Searches for charged Higgs bosons, supersymmetry, and exotica with tau leptons with the ATLAS and CMS detectors at the LHC

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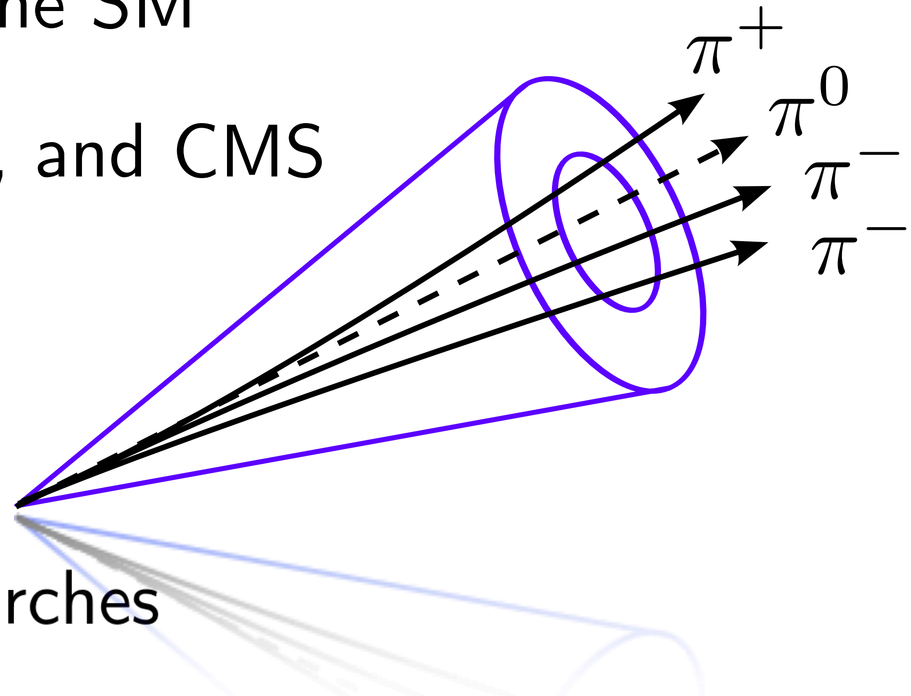
on behalf of the ATLAS and CMS collaborations

Outline

- Motivational questions about the SM
- Large Hadron Collider, ATLAS, and CMS
- Charged Higgs searches
- SUSY searches
- Exotics: Leptoquark and *Z'* searches



... all with taus.

Why the Standard Model?

- Why the **gauge group** $SU(3)_C \times SU(2)_L \times U(1)_Y$?
- Why are there **3 generations** of quarks and leptons?
- Why are lepton and hadron charges quantized in the same units? Why the existing **hypercharges**?

$$Q_{\text{EM}} = T_{3\text{L}} + Y/2$$

Is it because...

