ATLAS searches for heavy Higgs bosons and supersymmetry using tau decays

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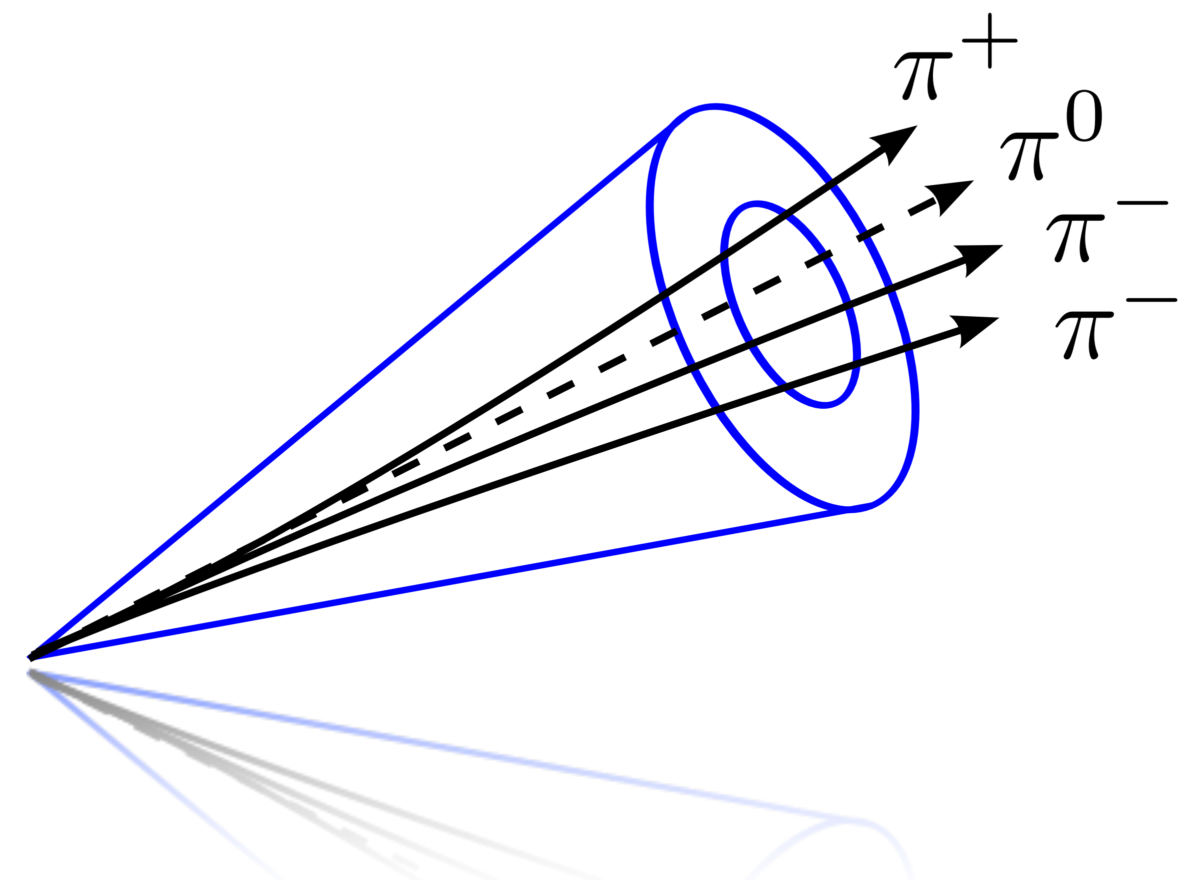
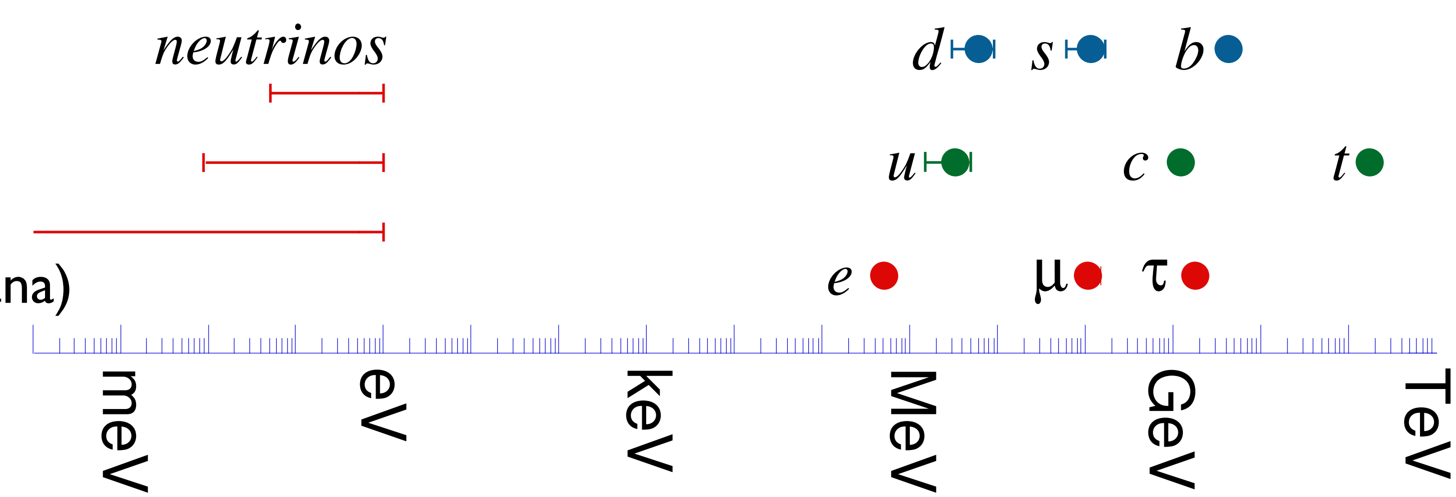
Outline

- Motivational questions about the SM
- ATLAS detector and dataset
- Neutral Higgs: $A/H \rightarrow \tau\tau$
- Charged Higgs: $H^{\pm} \rightarrow \tau^{\pm}\nu$
- SUSY searches
- Summary

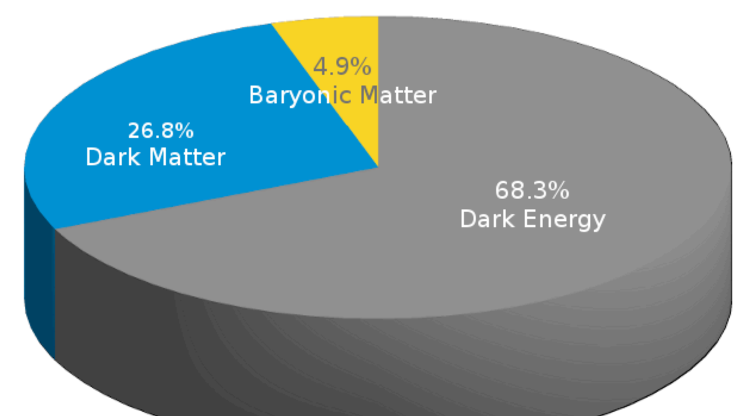


... *all with taus.*

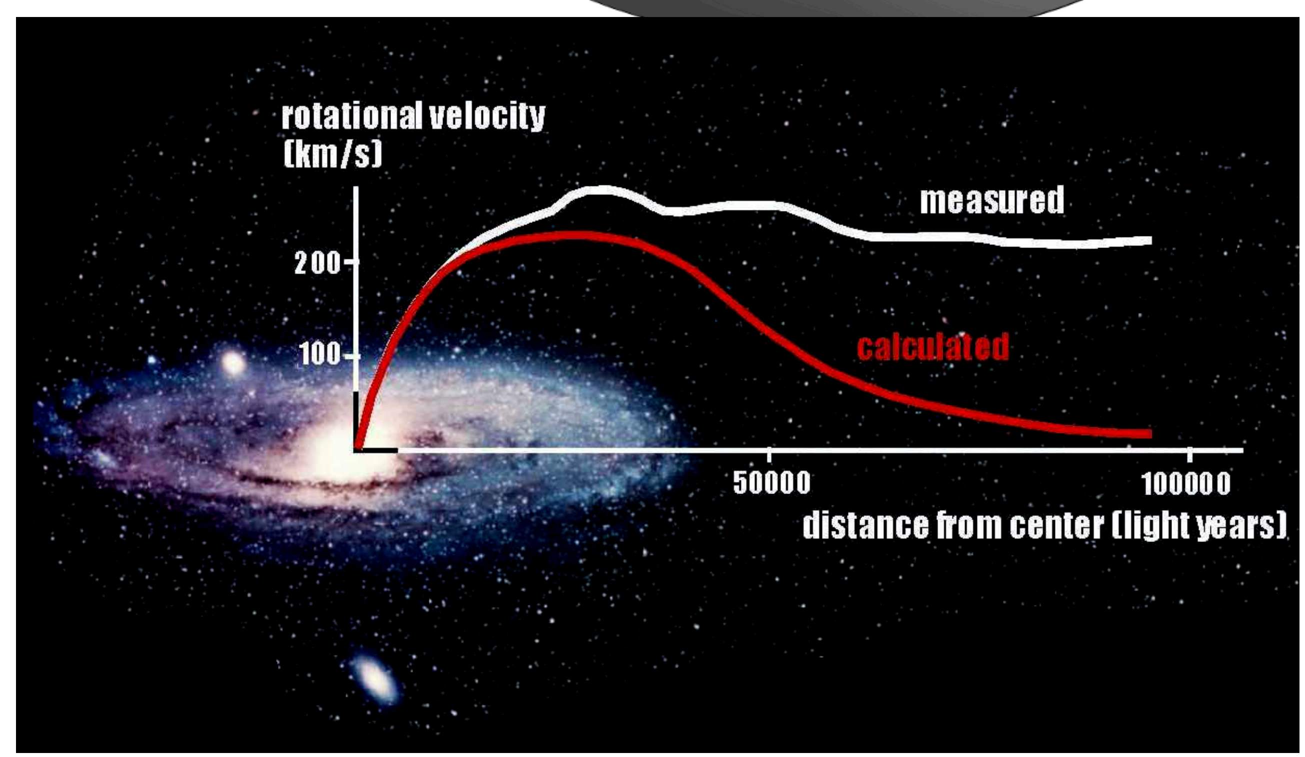
Unanswered problems in particle physics



- Ad hoc features
  - Why SU(3)xSU(2)xU(1) ?
  - Neutrino mixing and masses (Dirac or Majorana)
  - Matter-antimatter asymmetry
  - Strong CP-problem



- Dark matter and dark energy
  - 5% SM, 27% dark matter, 68% dark energy, (DM 85% of matter)
- Hierarchy problem(s)
  - m_{Higgs} vs m_{Planck}, EW naturalenss
  - quark masses range: 10^5, leptons: 10^9
- Fine-tuning:
  - EW-scale, flatness problem, vacuum stability, etc.
- Unification? Supersymmetry?
- Why such low entropy in the early universe?



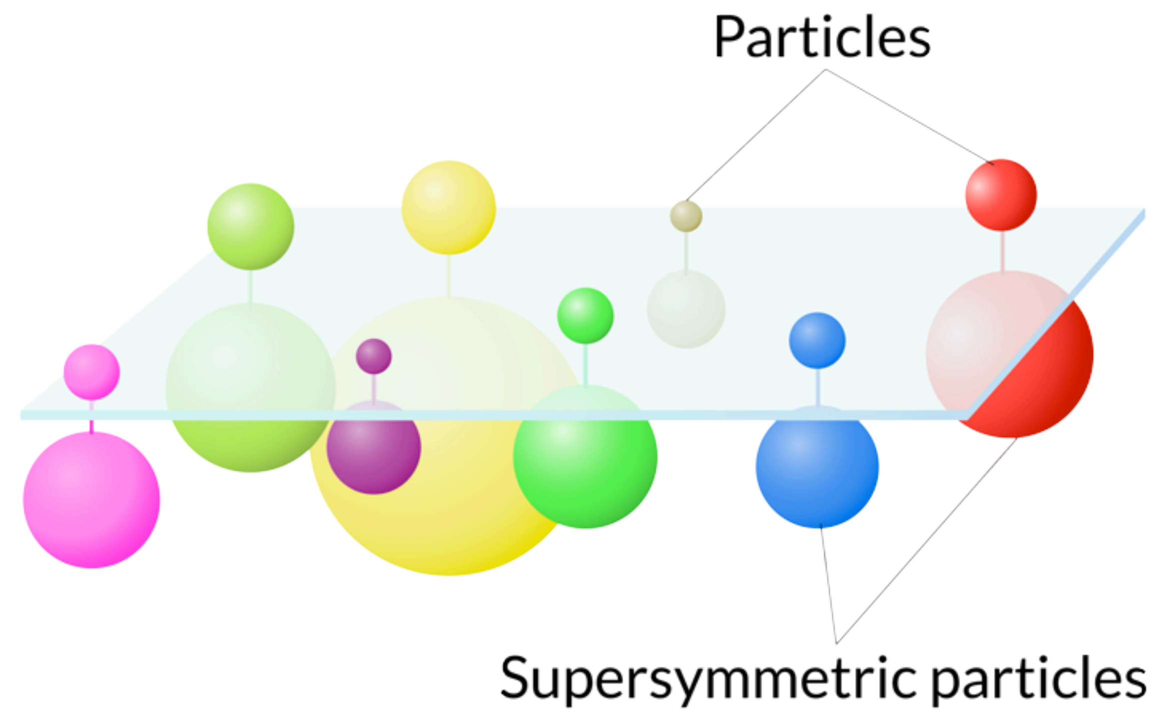
Supersymmetry

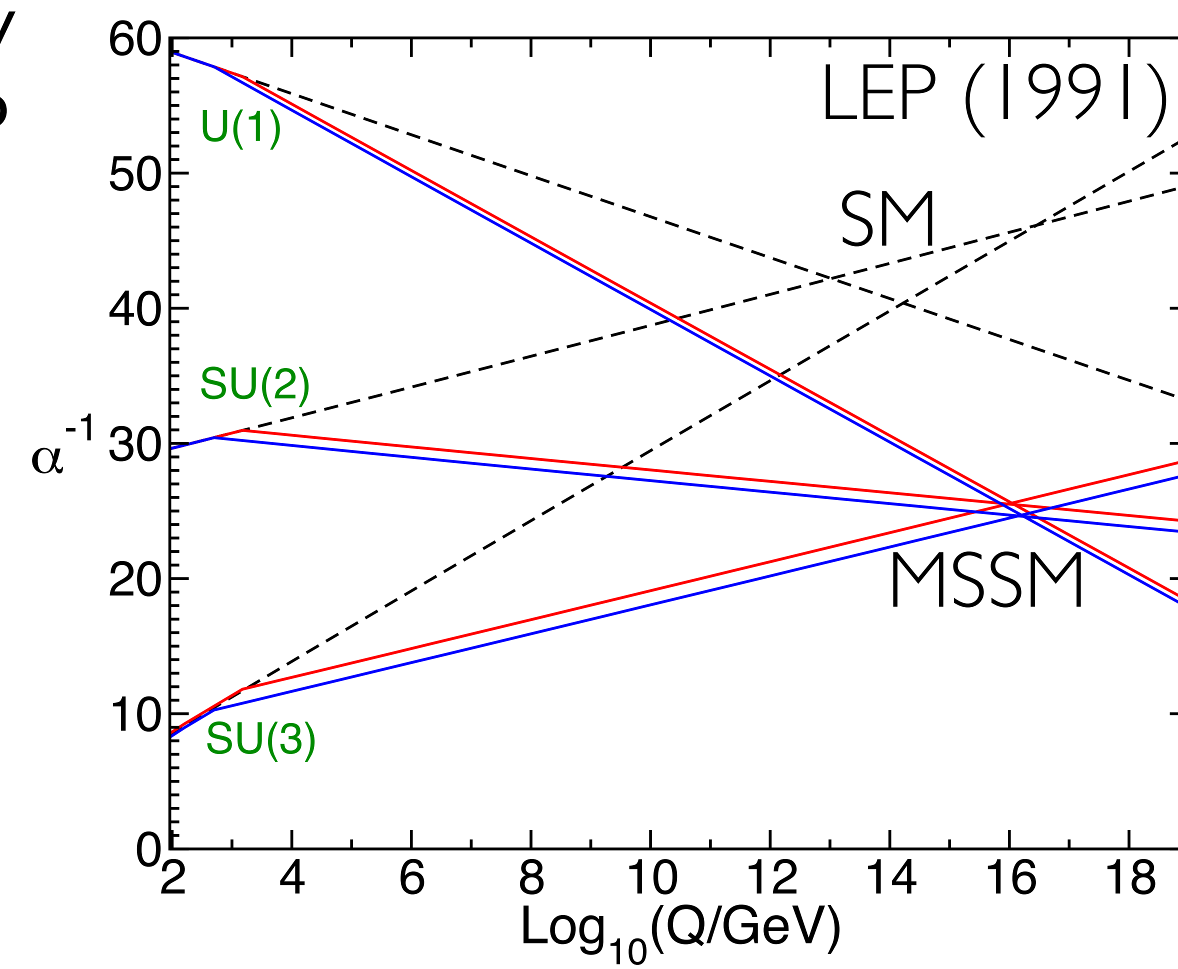
- **Supersymmetry** (SUSY) is a symmetry between bosons and fermions.
  $S_{SUSY} = |S_{SM} - ½|$
  Can be seen as spacetime having *fermionic dimensions*.

- According to the **HLS theorem** (Haag-Lopuszanski-Sohnius, 1975), under some basic assumptions, SUSY is the unique exception to the Coleman-Mandula theorem, being *the only way* to nontrivially extend the Poincaré group to include internal degrees of freedom.

- Experimental hints from the running of the SM couplings with SUSY partners included point at possible **gauge unification**.

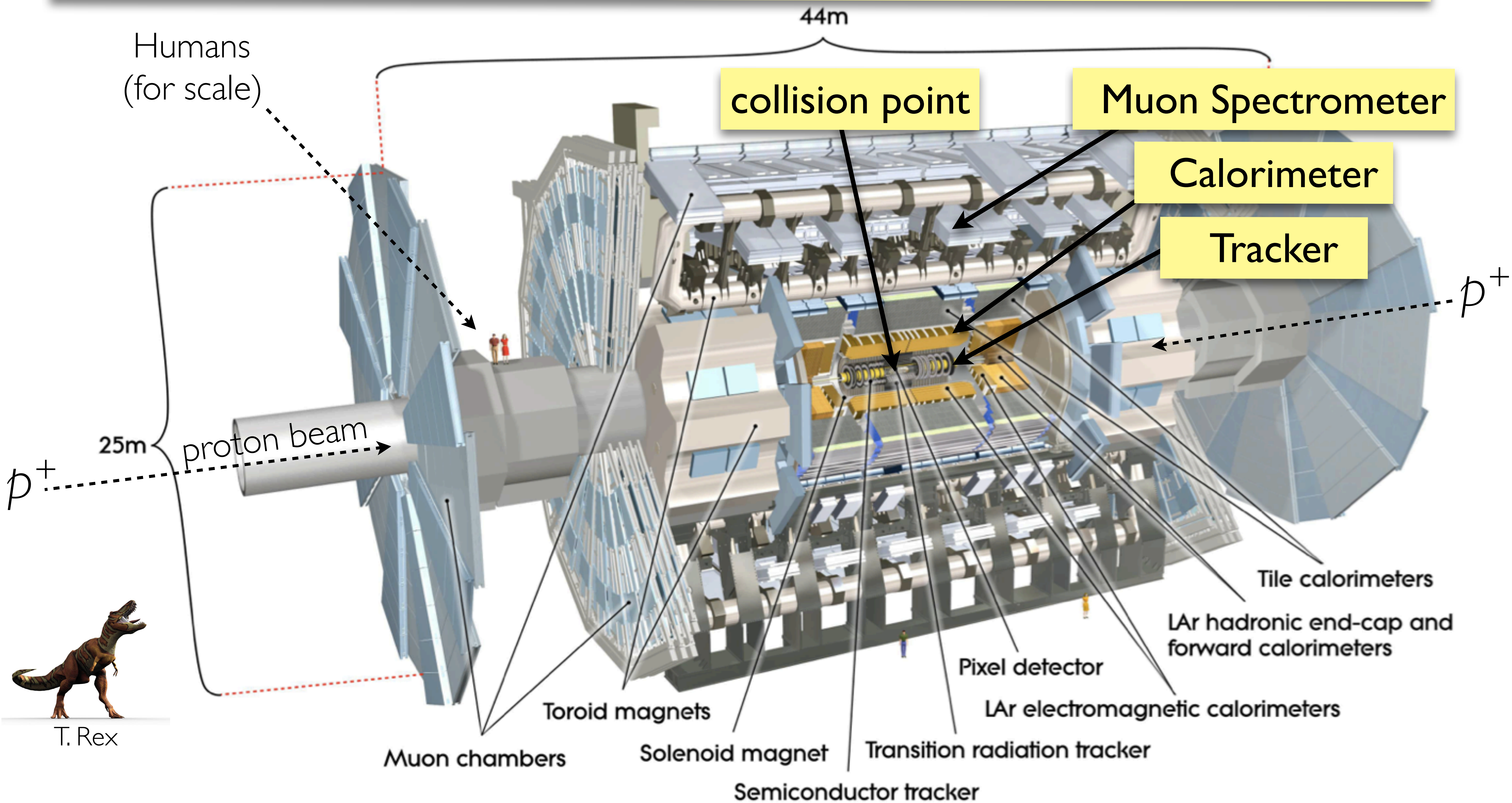
- In *R*-parity conserving models, the Lightest Supersymmetric Particle (LSP) provides a possible **dark matter candidate**.





