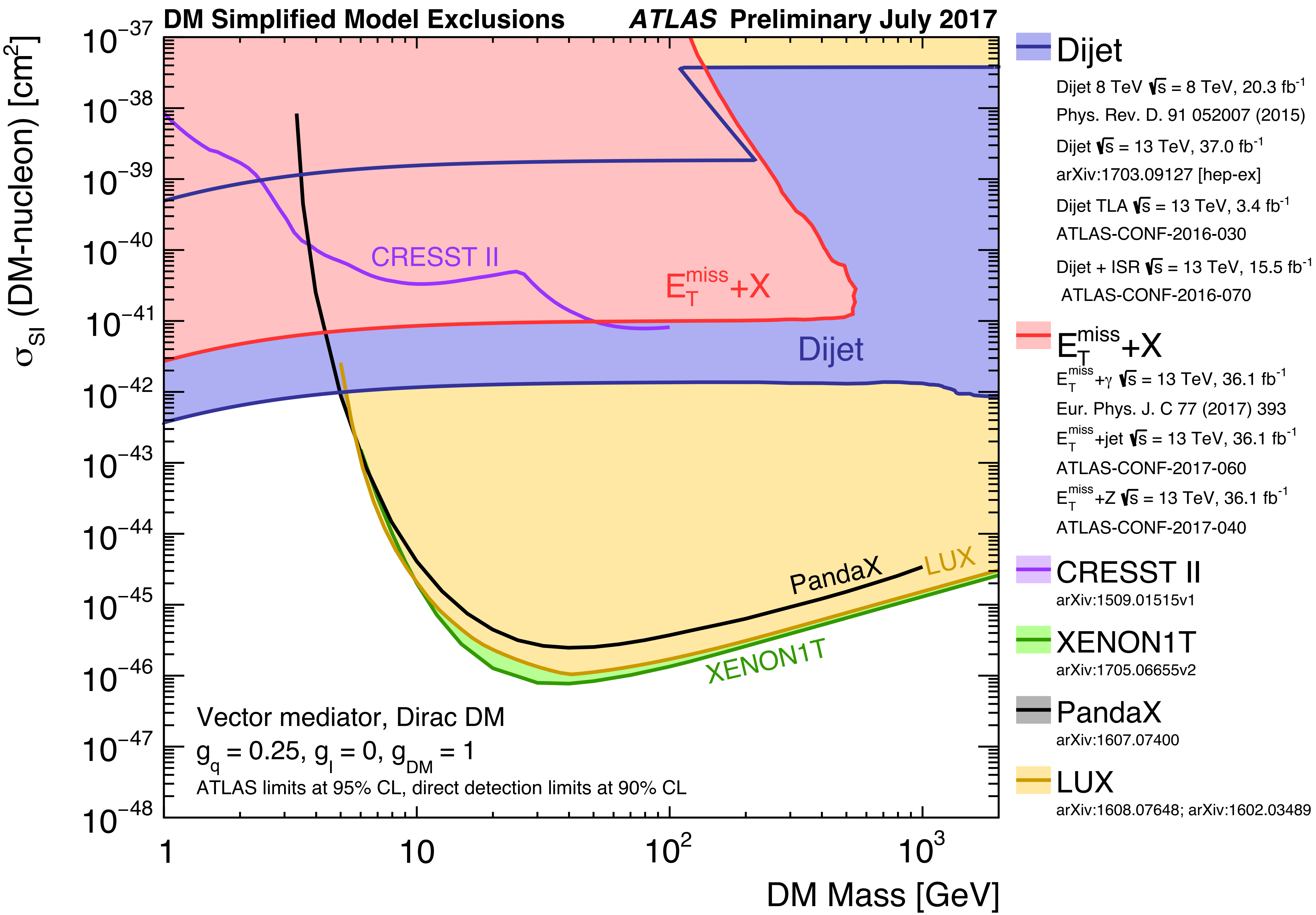
Higgsino Searches - CMS



DM @ The LHC

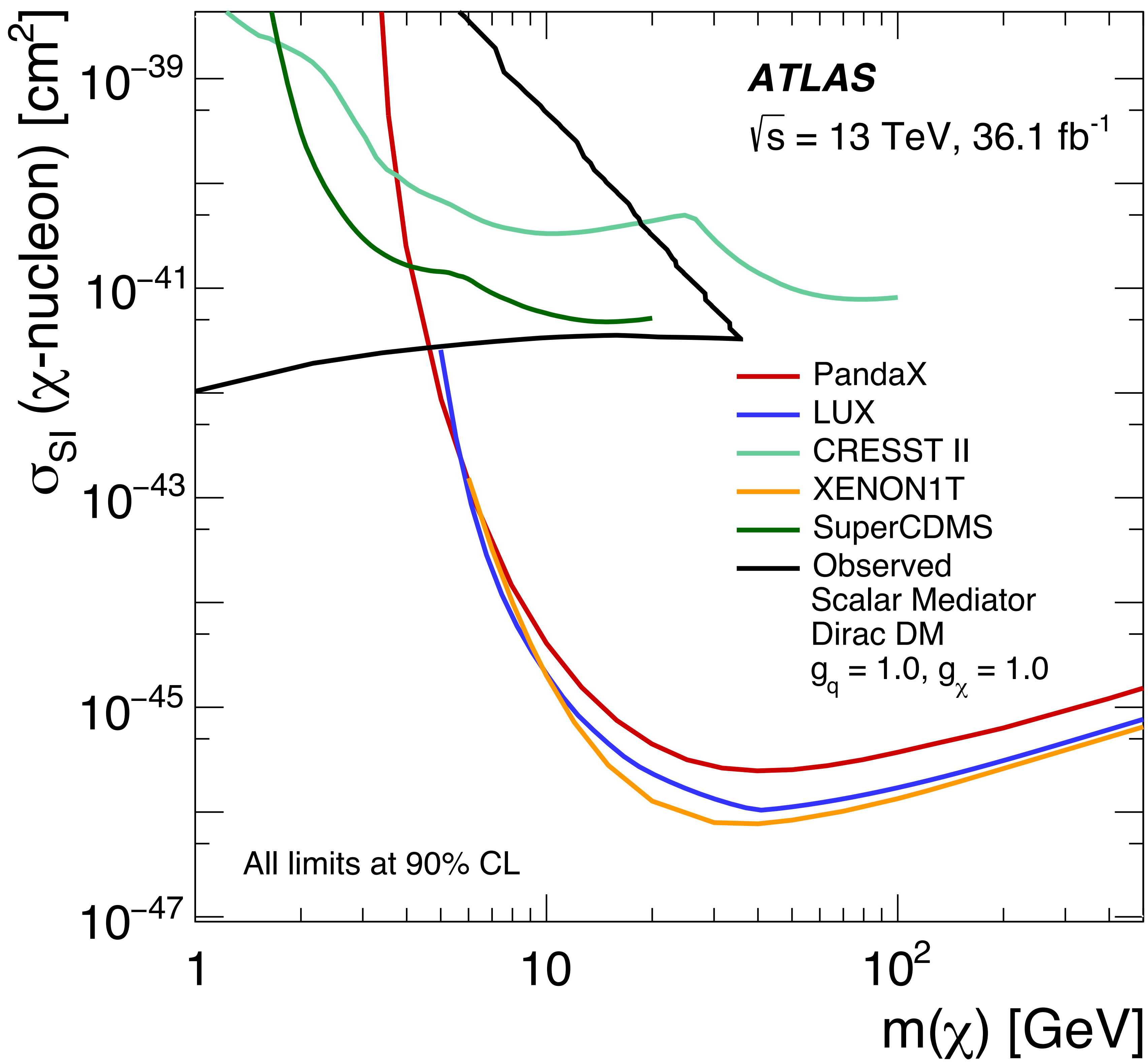

DM Simplified Model Exclusions
ATLAS Preliminary July 2017
σ_SI (DM-nucleon) [cm²]
DM Mass [GeV]
Dilepton
Dijet
CRESST II
E_T^miss+X
PandaX
LUX
XENON1T
Vector mediator, Dirac DM
g_q = 0.1, g_l = 0.01, g_DM = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
Dilepton
√s = 13 TeV, 36.1 fb⁻¹
CERN-EP-2017-119
Dijet
Dijet 8 TeV √s = 8 TeV, 20.3 fb⁻¹
Phys. Rev. D. 91 052007 (2015)
Dijet √s = 13 TeV, 37.0 fb⁻¹
arXiv:1703.09127 [hep-ex]
Dijet TLA √s = 13 TeV, 3.4 fb⁻¹
ATLAS-CONF-2016-030
Dijet + ISR √s = 13 TeV, 15.5 fb⁻¹
ATLAS-CONF-2016-070
E_T^miss+X
E_T^miss+γ √s = 13 TeV, 36.1 fb⁻¹
Eur. Phys. J. C 77 (2017) 393
E_T^miss+jet √s = 13 TeV, 36.1 fb⁻¹
ATLAS-CONF-2017-060
CRESST II
arXiv:1509.01515v1
XENON1T
arXiv:1705.06655v2
PandaX
arXiv:1607.07400
LUX
arXiv:1608.07648; arXiv:1602.03489

DM @ The LHC



DM Simplified Model Exclusions
ATLAS Preliminary July 2017