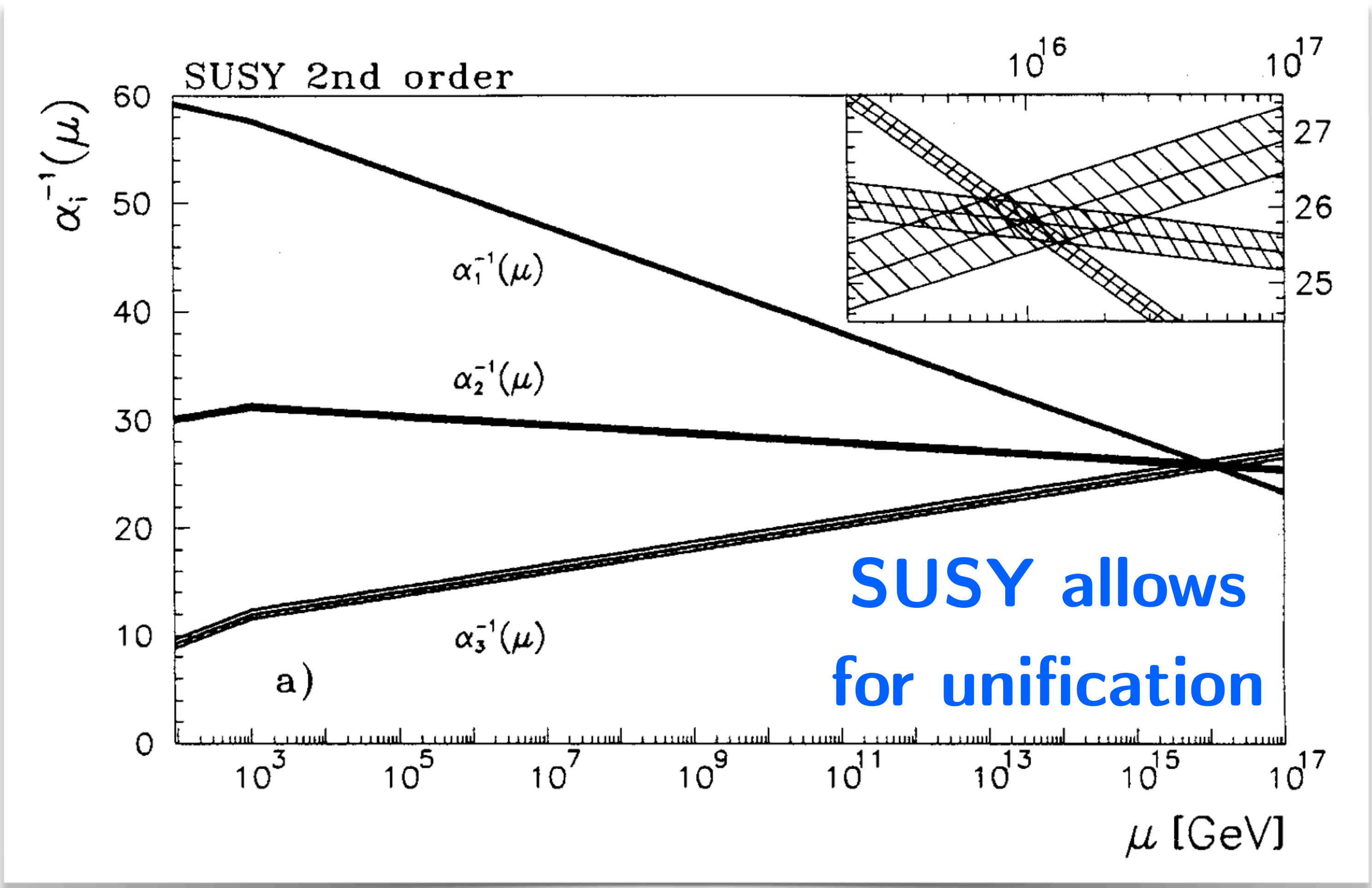
- ***the gauge group of Nature is actually bigger?***

$SO(10) \to SU(5) \times U(1)$	Georgi-Glashow	1974
$SO(10) \to SU(4)_C \times SU(2)_L \times SU(2)_R$	Pati-Salam	

- *e.g.* Pati-Salam SO(10): $Q_{\text{EM}} = T_{3\text{L}} + T_{3\text{R}} + 1/2(B - L)$
- lifetime of the proton $> 10^{33}$ years $\Rightarrow$ if unification happens it must suppress proton decay, *e.g.* it happens at a high energy scale

Gauge coupling unification

1991



Using renormalization group equations one can evolve the electroweak and strong coupling constants, as measured at LEP.

[Amaldi, de Boer, and Furstenau 1991]