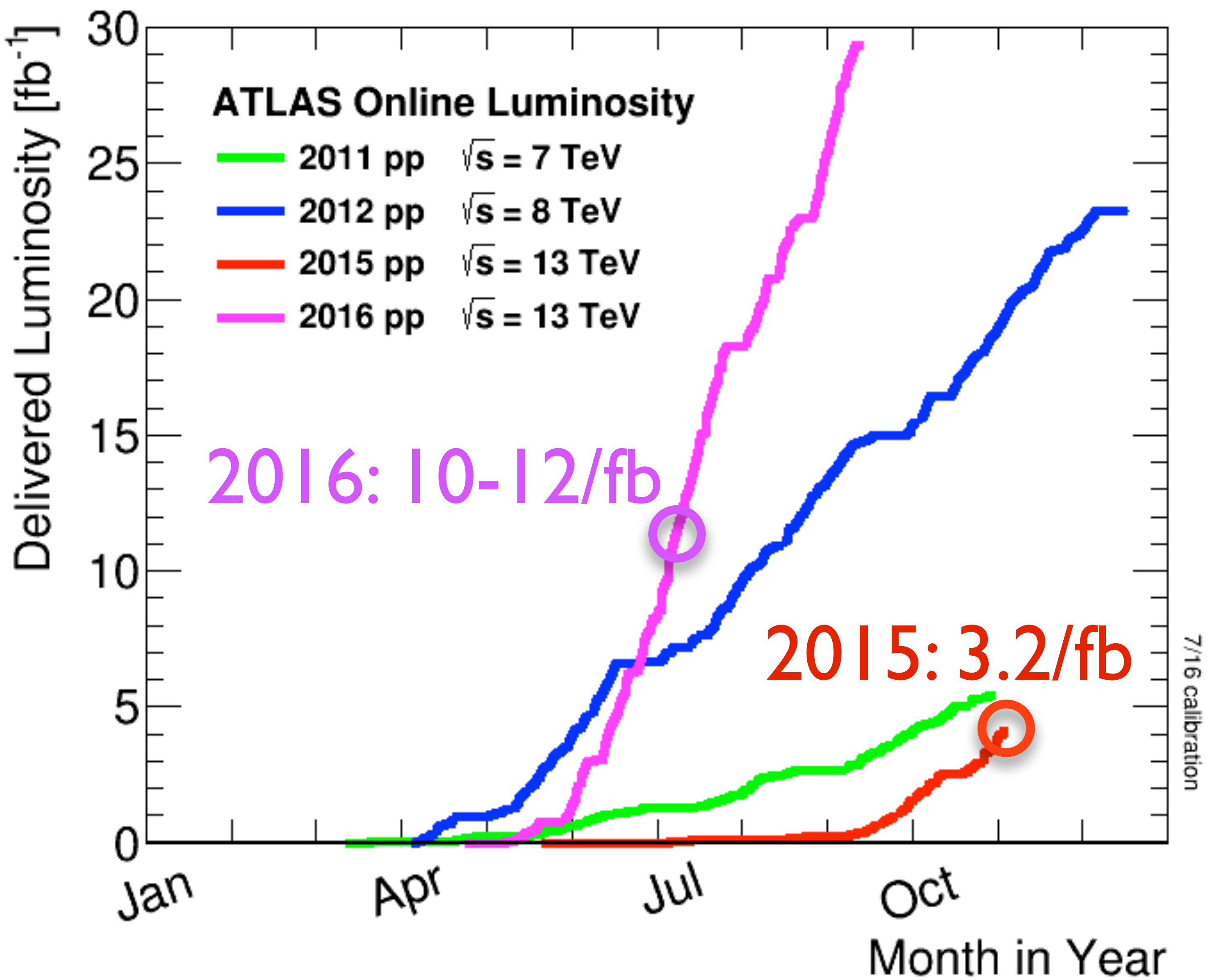
ATLAS Detector

ATLAS is a 7 story tall, 100 megapixel "camera", taking 3-D pictures of proton-proton collisions 40 million times per second, saving 10 million GB of data per year, using a world-wide computing grid with over 100,000 CPUs. The collaboration involves more than 3000 scientists and engineers.

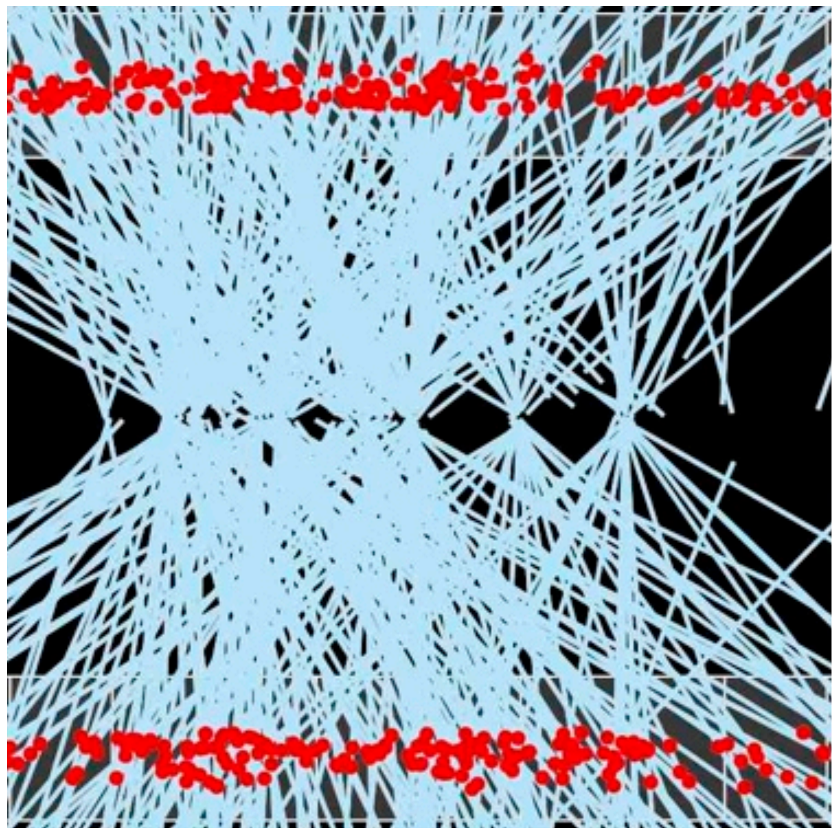


Datasets

The LHC has performed extremely well!!



Recently broke inst. lumi. records > 10^{34} cm^{-2}s^{-1}

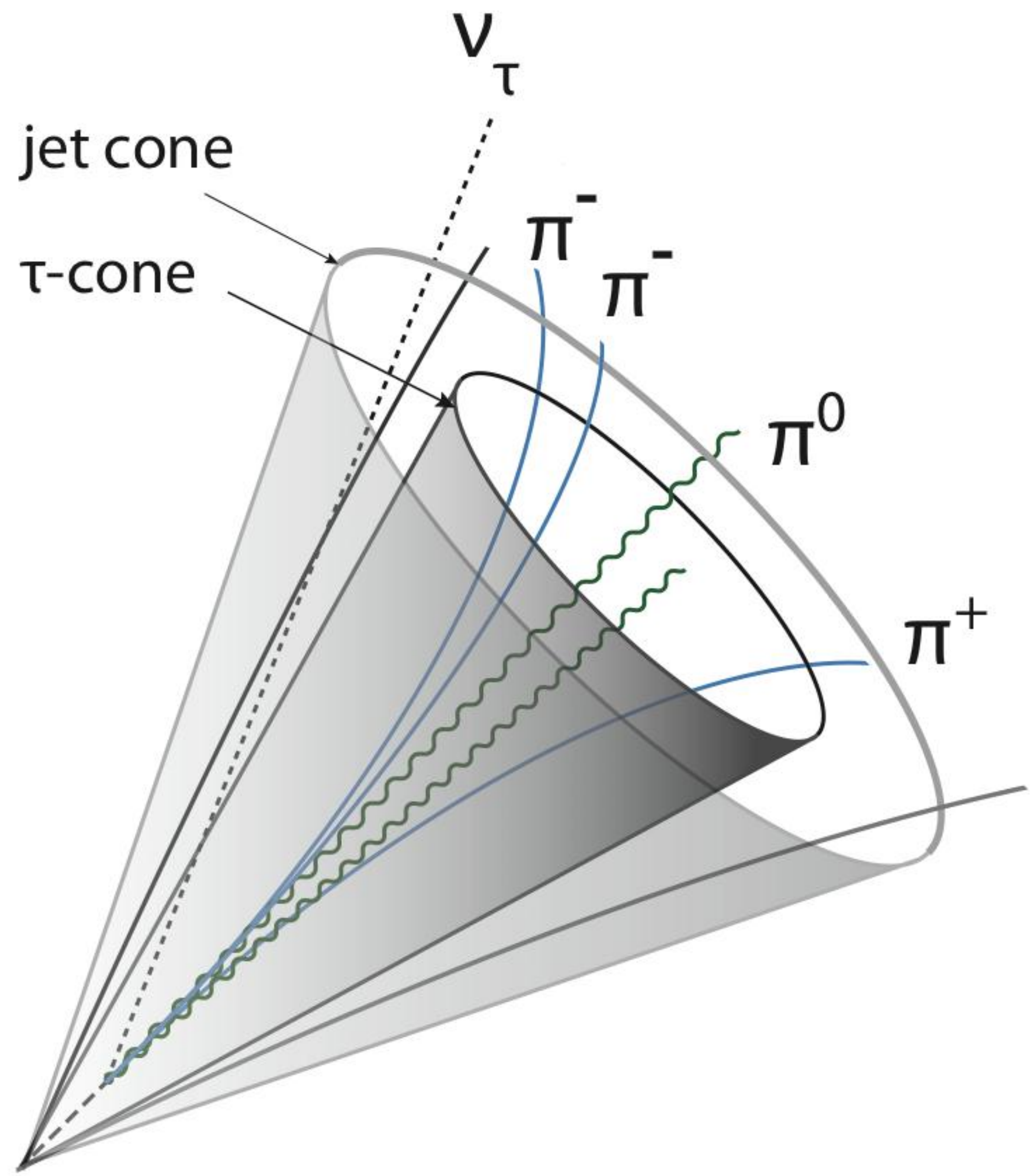


Typically 20-40 verticies per bunch crossing

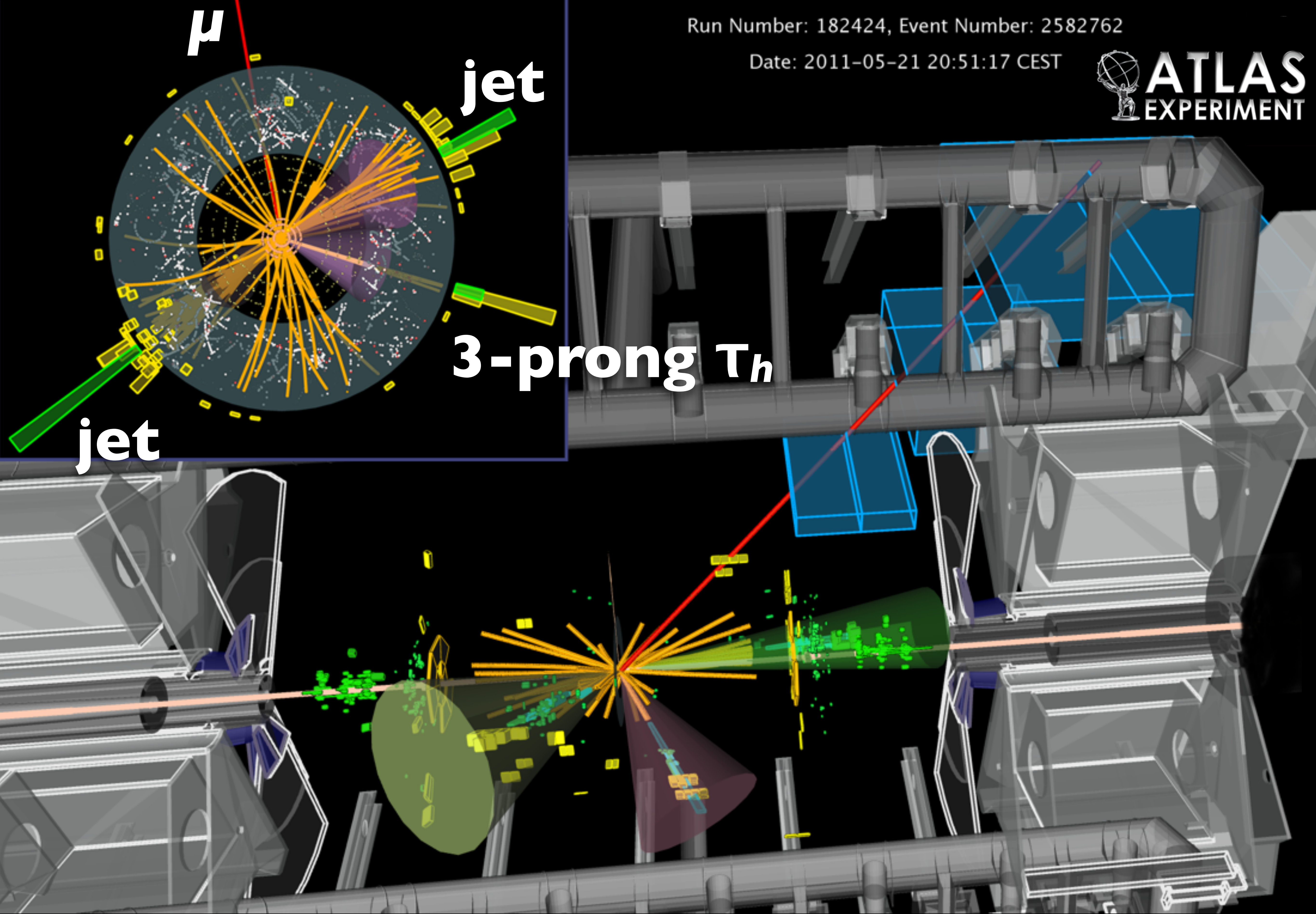
Analyses discussed here combine collision data at $\sqrt{s}$=13TeV collected in the years 2015 and 2016, giving a total integrated lumi ≈ 13-15 fb^{-1}.

Tau Reconstruction

- Tau candidates are seeded by anti-k_t calorimeter jets (R=0.4) formed from topological clusters with local hadronic calib.
- Tracks are matched to this calorimeter object and discrimianting variables calculated from the combined tracking+calo information.
- Best vertex chosen from those matching tracks in core cone $\Delta R<0.2$.
- Core track with $\Delta R<0.2$ associated to the tau.
- Annulus $0.2<\Delta R<0.4$ used to calculate tracking and calorimeter isolation variables.
- *New in Run-2*: π^0 counting using strips in EM calorimeter and subtracting charged energy matched to tracks. Improves jet rejection and energy resolution.

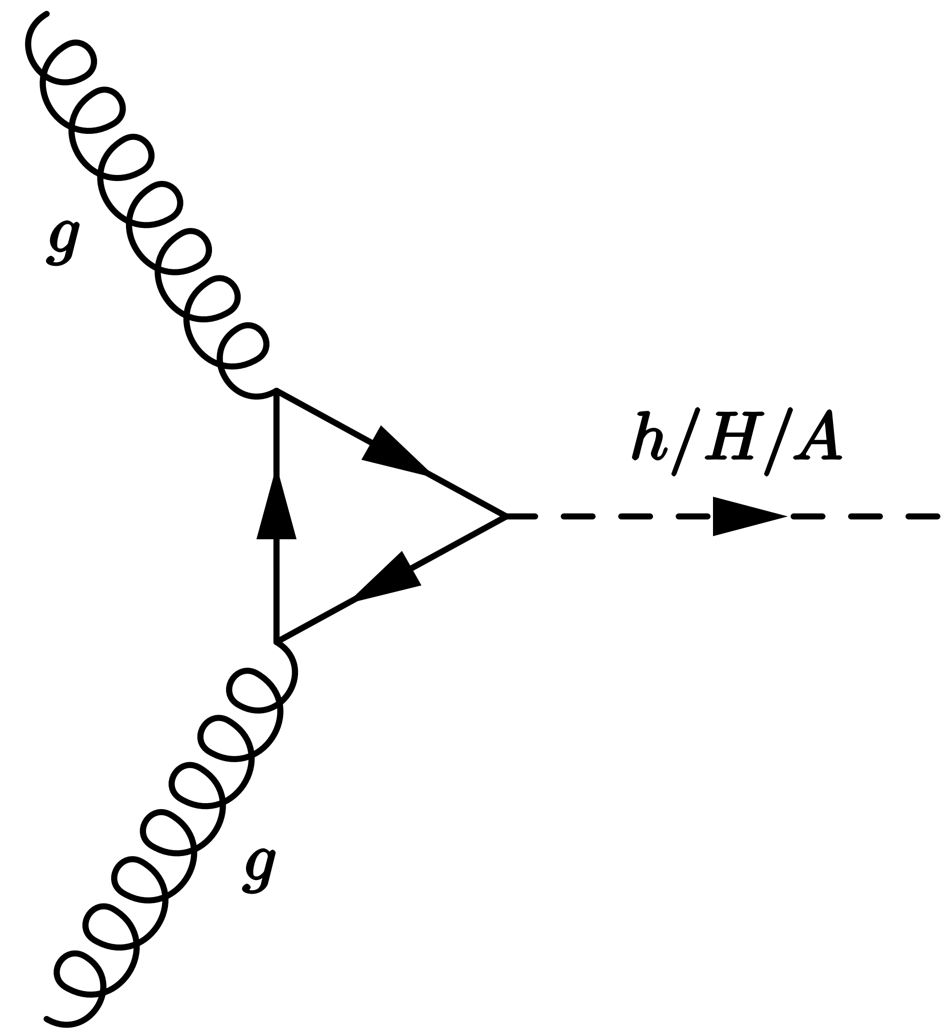


➡ See talk on ATLAS tau reco by Cristina Galea on Wed Sept 21.