σ_SI (DM-nucleon) [cm²]
DM Mass [GeV]
CRESST II
E_T^miss+X
Dijet
PandaX
LUX
XENON1T
Vector mediator, Dirac DM
g_q = 0.25, g_l = 0, g_DM = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
Dijet
Dijet 8 TeV √s = 8 TeV, 20.3 fb⁻¹
Phys. Rev. D. 91 052007 (2015)
Dijet √s = 13 TeV, 37.0 fb⁻¹
arXiv:1703.09127 [hep-ex]
Dijet TLA √s = 13 TeV, 3.4 fb⁻¹
ATLAS-CONF-2016-030
Dijet + ISR √s = 13 TeV, 15.5 fb⁻¹
ATLAS-CONF-2016-070
E_T^miss+X
E_T^miss+γ √s = 13 TeV, 36.1 fb⁻¹
Eur. Phys. J. C 77 (2017) 393
E_T^miss+jet √s = 13 TeV, 36.1 fb⁻¹
ATLAS-CONF-2017-060
E_T^miss+Z √s = 13 TeV, 36.1 fb⁻¹
ATLAS-CONF-2017-040
CRESST II
arXiv:1509.01515v1
XENON1T
arXiv:1705.06655v2
PandaX
arXiv:1607.07400
LUX
arXiv:1608.07648; arXiv:1602.03489

DM @ The LHC



ATLAS
√s = 13 TeV, 36.1 fb-1
PandaX
LUX
CRESST II
XENON1T
SuperCDMS
Observed
Scalar Mediator
Dirac DM
g_q = 1.0, g_χ = 1.0
All limits at 90% CL
σ_SI (χ-nucleon) [cm^2]
10^-39
10^-41
10^-43
10^-45
10^-47
1
10
10^2
m(χ) [GeV]