GUT Motivations

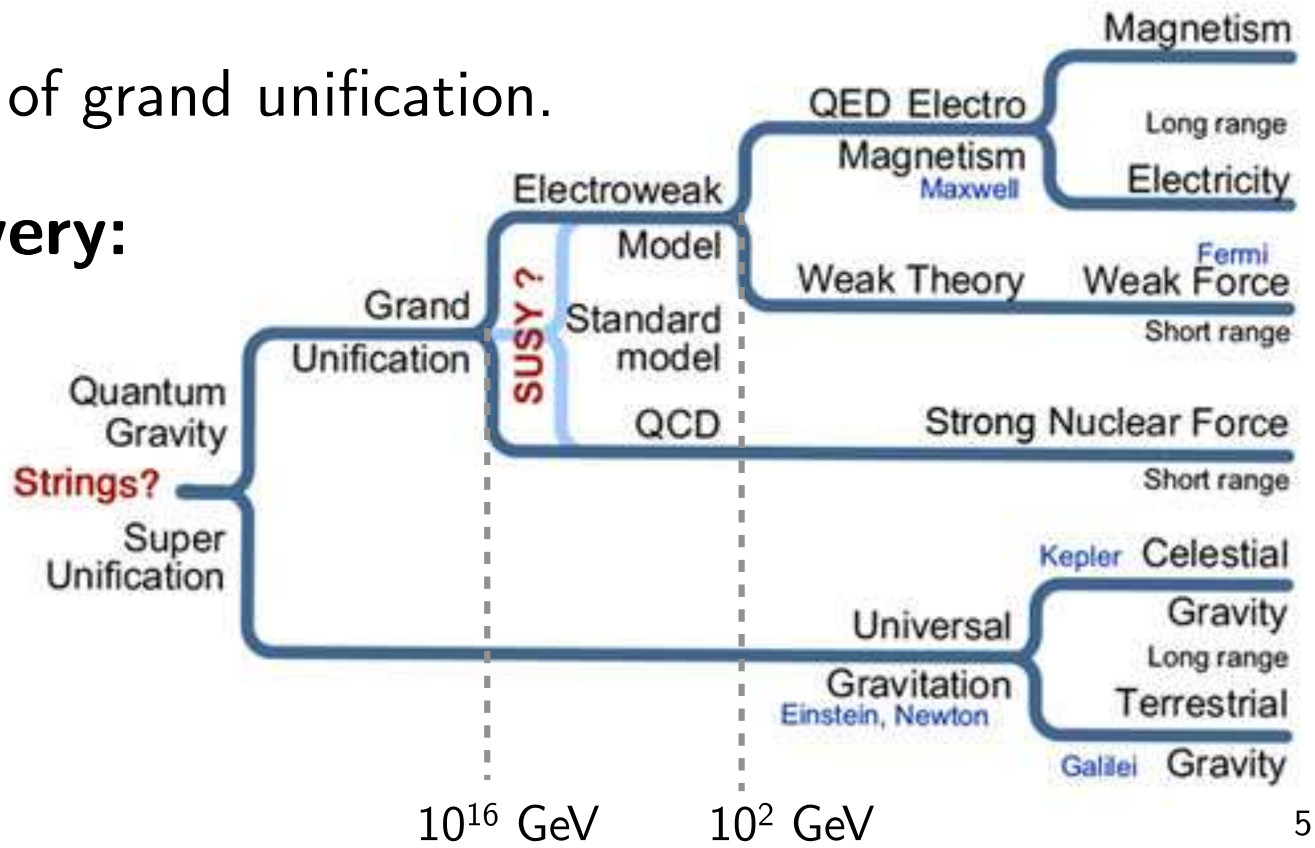
It is interesting that:

- the structure of SM can be embedded in larger groups, and this could explain the SM hypercharges,
- the SM couplings apparently converge when run to very high energies.

Motivates the possibility of grand unification.

Avenues of discovery:

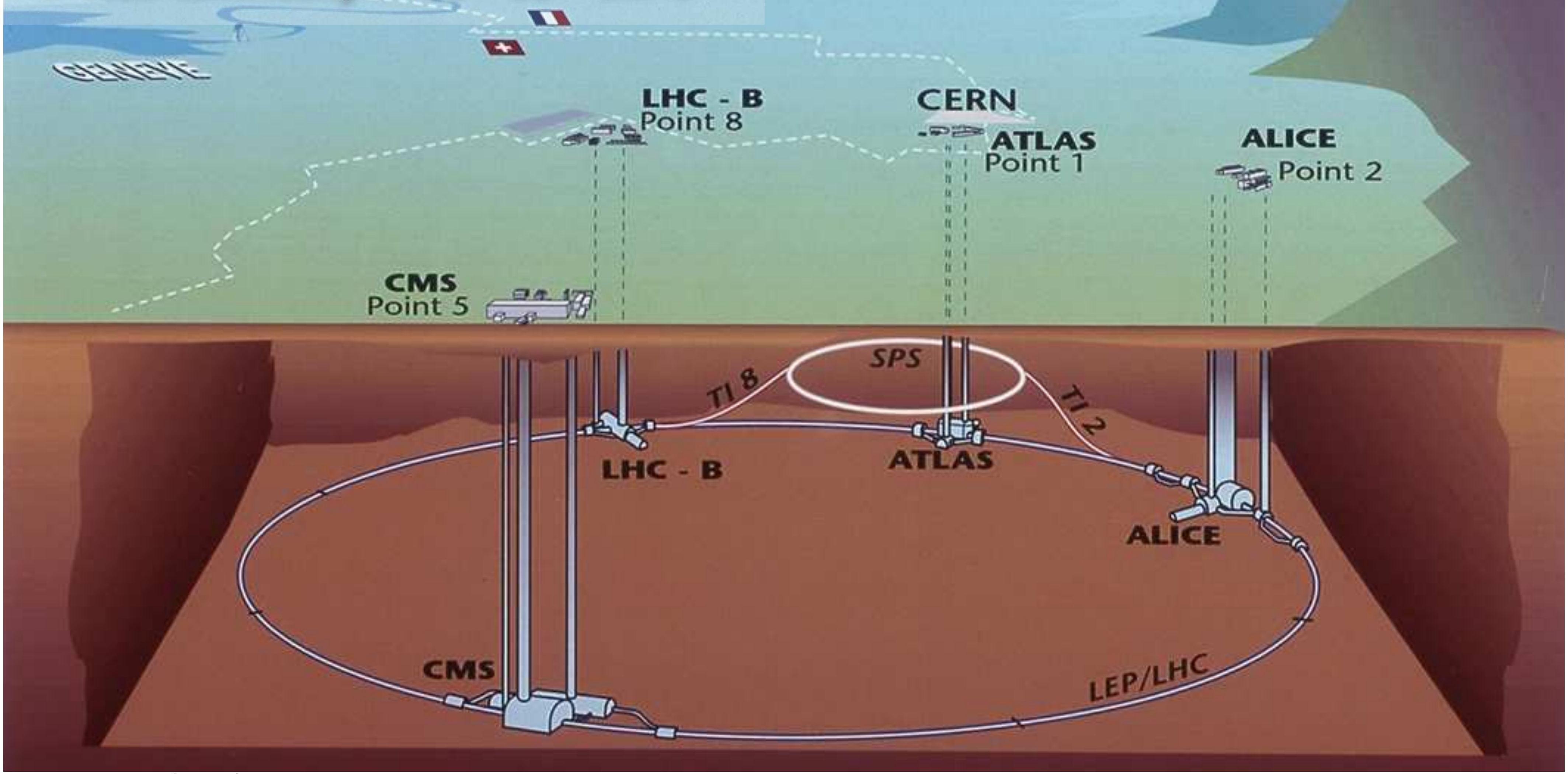
- **Higgs sector**
- **supersymmetry**
- **leptoquarks**
- ***Z'***



The LHC,
ATLAS, and CMS

Overall view of the LHC experiments.