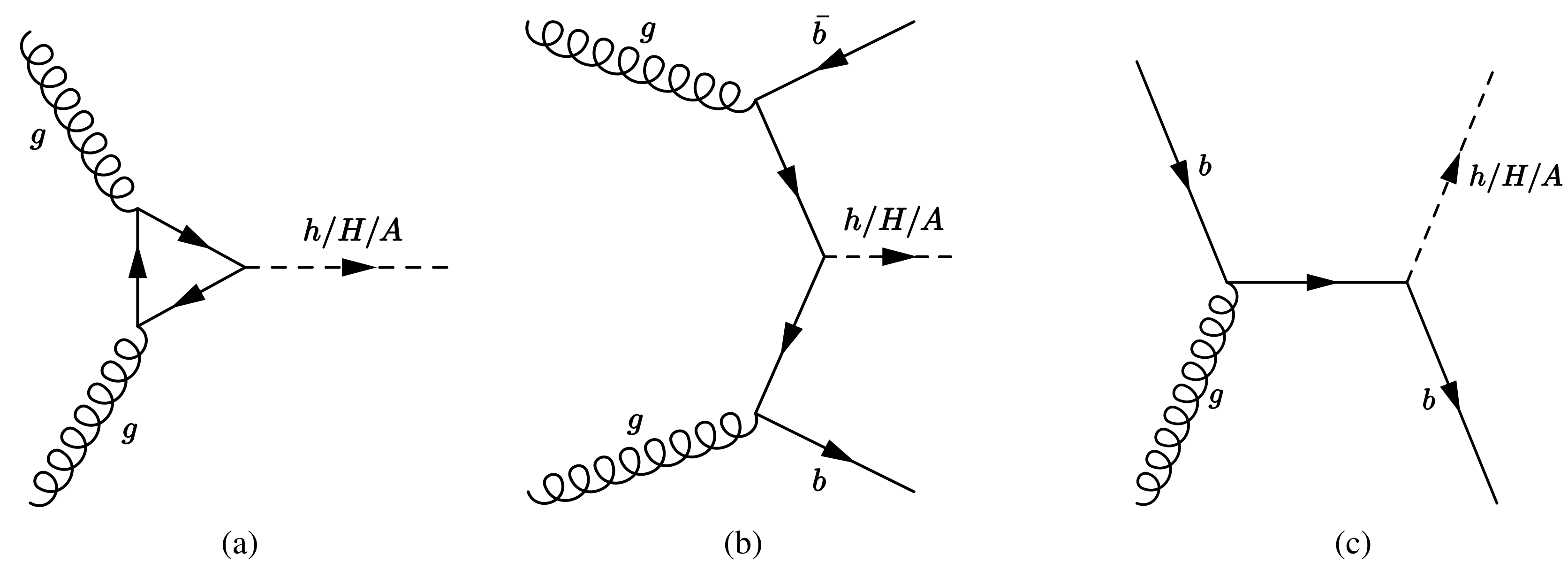
$t\bar{t} \rightarrow b\bar{b}(\mu\nu)(\tau_{\rm h}\nu)$ candidate

Neutral Higgs



$A/H \to \tau\tau$ search

- 2HDM, five spin-0 states: CP-even h and H, CP-odd A, CP-even $H^{\pm}$
- Defining Higgs sector of MSSM. $\tan\beta \equiv v_u/v_d$
- Dataset: ≈13.3 fb^{-1} at $\sqrt{s}$=13 TeV (3.2 fb^{-1} from 2015 and 10.1 fb^{-1} from 2016)
- Improvement on the limits from the 2015 result submitted to EPJC [arix:1608.00890].
- Five signal regions: ($l\tau_h$, $\tau_h\tau_h$) ⊗ (b-tag/no) ⊕ high-MET $l\tau_h$



no b-tag ggF (small tan β) associated b-jets (high tan β)

$A/H \to \tau\tau$ search

Event selection

- **$l\tau_h$ channel**:
  single lepton triggers,
  $p_T(e/\mu) > 30$ GeV offline and isolated,
  use MET trigger for MET > 150 GeV,
  medium τ_h (eff 55%) with $p_T > 25$ GeV,
  opposite charges, no more leptons,
  $\Delta\phi(\tau_h, e/\mu) > 2.4$,
  $m_T(e/\mu, \text{MET}) < 40$ GeV (reject W+jets)
  veto $m_{vis}(e, \tau_h)$= 80-110 GeV (reject $Z \to ee$)
  b-tag (eff 77%) or no-btag.

- **$\tau_h\tau_h$ channel**:
  single τ_h triggers,
  $p_T(\tau_h) > 80$ GeV or 110 GeV (run dependent),
  medium τ_h (eff 55%) with $p_T > 140$ GeV,
  loose (60%) 2nd τ_h with $p_T > 55$ GeV,
  opposite charges, no leptons,
  $\Delta\phi(\tau_{h1}, \tau_{h2}) > 2.7$,
  b-tag (eff 77%) or no b-tag.

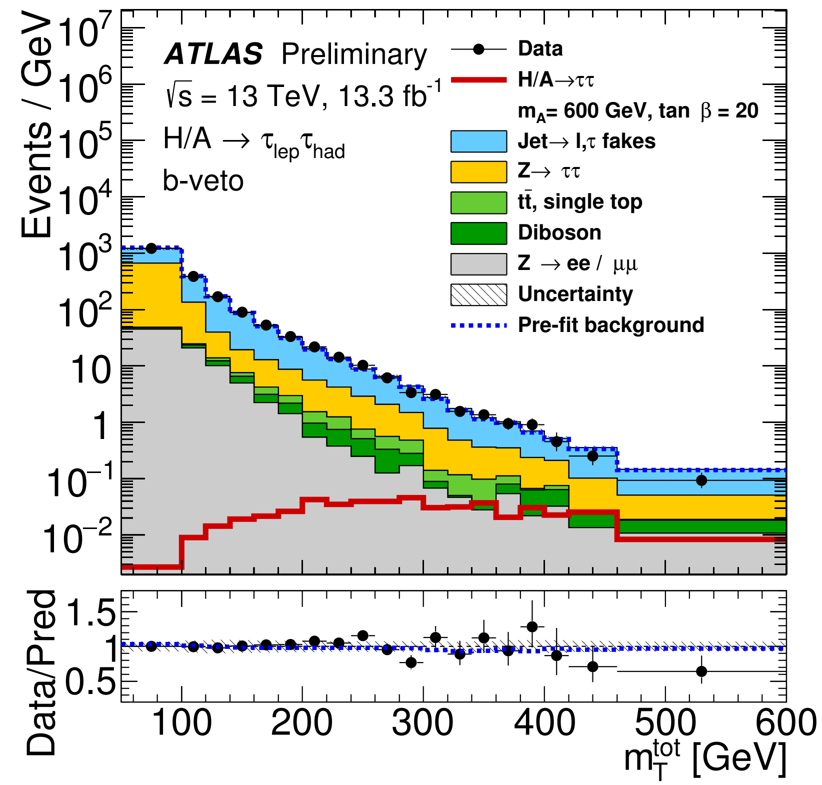
Background estimation

- Sensitivity to jet shapes makes MC modeling of the rates of jets-faking taus poor. Jets-faking taus are data-driven with the *fake-factor method*, weighting taus in data that failed ID by a fake factor measured in fake-rich control regions.

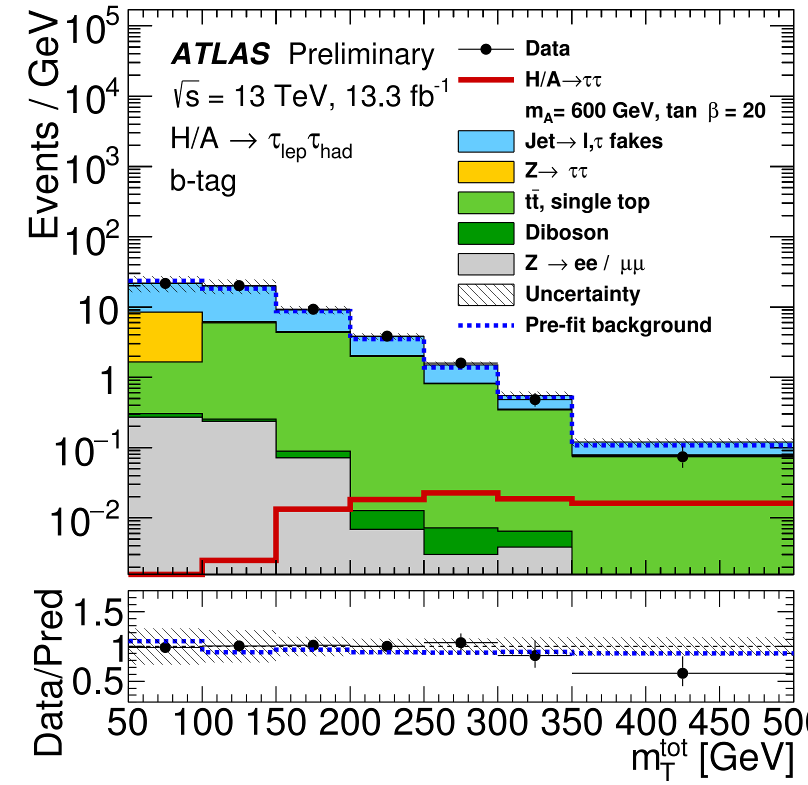
- Other backgrounds from $Z \to \tau\tau$, *tt*, and others are estimated with MC (with appropriate scale-factors), checked in validation regions.

A/H→ττ search

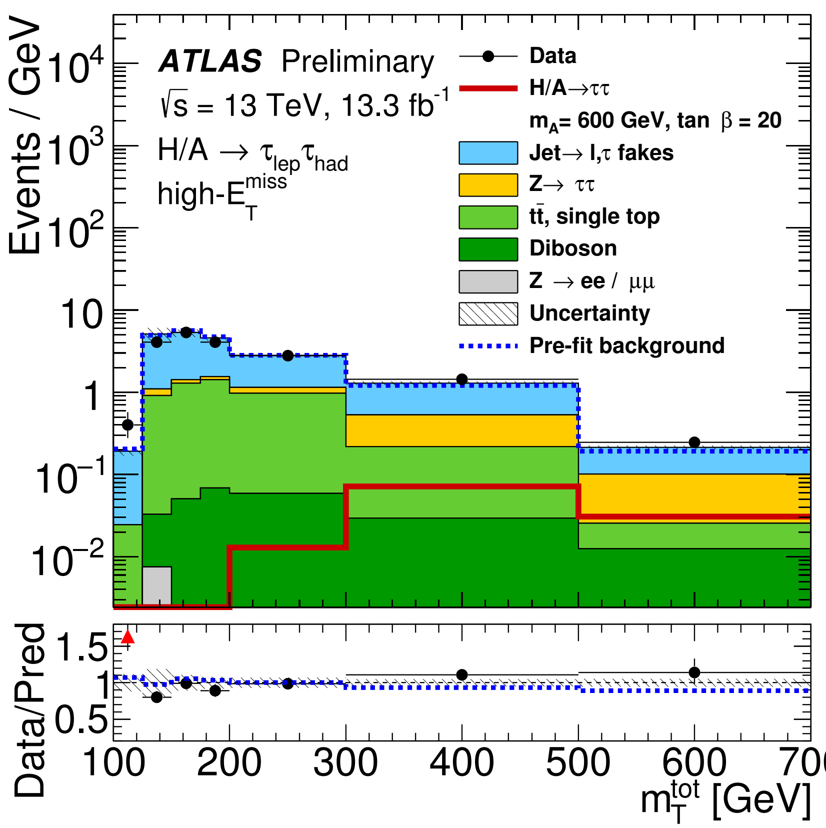
Hypothesis tests are done with frequentist CLs method, using the total transverse mass, m_T^{tot}, as the discriminating variable. Post fit plots in all categories (consistent with the SM):



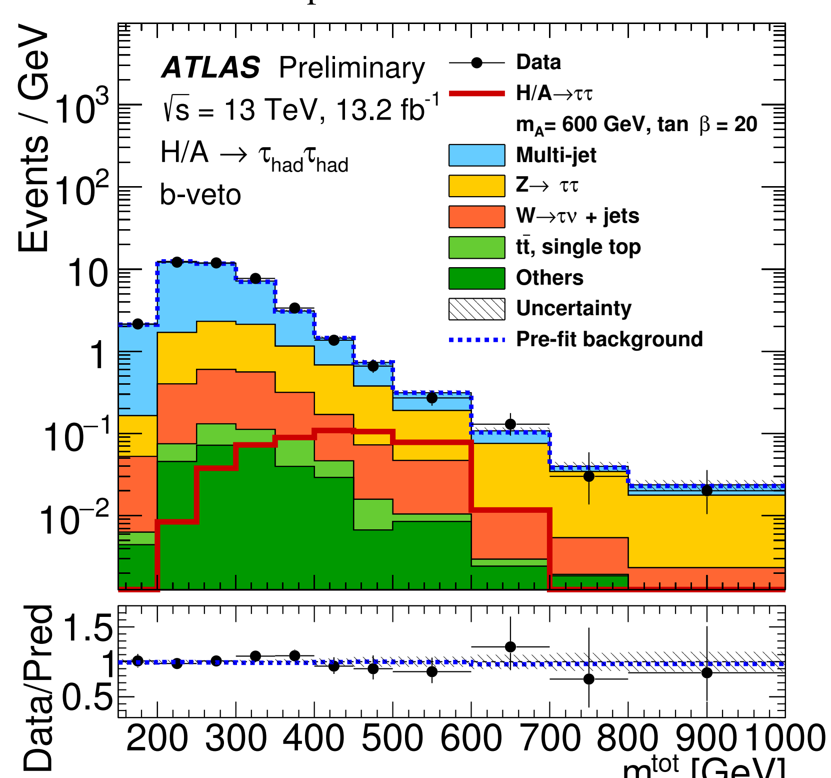
(a) $\tau_{lep}\tau_{had}$ b-veto category



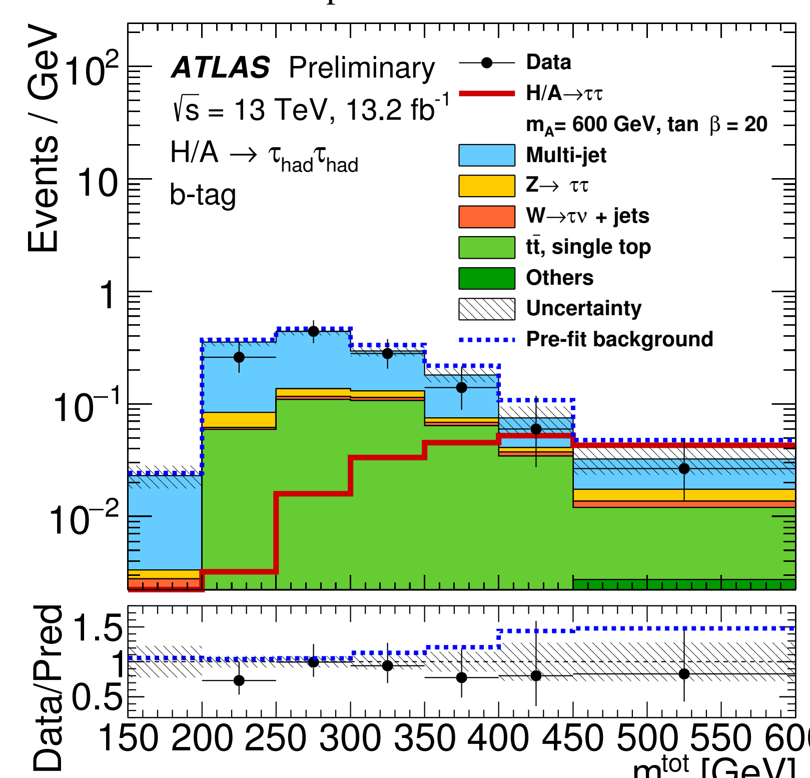
(b) $\tau_{lep}\tau_{had}$ b-tag category



(c) $\tau_{lep}\tau_{had}$ high-E_T^{miss} category



(d) $\tau_{had}\tau_{had}$ b-veto category

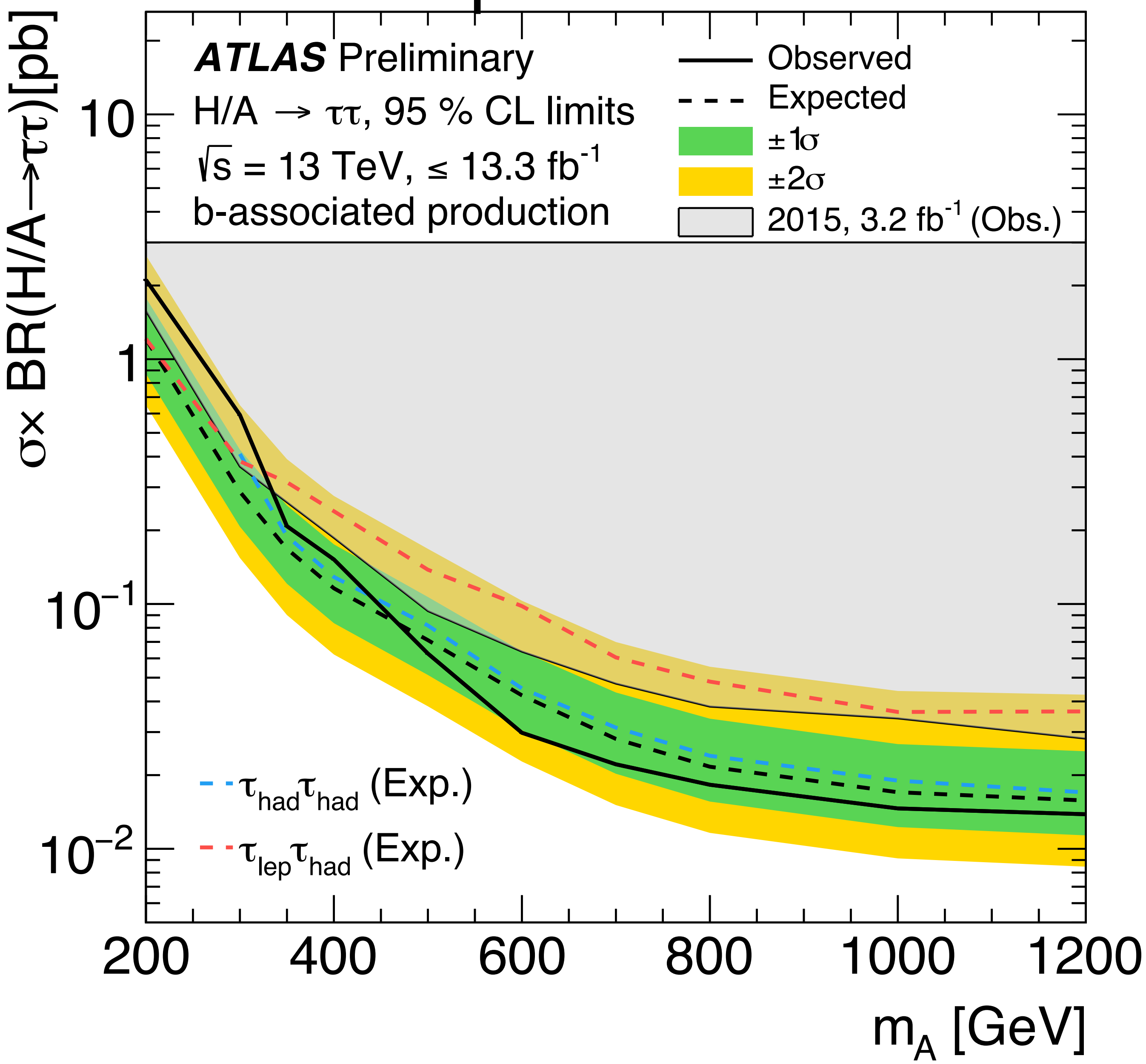


(e) $\tau_{had}\tau_{had}$ b-tag category

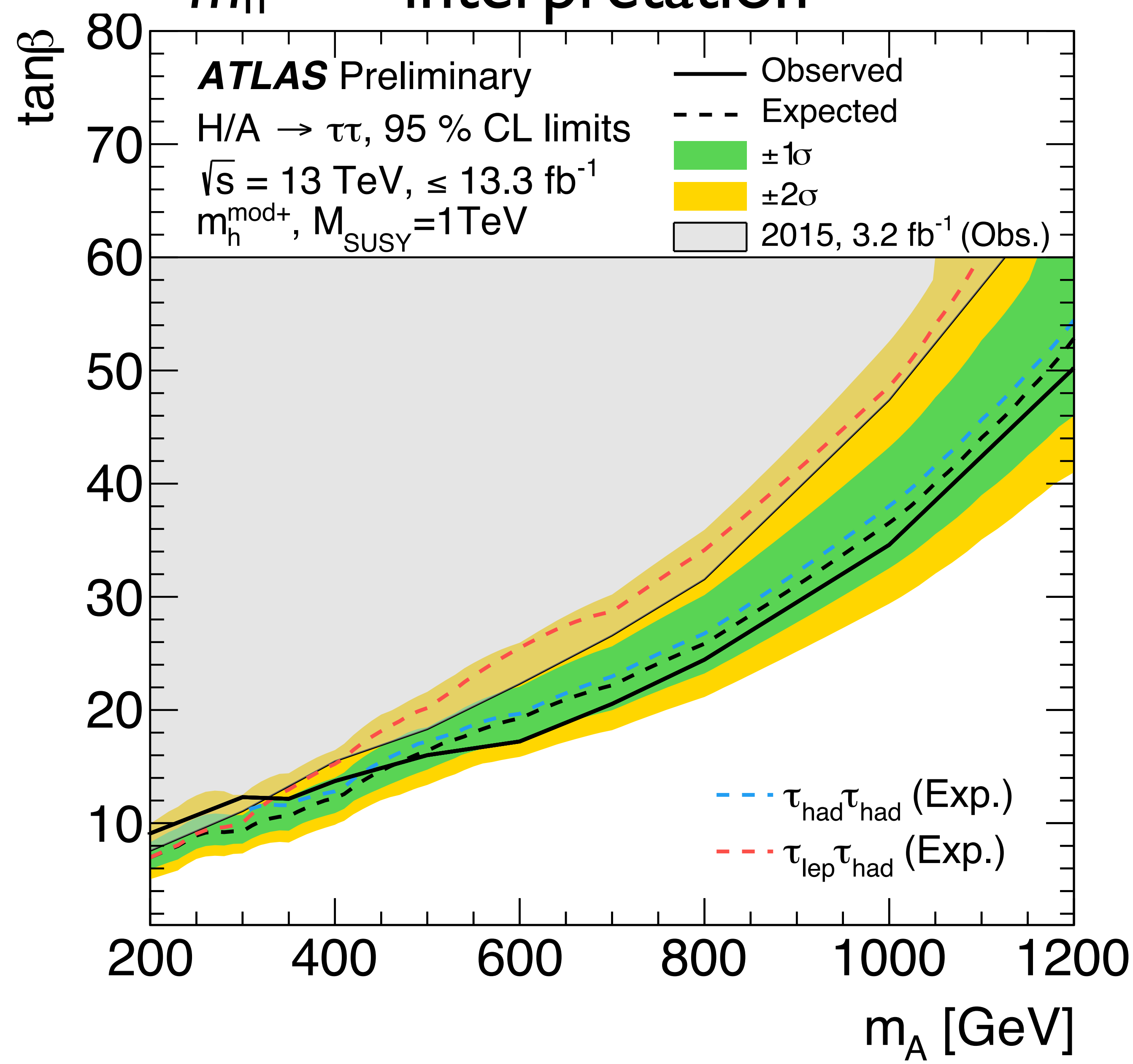
A/H→ττ search

- Set limits on the m_h^{mod+} and hMSSM benchmark models.
- In both cases, exclude tan β ≳ 10 for m_A ≈ 200-400 GeV, tan β ≳ 25-35 for m_A ≈ 1 TeV @ 95% CL.

Model indepedent limit

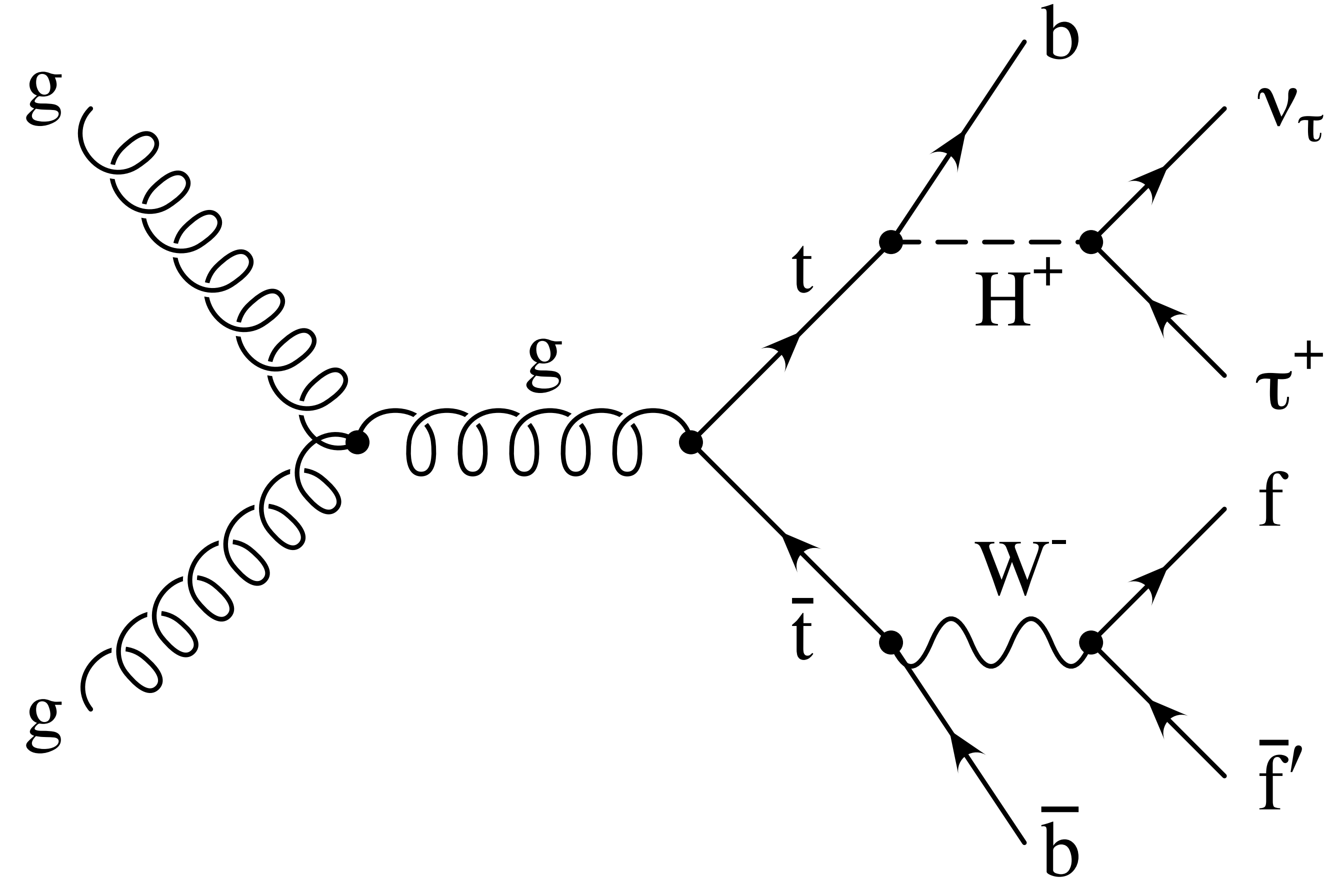


m_h^{mod+} interpretation



[ATLAS-CONF-2016-085]

Charged Higgs



Charged Higgs

- 2HDM, five spin-0 states:

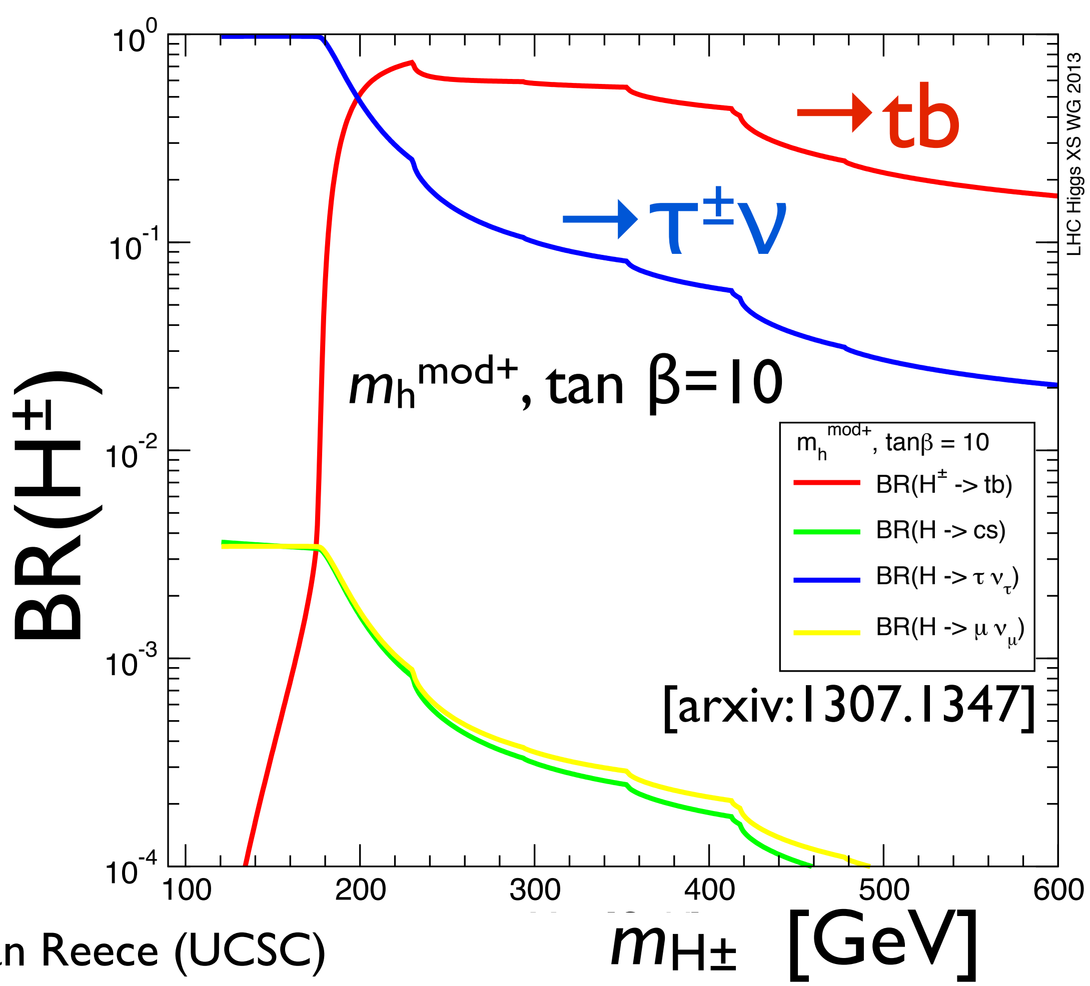
  CP-even h and H, CP-odd A, CP-even $H^{\pm}$

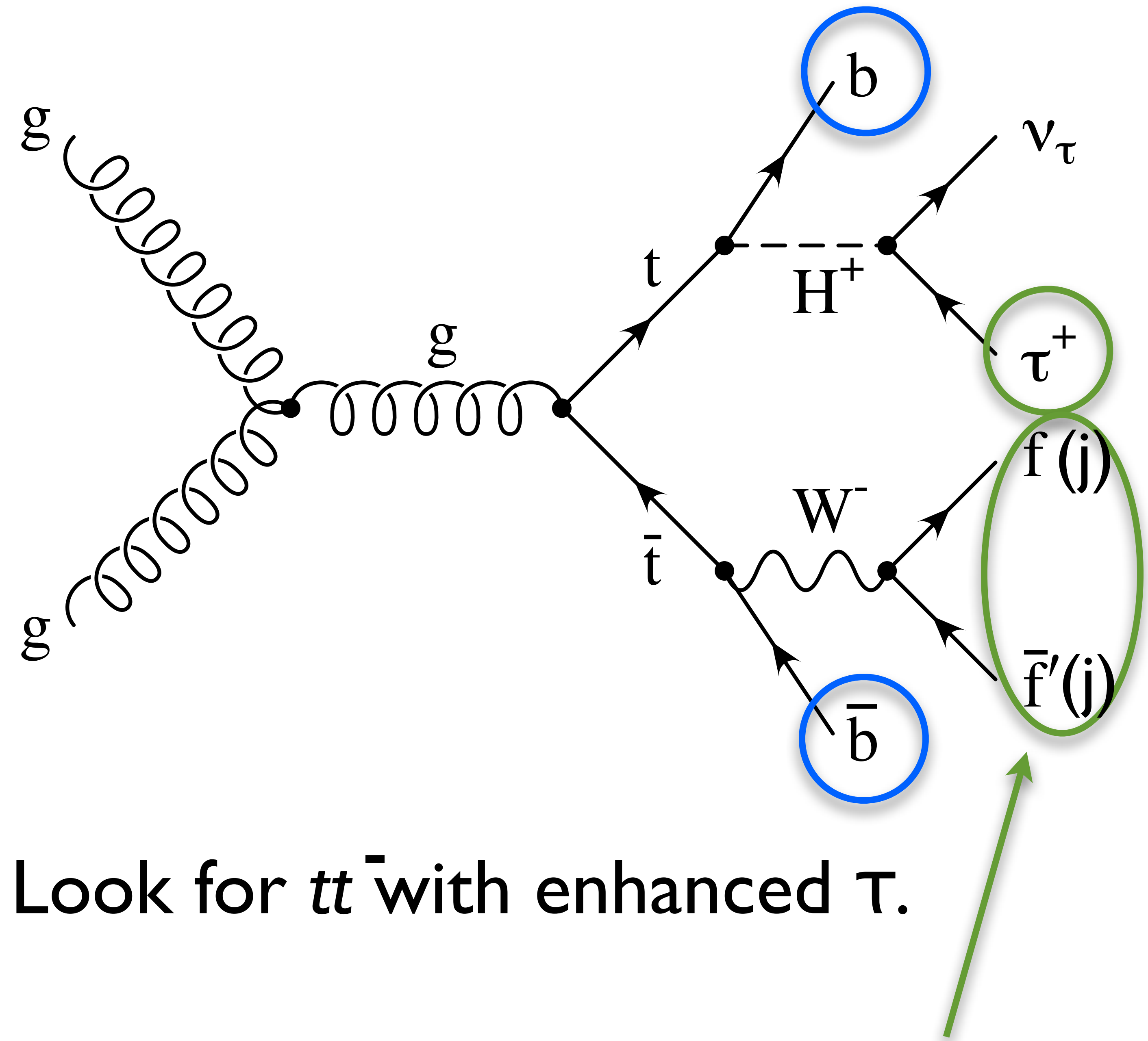
- Produced through top decays:

  $t^{\pm} \to bH^{\pm}$ (for $m_{H^+} < m_t$)

- For tan β > 2 and $m_{H+} < m_t$,

  $H^{\pm} \to \tau^{\pm}\nu$ dominant decay





Look for $t\bar{t}$ with enhanced τ.

Search uses the $bb\tau_h\nu jj$ mode.

Charged Higgs

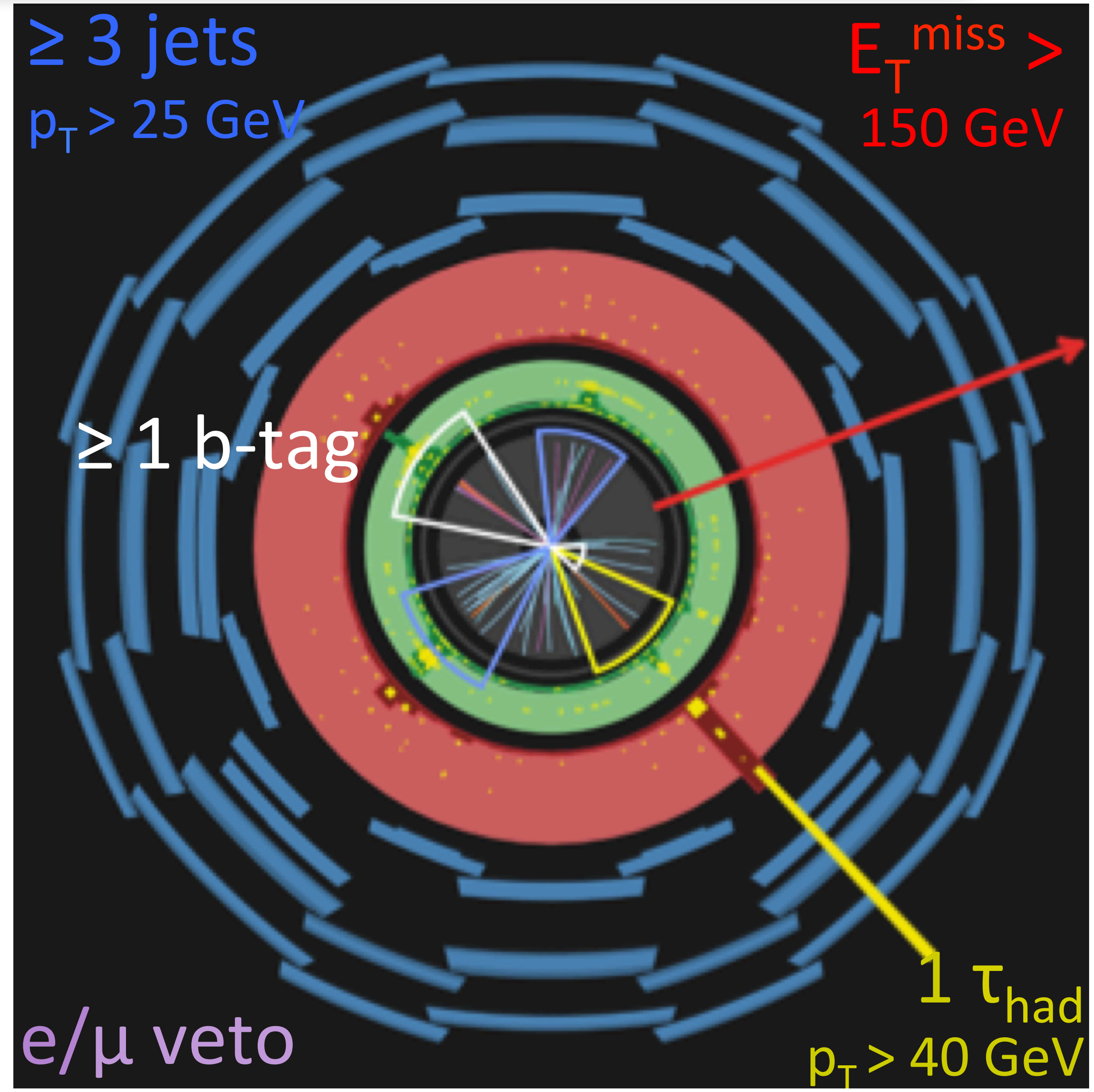
Dataset ≈14.7 fb^{-1} at $\sqrt{s}$=13 TeV, 2015+2016

Event selection

- ***bbτhνjj* topology**
  MET trigger with MET > 70-90 GeV,
  offline MET > 150 GeV,
  1 medium τ_h (eff 55%) with p_T > 40 GeV,
  3 or more jets with p_T > 25 GeV,
  1 of which must be b-tagged,
  no electrons or muons.

- discriminating variable:

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi_{\tau, E_{\mathrm{T}}^{\mathrm{miss}}})},$$

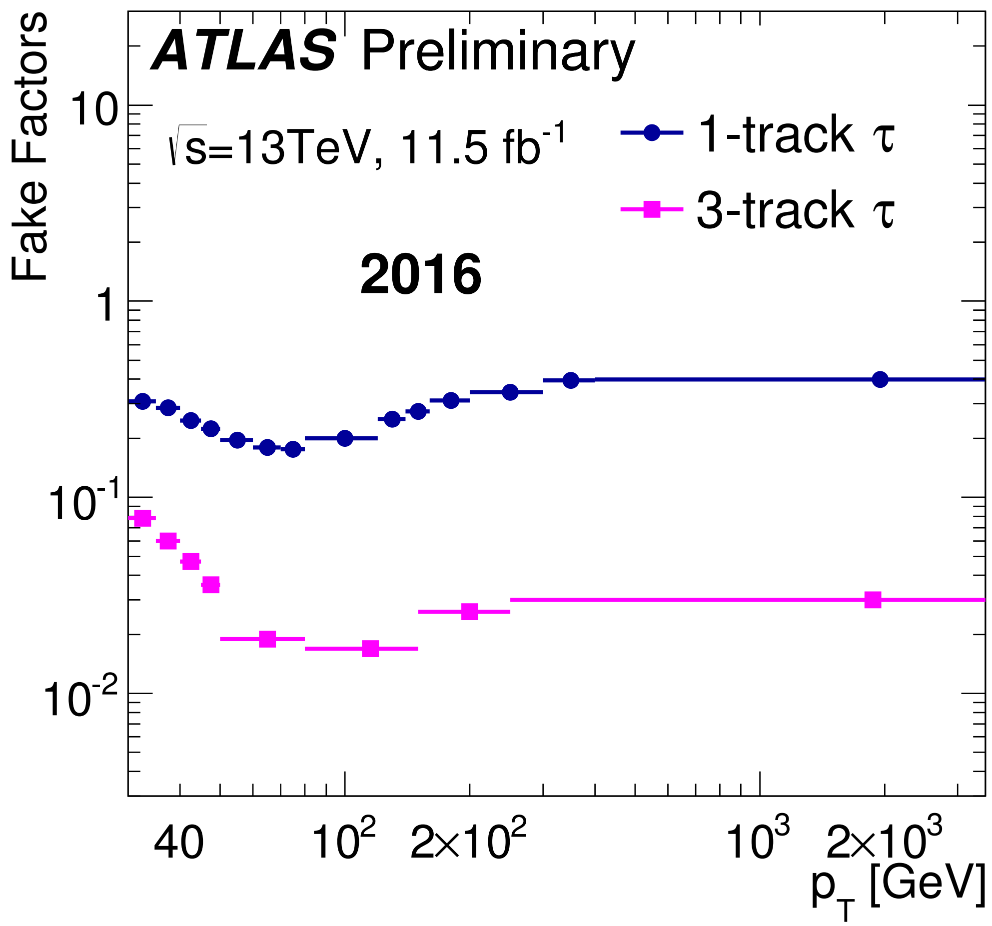


Background estimation

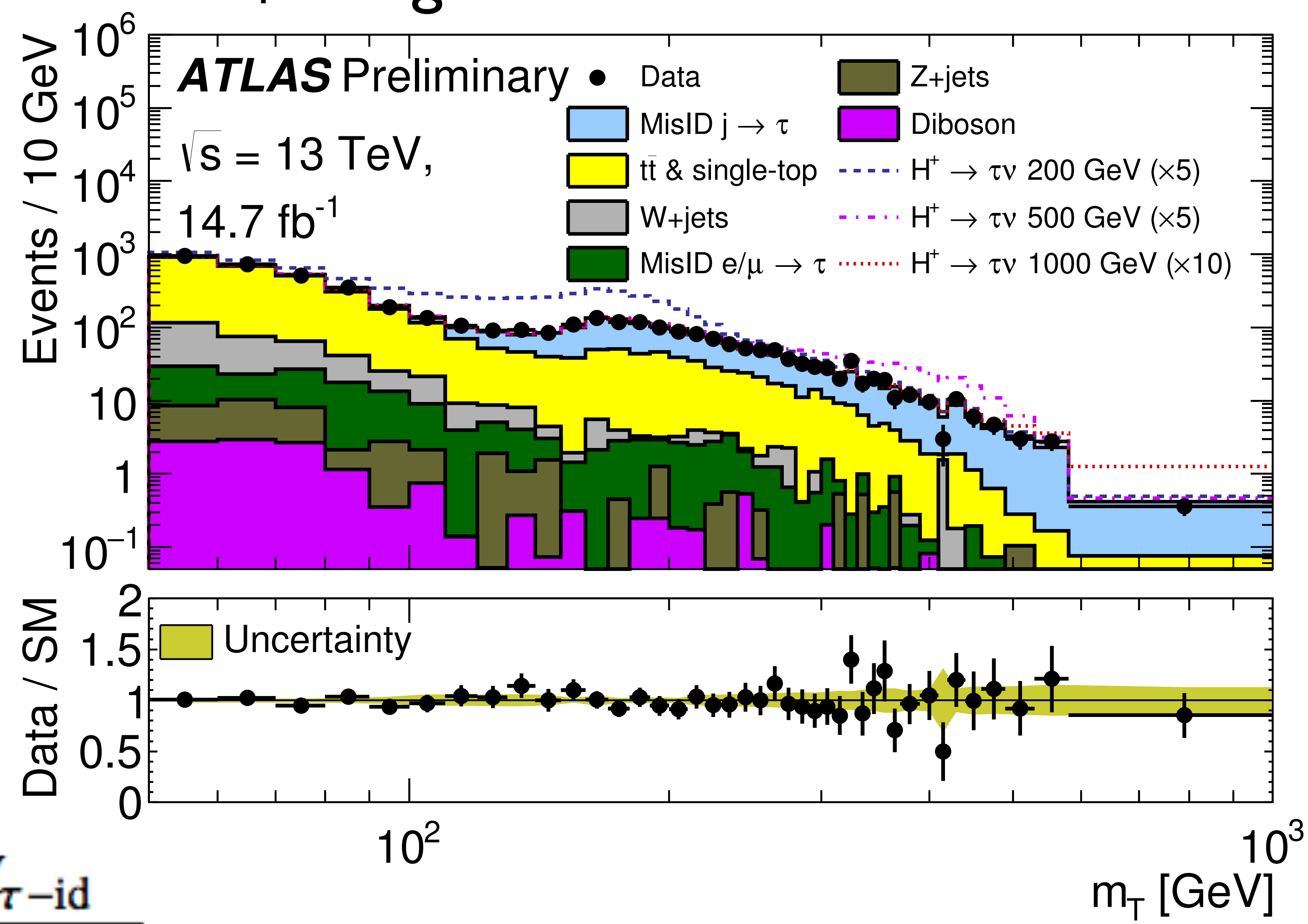
- Jets-faking taus are data-driven with the *fake-factor method*, weighting taus in data that failed ID by a fake factor measured in fake-rich control regions.
- Other backgrounds from *Z*→ττ, *W*+jets, *tt*, and others are estimated with MC (with appropriate scale-factors), checked in validation regions.

Charged Higgs

Fake factors



m_T in signal selection

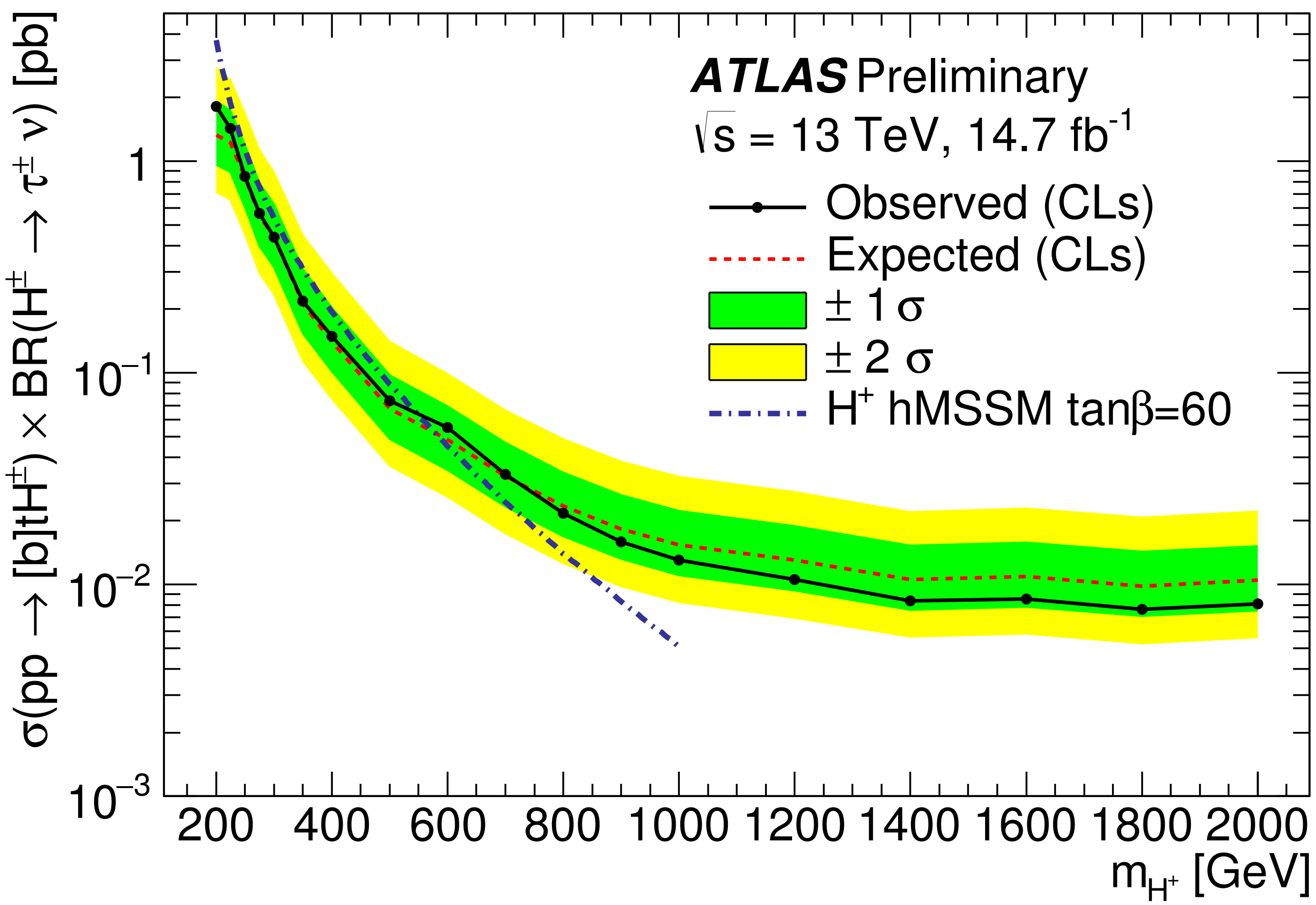


$$N_{\mathrm{fakes}}^{\tau} = N_{\mathrm{fakes}}^{\mathrm{anti}-\tau} \times FF \qquad FF = \frac{N_{\tau-\mathrm{id}}}{N_{\mathrm{anti}-\tau-\mathrm{id}}}$$

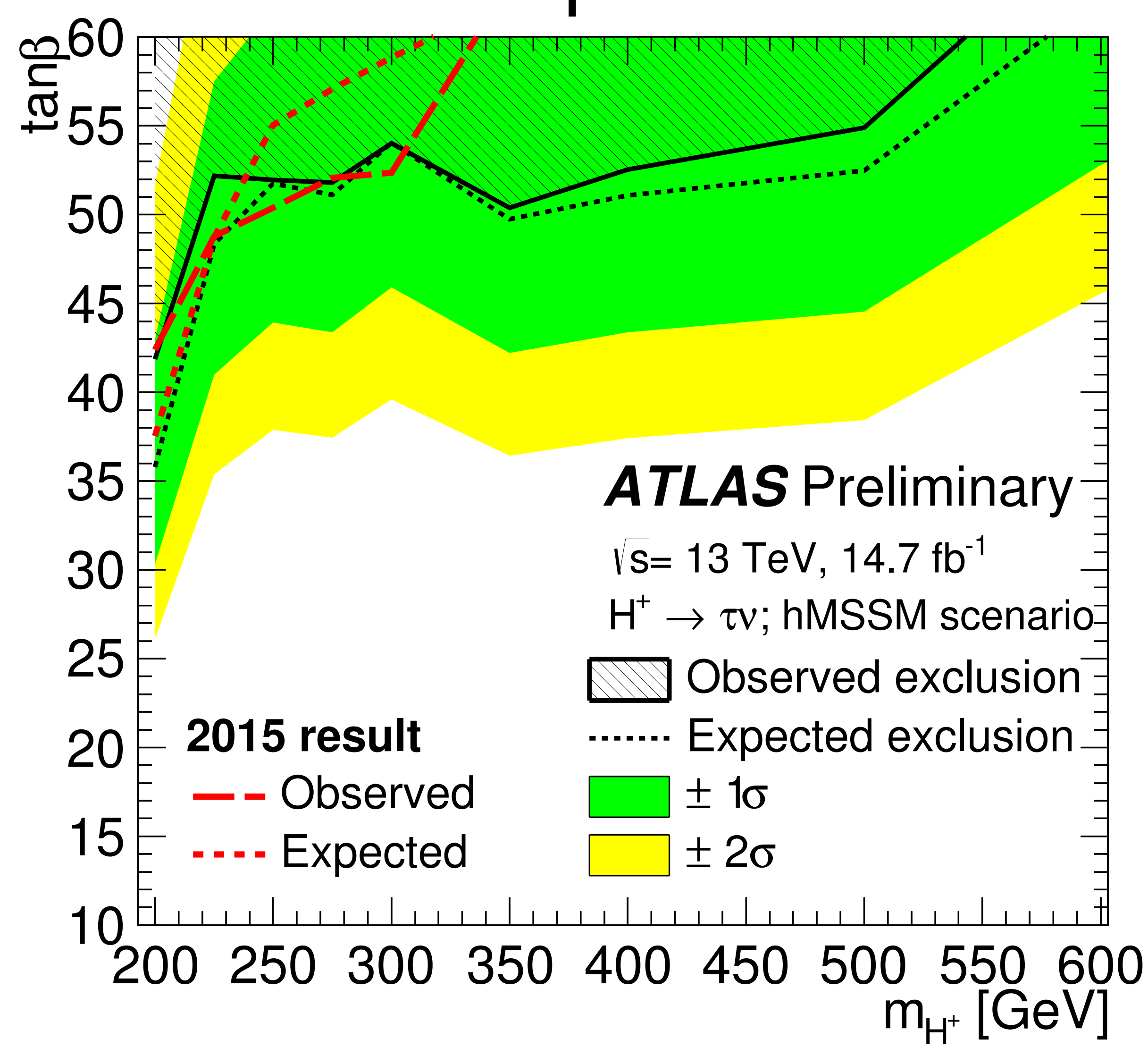
- Fake factors are 1-30% (weighting events in data down improves stats).
- Signal region dominated by top events with fakes in the tail.

Charged Higgs

Model indepedent limit

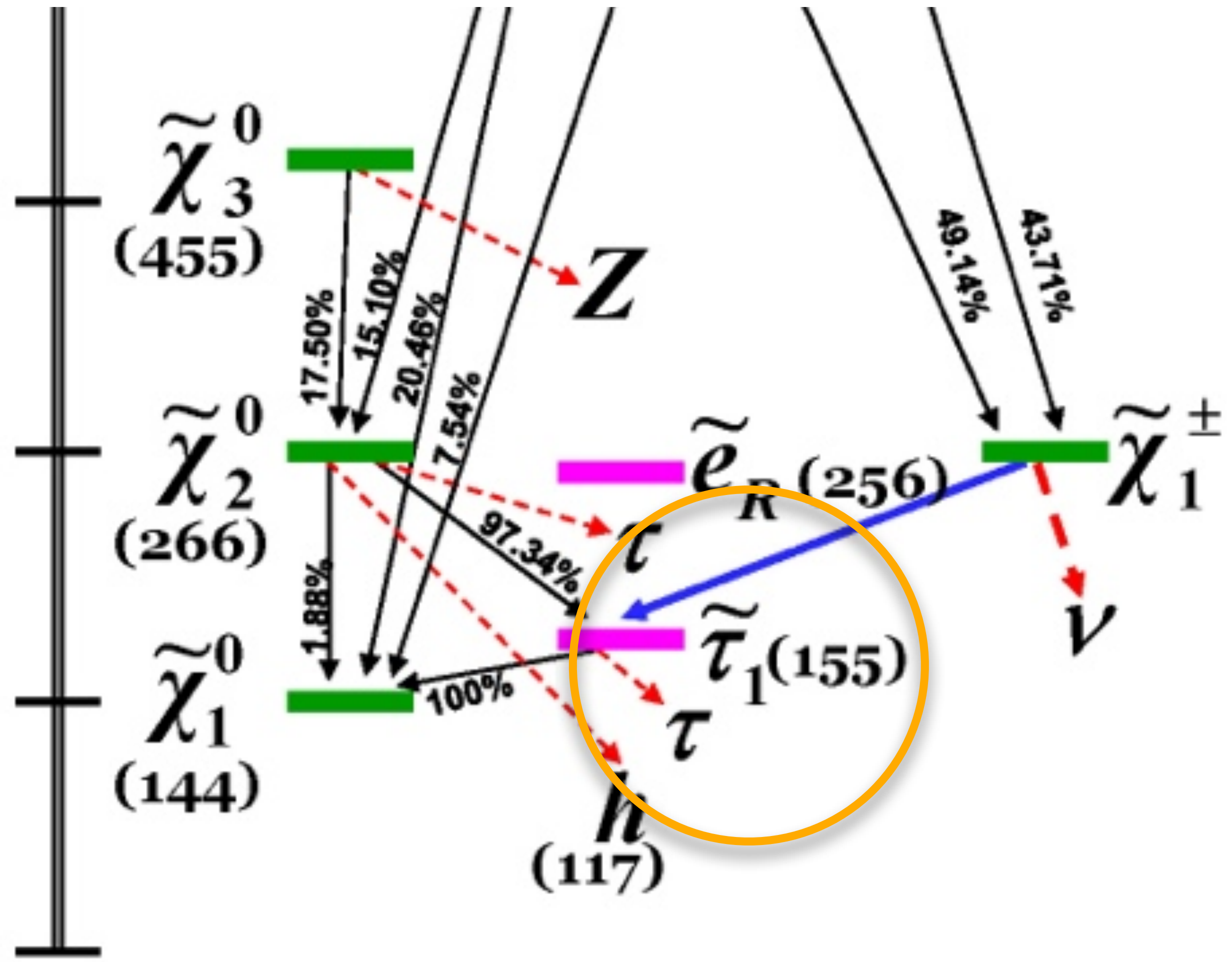


hMSSM interpretation



- $\sigma\times BR \lesssim 2$ pb for $m_{H\pm} = 200$ GeV, $\sigma\times BR \lesssim 8$ fb for 2 TeV @ 95% CL
- Excludes tan $\beta \gtrsim 40$-60 for $m_{H\pm} = 200$-600 GeV @ 95% CL.
- Updates previous result with only 2015 data [arxiv:1603.09203].

SUSY



(455)
(266)
(144)
Z
17.50%
15.10%
20.46%
7.54%
49.14%
43.71%
(256)
97.34%
1.88%
100%
(155)
τ
ν
h
(117)

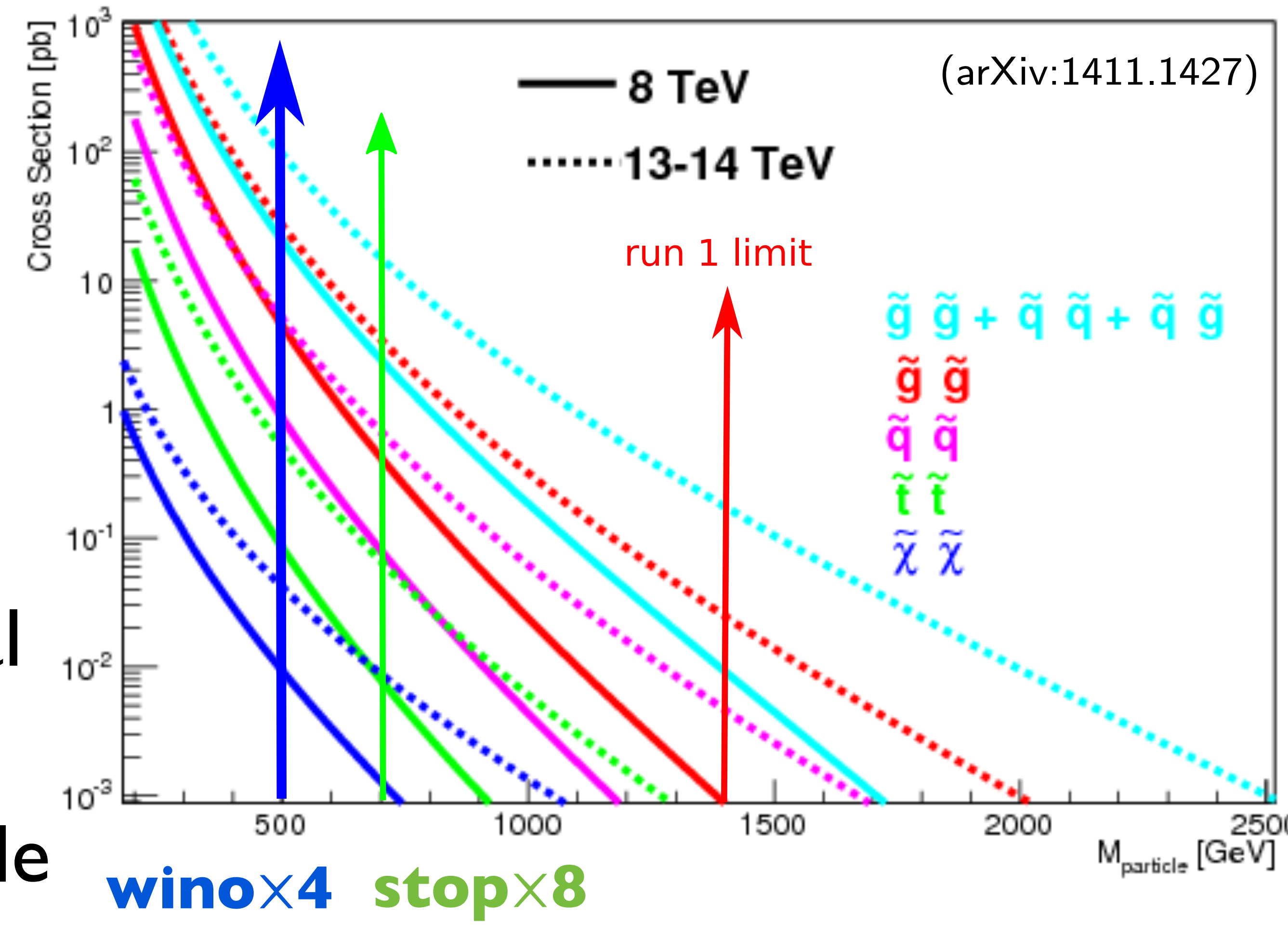
Why SUSY again?

Why SUSY?

- alleviates the EW hierarchy problem
- could explain dark matter
- allows for gauge unification

Challenges:

- more than 100 parameters in general
- theoretically attractive, but experimentally challenging to untangle
- collider phenomenology dominated by the type of NLSP, how it is produced and decays.
- Third generation especially important for EW naturalness.
- Tau motivation: interesting possibilities with stau NLSP.



Run-2 advantage:

- increasing $\sqrt{s}$ from 8 to 13 TeV significantly opens up possiblities for SUSY production!
- two SUSY searches discussed here use 13.2 and 14.8 fb^{-1} of data at 13 TeV from 2015+2016.

Stop to stau search

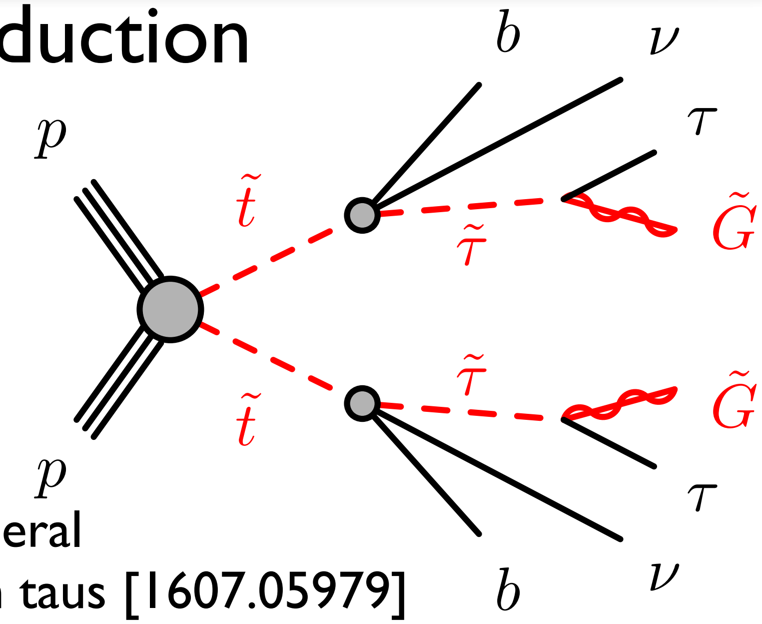
Event selection

- single lepton triggers
- 1 p_T(e/μ) > 25 GeV offline and isolated
- 1 medium τ_h (eff 55%) with p_T > 70 GeV,
- opposite charges, no more leptons,
- 2 jets p_T > 50, 20 GeV, at least 1 b-tag (eff 77%),
- MET > 180 GeV,
- m_{T2} > 100 GeV "stranverse mass" [arxiv:9906349] :

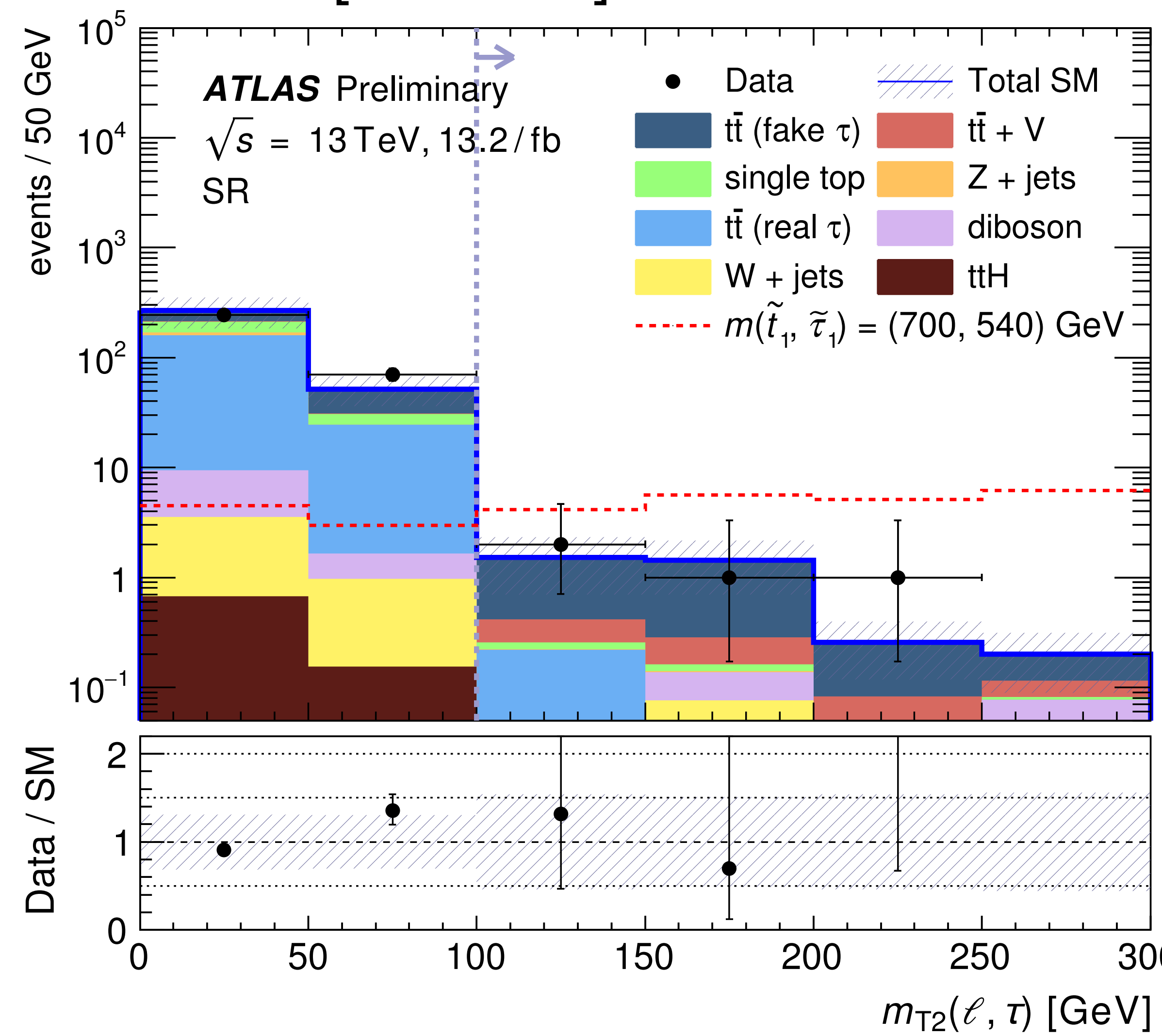
$$m_{T2}^2 = \min_{\vec{q}_1+\vec{q}_2=\vec{E}_T^{miss}} \left[\max\left\{m_T^2(\vec{p}_1,\vec{q}_1), m_T^2(\vec{p}_2,\vec{q}_2)\right\}\right]$$

$\leq M^2$ (visible-invisible pair)

strong production stau NLSP



expands more general strong search with taus [1607.05979]

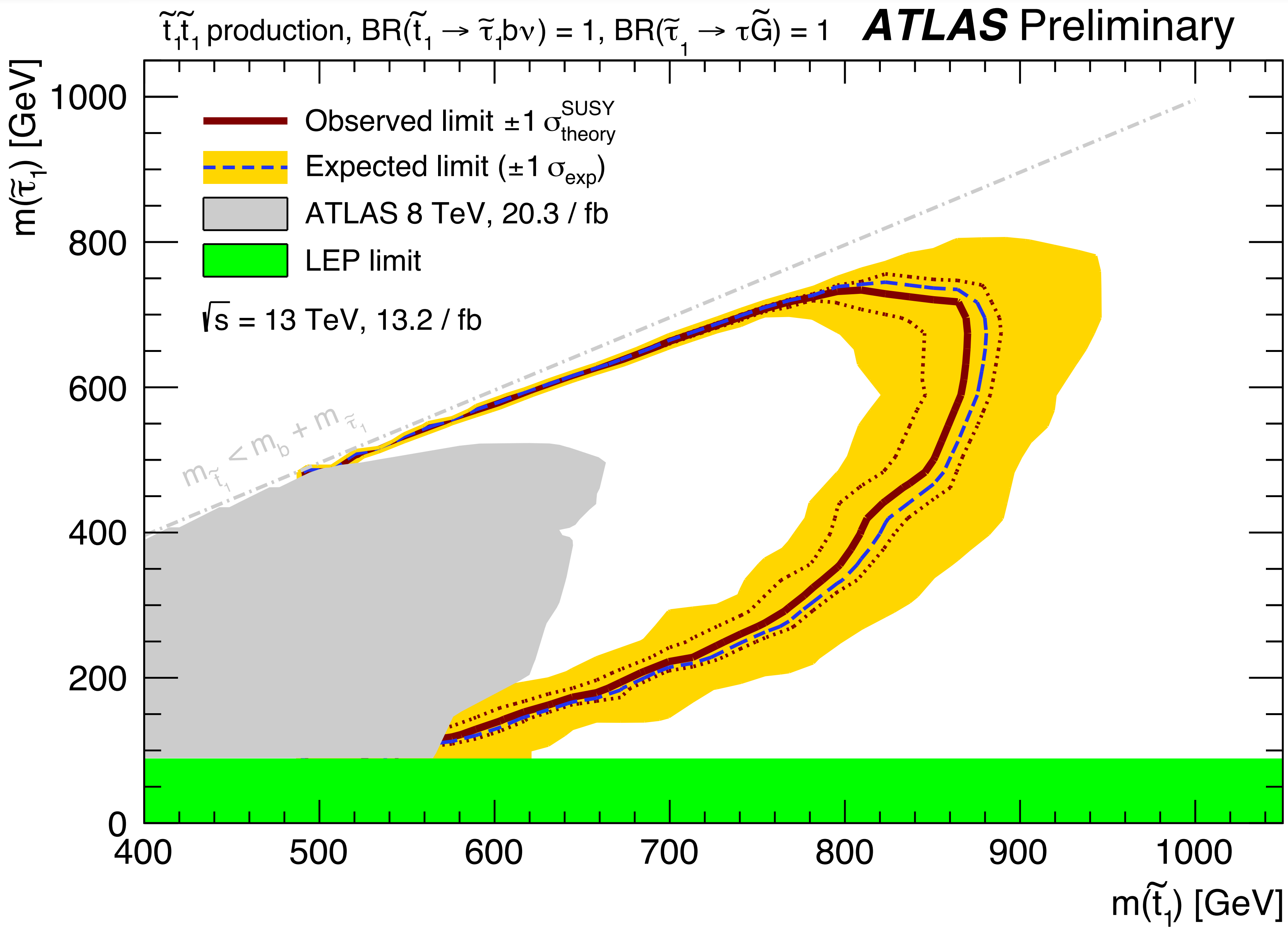


Background estimation

- estimated with MC normalized in control regions
- separate CRs for W+jets and ttbar, with and without a fake hadronic tau.

[ATLAS-CONF-2016-048]

Stop to stau search



- Motivated by GMSB with natural gauge mediation (nGM) ⇒ only 3 light sparticles: stop, stau, nearly massless gravitino.
- Excludes stop masses ≲ 600-870 GeV @ 95% CL depending on stau mass.
- Significantly extends the previous Run-1 limit.

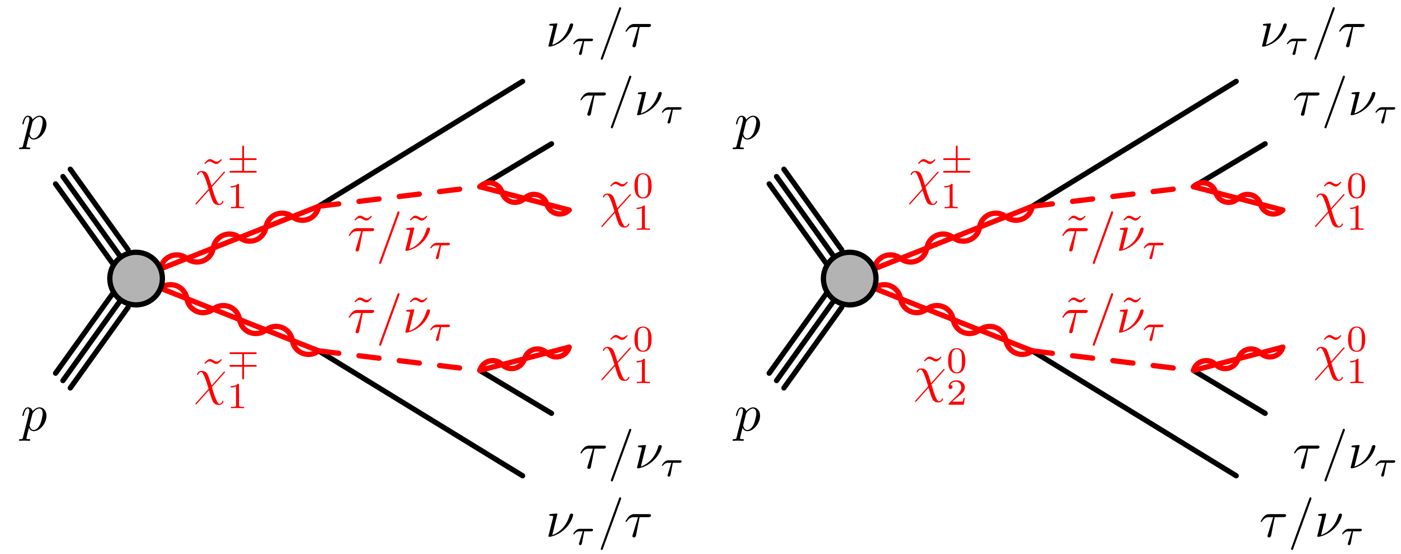
EW SUSY ditau search

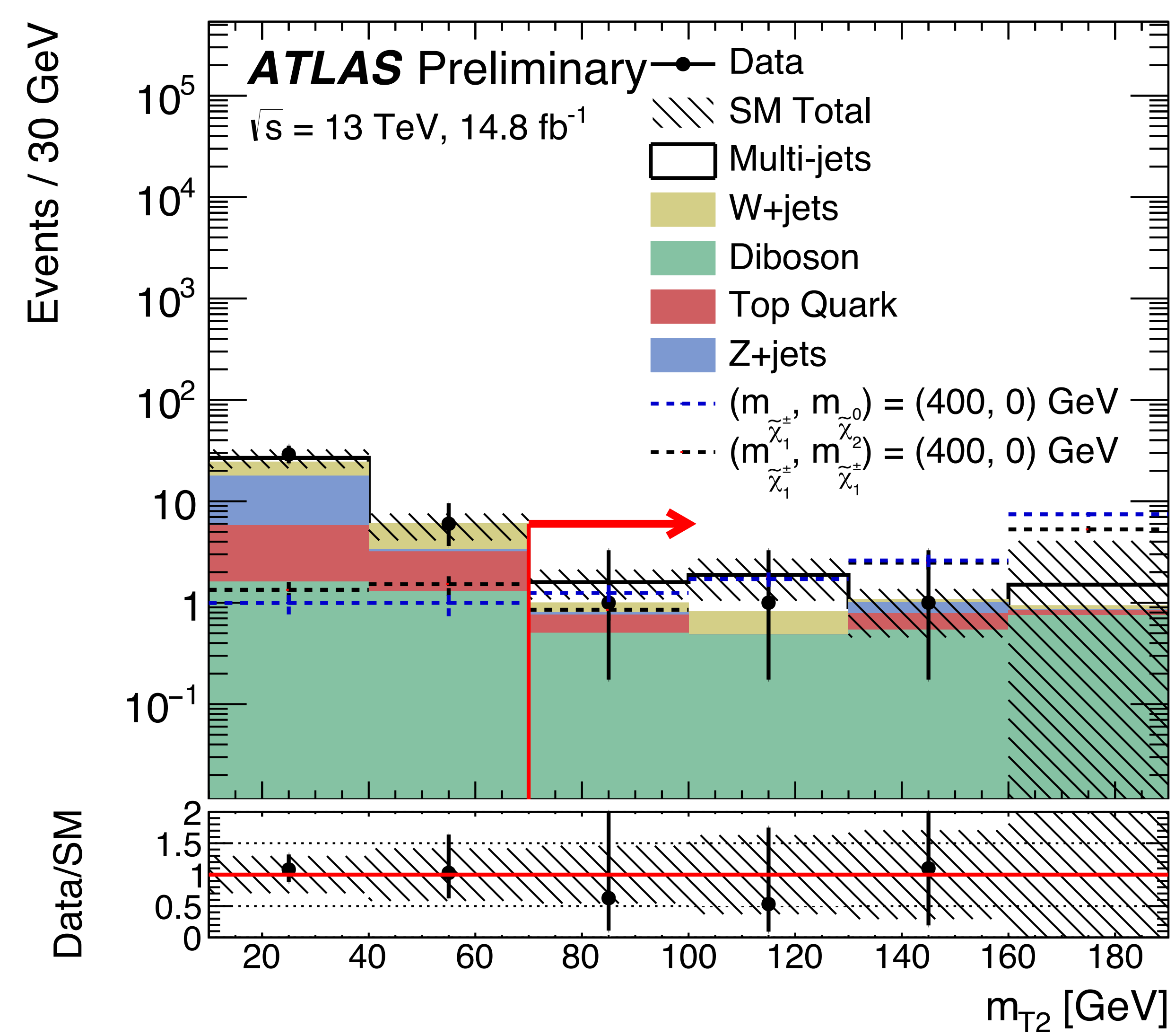
Event selection

- ditau + MET trigger
- at least 2 medium τ_h (eff 55%) with p_T > 50/40/20 GeV,
- at least 2 of which have opposite charges,
- MET > 150 GeV,
- no b-jets, Z→ττ veto
- m_{T2} > 70 GeV (stranverse mass)
- no leptons (in a 2nd signal region)

$$m_{T2}^2 = \min_{\vec{q}_1+\vec{q}_2=\vec{E}_T^{miss}} \left[\max\left\{m_T^2(\vec{p}_1,\vec{q}_1), m_T^2(\vec{p}_2,\vec{q}_2)\right\}\right]$$

$\leq M^2$ (visible-invisible pair)

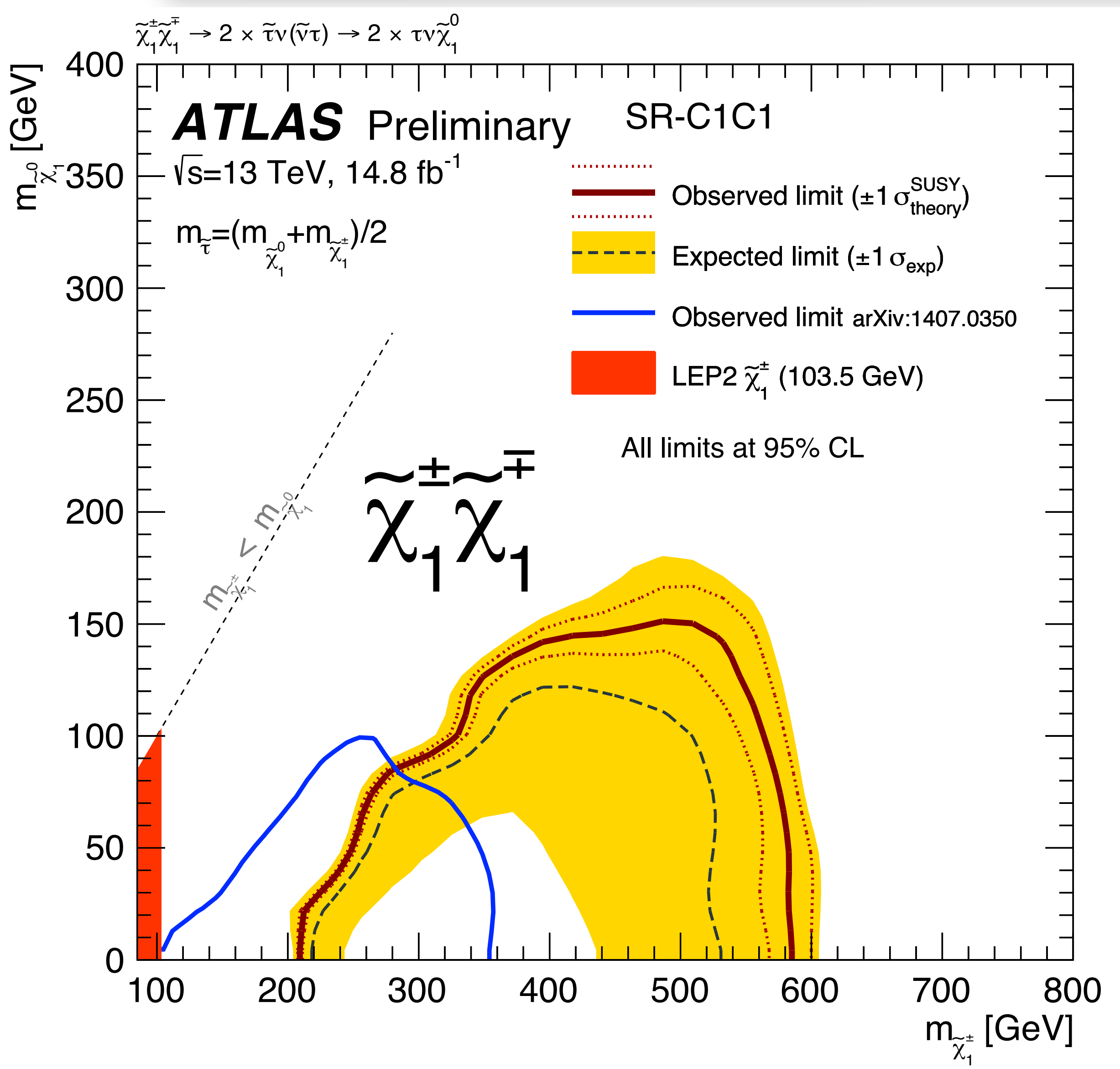


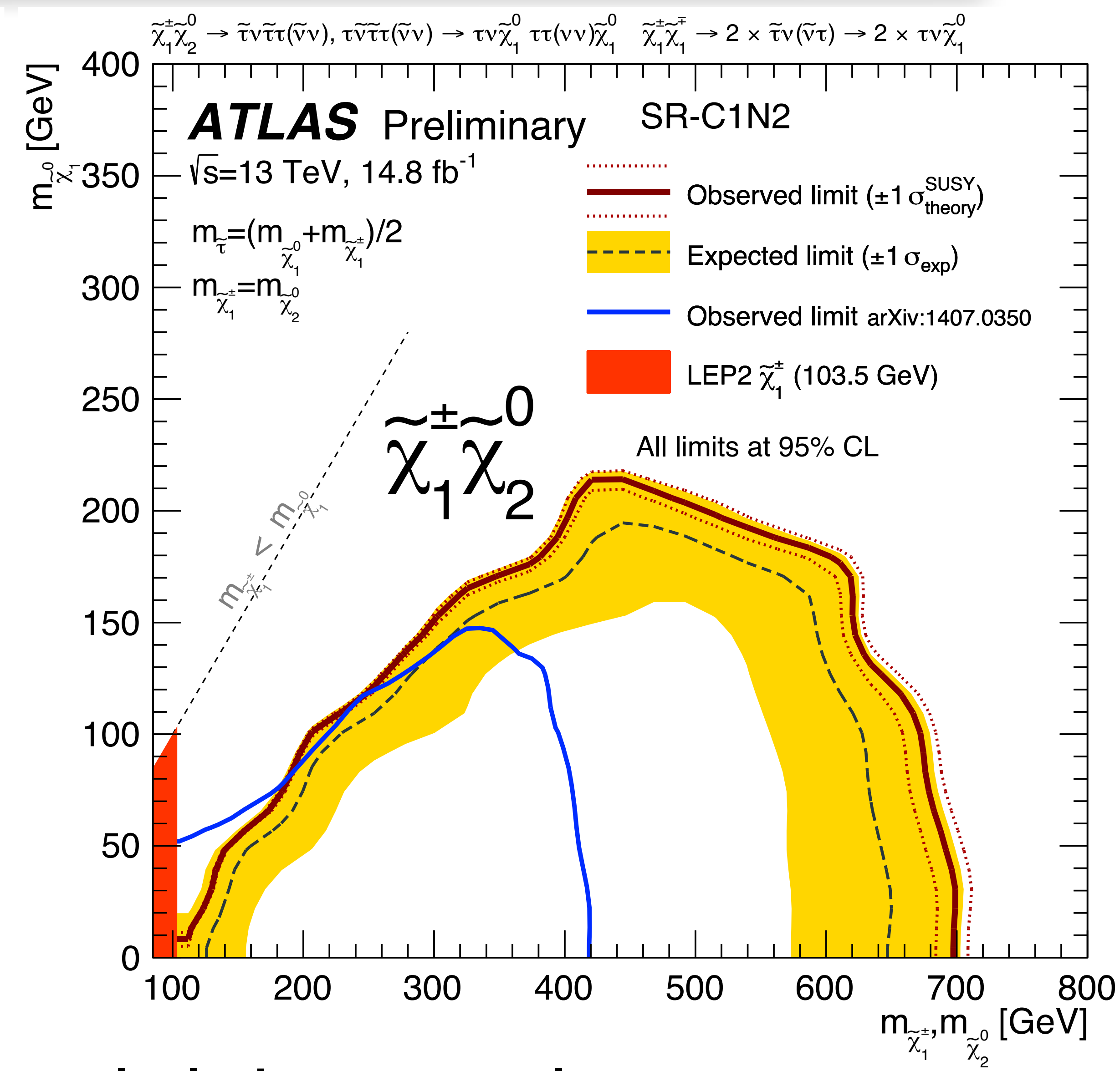


Background estimation

- fake taus from multijets data-driven (ABCD)
- fake taus W+jets with MC normalized in CR
- top and diboson from MC

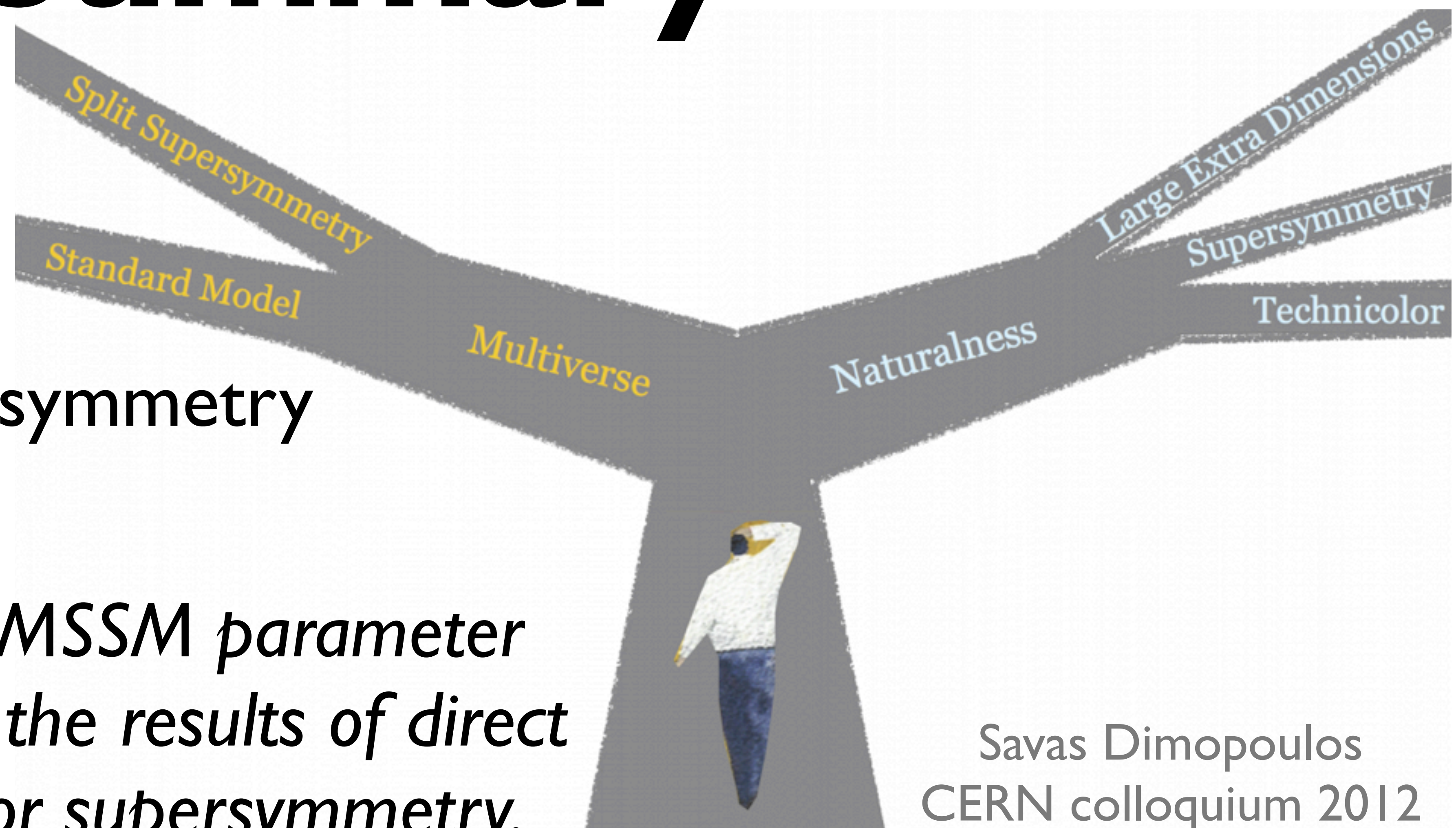
EW SUSY ditau search





- Interpreted in simplified models with only light sparticles are: $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$, $\tilde{\tau}_\mathrm{L}$ and $\tilde{\nu}_\tau$
- Signal models scanned in chargino and neutralino masses, with degenerate stau and tau sneutrino mass placed halfway between $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$.
- Excludes $\tilde{\chi}_1^{\pm}$/$\tilde{\chi}_2^0$ masses < 580/700 GeV for massless $\tilde{\chi}_1^0$ @ 95% CL.

Summary



Savas Dimopoulos
CERN colloquium 2012

- ATLAS has extended many exclusions for new physics.
- Unification and supersymmetry remain hidden.
- "*Robust regions of the MSSM parameter space, compatible with the results of direct and indirect searches for supersymmetry, remain unconstrained.*"
  -- Howie Haber, PDG 2015 SUSY Review, Part I
- The Higgs sector and the third generation will continue to be interesting probes for new physics.
- Tension in EW naturalness can continue to grow, or expose something new.

References

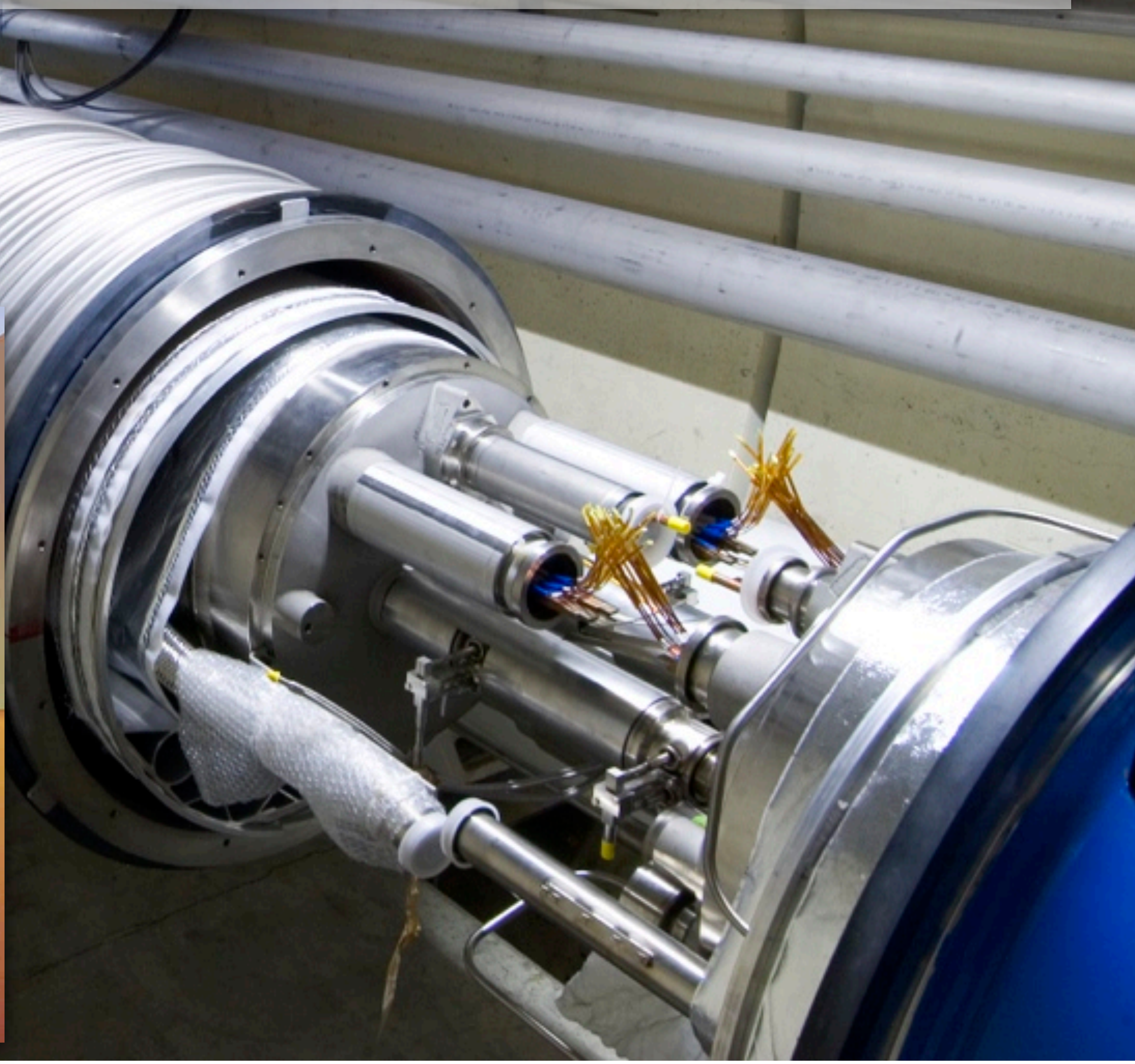
- Search for $A/H \to \tau\tau$, 13.3 fb^{-1}, [ATLAS-CONF-2016-085]
- Search for $H^{\pm} \to \tau^{\pm}\nu$, 13.7 fb^{-1}, [ATLAS-CONF-2016-088]
- Search for top-squark pair production with taus, 13.2 fb^{-1} [ATLAS-CONF-2016-048]
- Search for electroweak production of SUSY with taus, 14.8 fb^{-1}, [ATLAS-CONF-2016-093]

Back-up slides

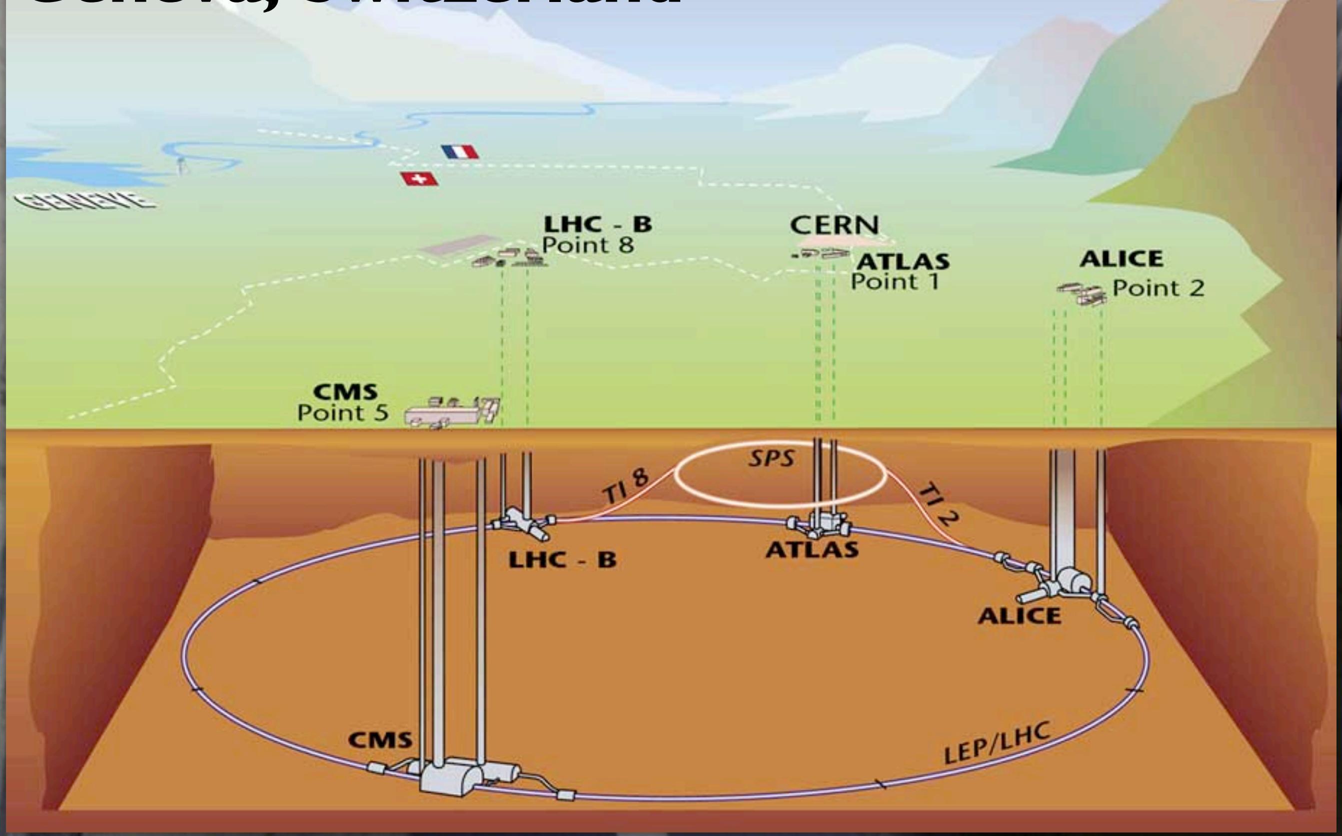
Large Hadron Collider

- p-p collisions at $\sqrt{s}$ = 7-13 TeV
- inst. luminosity = 10^{32}-10^{34} $cm^{-2}s^{-1}$
- 27 km circumference
- 1232 dipoles: 15 m , 8.3 T
- 100 tons liquid He, 1.9 K

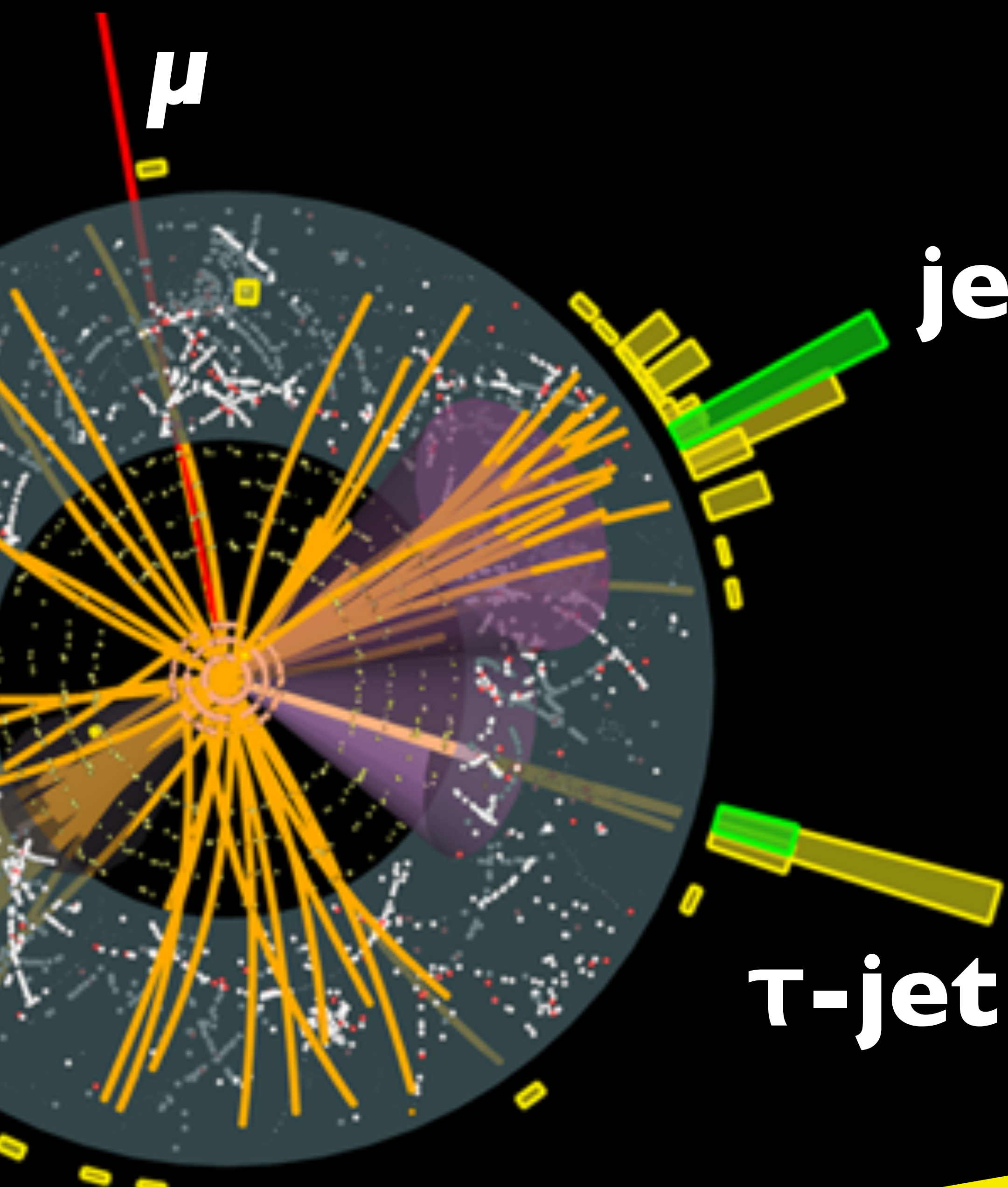
- ~10^{11} protons / bunch
- ~1000 bunches/ beam
- 40 MHz , 25 ns bunch spacing
- 1-40 interactions / crossing
- ~10^{9} interactions / sec



Geneva, Switzerland



What do we reconstruct?



(main objects)

- muons
- electrons & photons
- jets of hadrons
- τ- and *b*-tagged jets
- missing energy

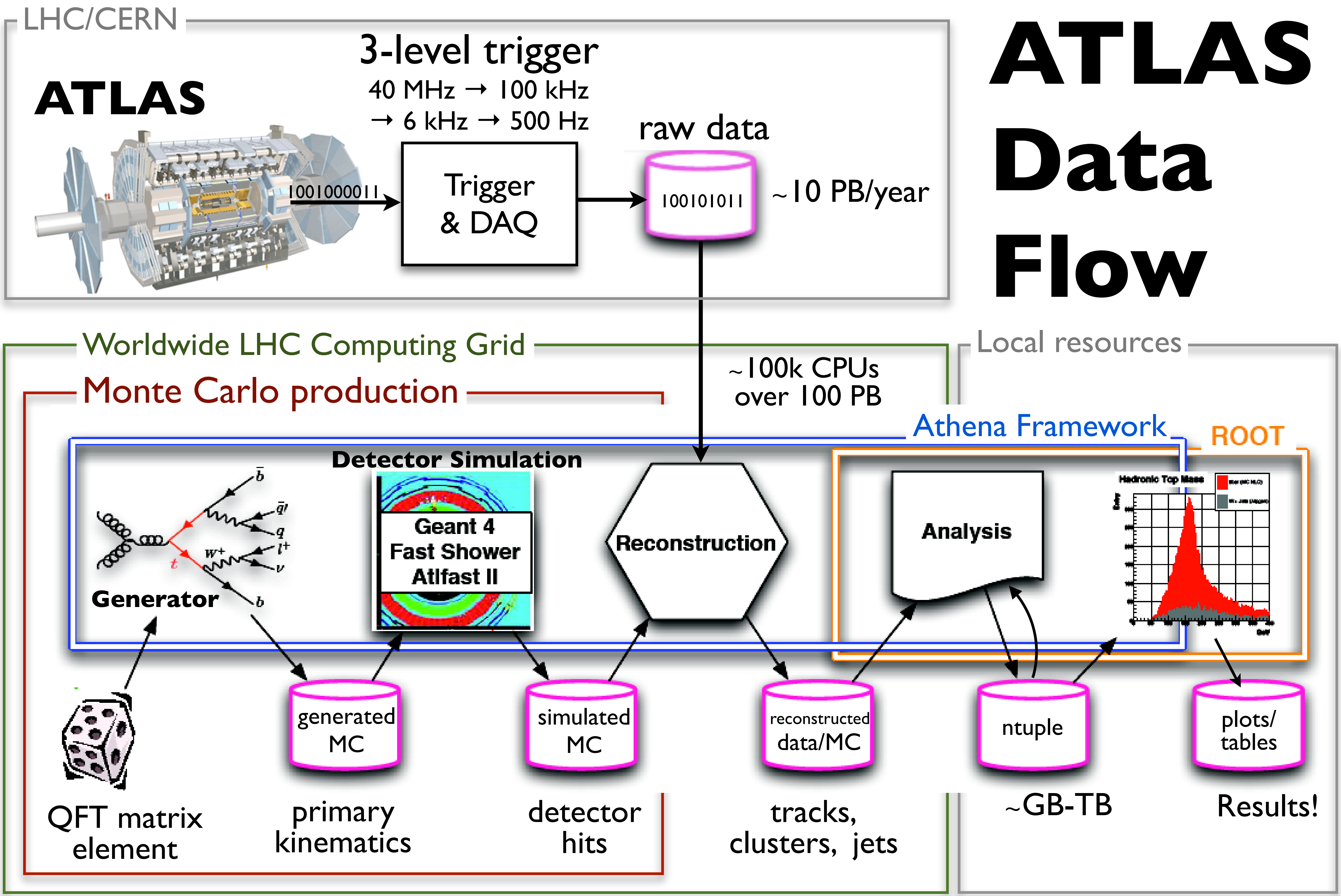
How do we search?

ATLAS Physics Groups

- **SM** — *W*, *Z*, top,...
- **Higgs** — *H*→γγ, *ZZ*, *WW*, ...
- **SUSY** — *l*+jets,γ+jets, ...
- **Exotics** — *Z'*,*W'*, ...

Currently ATLAS has published 579+ papers

ATLAS Data Flow

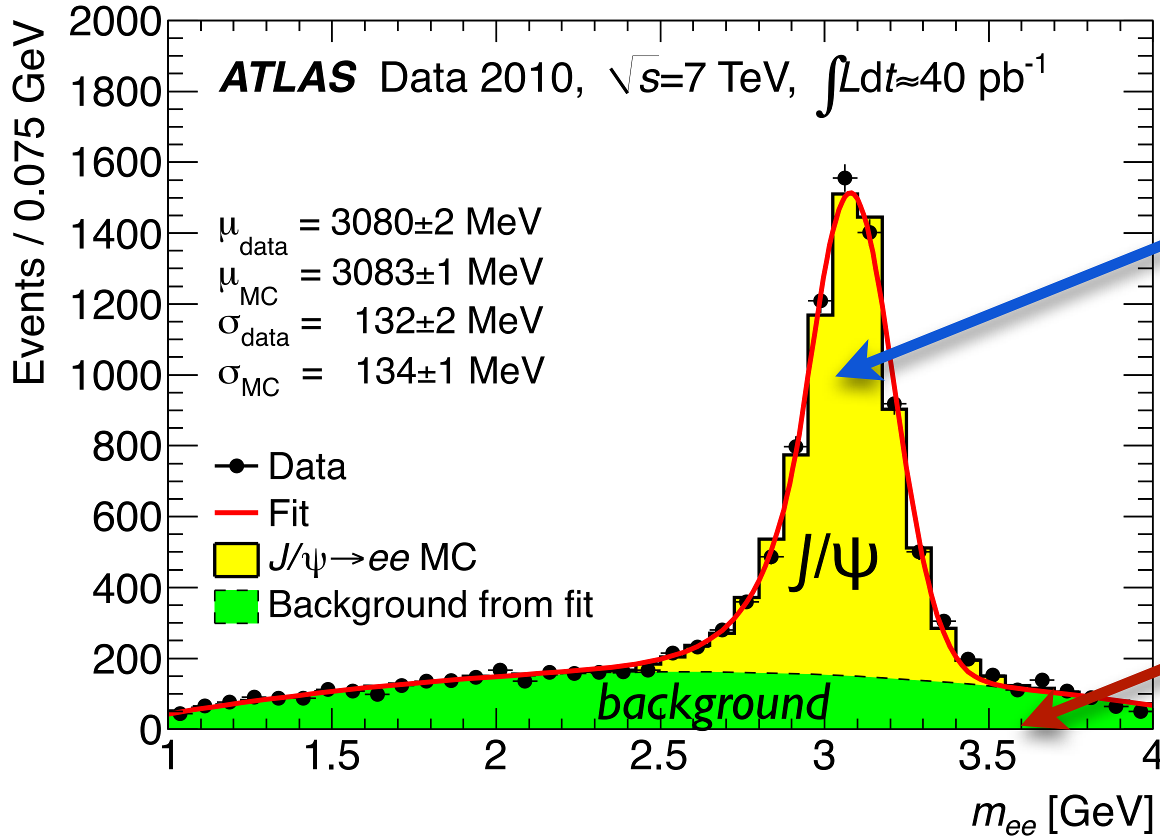


Building a model

$N(expected) = N(correct\text{-}ID) + N(fake)$

- ***Bottom-up***
  - well-identified objects have scale factors from control regions
  - estimated with detailed Monte Carlo simulation

- ***Top-down*, "data-driven"**
  - various magic with data depending on the analysis and your creativity
  - side-band fit
  - fake-factor method



Bottom-up
Monte Carlo

Data-driven
side-band fit

[arxiv:1110.3174]

MSSM benchmarks

– The m_h^{max} scenario: This scenario can be used to derive conservative lower bounds on M_A, $M_{H^\pm}$ and $\tan\beta$ [648].

$$\begin{aligned} M_{SUSY} &= 1000 \text{ GeV}, \mu = 200 \text{ GeV}, M_2 = 200 \text{ GeV}, \\ X_t^{OS} &= 2\, M_{SUSY} \text{ (FD calculation)}, X_t^{\overline{MS}} = \sqrt{6}\, M_{SUSY} \text{ (RG calculation)}, \\ A_b &= A_\tau = A_t, M_{\tilde{g}} = 1500 \text{ GeV}, M_{\tilde{l}_3} = 1000 \text{ GeV}\,. \end{aligned} \quad (361)$$

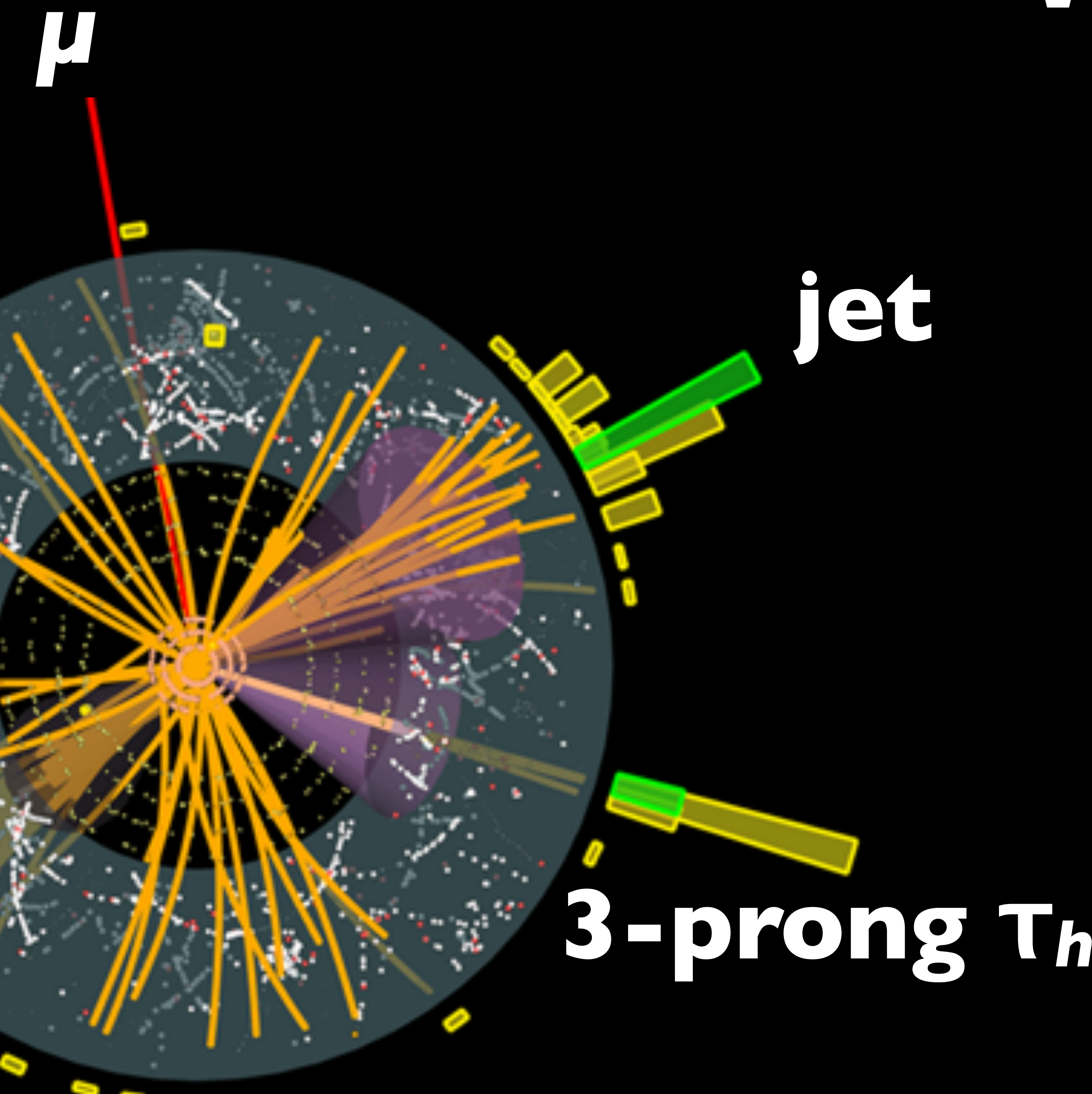
– The m_h^{mod} scenario:
Departing from the parameter configuration that maximizes M_h, one naturally finds scenarios where in the decoupling region the value of M_h is close to the observed mass of the signal over a wide region of the parameter space. A convenient way of modifying the m_h^{max} scenario in this way is to reduce the amount of mixing in the stop sector, i.e. to reduce $|X_t/M_{SUSY}|$ compared to the value of ≈ 2 (FD calculation) that gives rise to the largest positive contribution to M_h from the radiative corrections. This can be done for both signs of X_t.

$$\begin{aligned} m_h^{mod+}: \quad M_{SUSY} &= 1000 \text{ GeV}, \mu = 200 \text{ GeV}, M_2 = 200 \text{ GeV}, \\ X_t^{OS} &= 1.5\, M_{SUSY} \text{ (FD calculation)}, X_t^{\overline{MS}} = 1.6\, M_{SUSY} \text{ (RG calculation)}, \\ A_b &= A_\tau = A_t, M_{\tilde{g}} = 1500 \text{ GeV}, M_{\tilde{l}_3} = 1000 \text{ GeV}\,. \end{aligned} \quad (362)$$

$$\begin{aligned} m_h^{mod-}: \quad M_{SUSY} &= 1000 \text{ GeV}, \mu = 200 \text{ GeV}, M_2 = 200 \text{ GeV}, \\ X_t^{OS} &= -1.9\, M_{SUSY} \text{ (FD calculation)}, X_t^{\overline{MS}} = -2.2\, M_{SUSY} \text{ (RG calculation)}, \\ A_b &= A_\tau = A_t, M_{\tilde{g}} = 1500 \text{ GeV}, M_{\tilde{l}_3} = 1000 \text{ GeV}\,. \end{aligned} \quad (363)$$

[arxiv:1307.1347]

What's a tau?



- Only lepton massive enough to decay hadronically (1.8 GeV).
- 65% hadronic
  50% 1-prong, 15% 3-prong.
- Decay in beam pipe: $c\tau \approx 87$ μm.
- **Signature:** narrow jet with 1 or 3 tracks, possibly additional EM clusters from π^0s.
- **Challenge:** large multijet background at hadron colliders.
- **Importance:** can have preferred couplings to new physics:
  SM $H\to\tau\tau$, $H^+\to\tau^+\nu$, $Z'\to\tau\tau$, high-tanβ SUSY,...