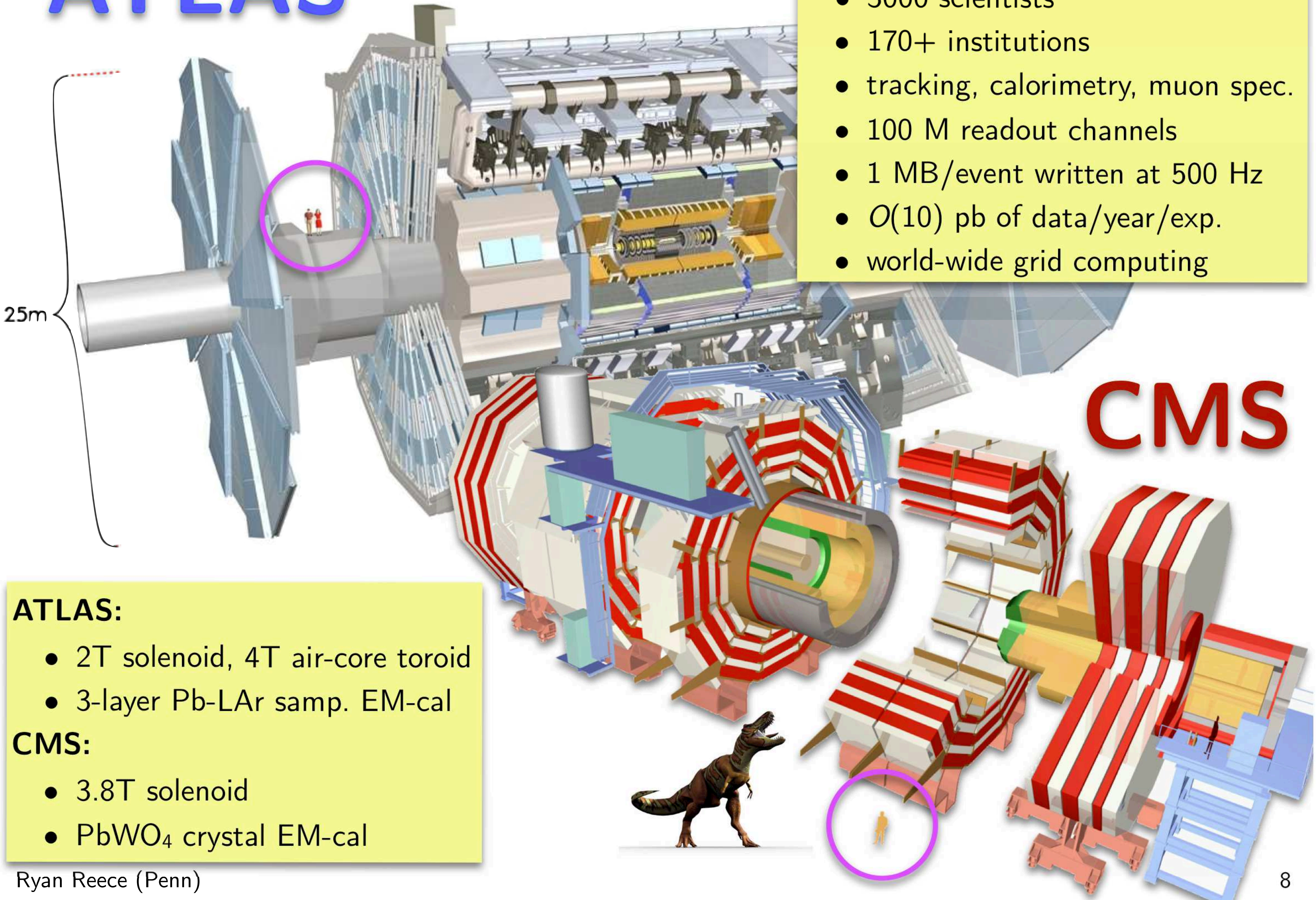
- 27 km circumference
- 1232 dipoles: 15 m , 8.3 T
- 96 tonnes liquid He, 1.9 K
- p-p collisions at $\sqrt{s}$ = 7-8 TeV
- inst. luminosity = 10^{32}-10^{34} cm^{-2}s^{-1}
- 10^{11} protons / bunch × 1000 bunches
- 20 MHz , 50 ns bunch spacing
- 1-30 interactions / crossing
- 0.5 × 10^{9} interactions / sec



ATLAS

Each experiment has:

- 3000 scientists
- 170+ institutions
- tracking, calorimetry, muon spec.
- 100 M readout channels
- 1 MB/event written at 500 Hz
- $\mathcal{O}(10)$ pb of data/year/exp.
- world-wide grid computing



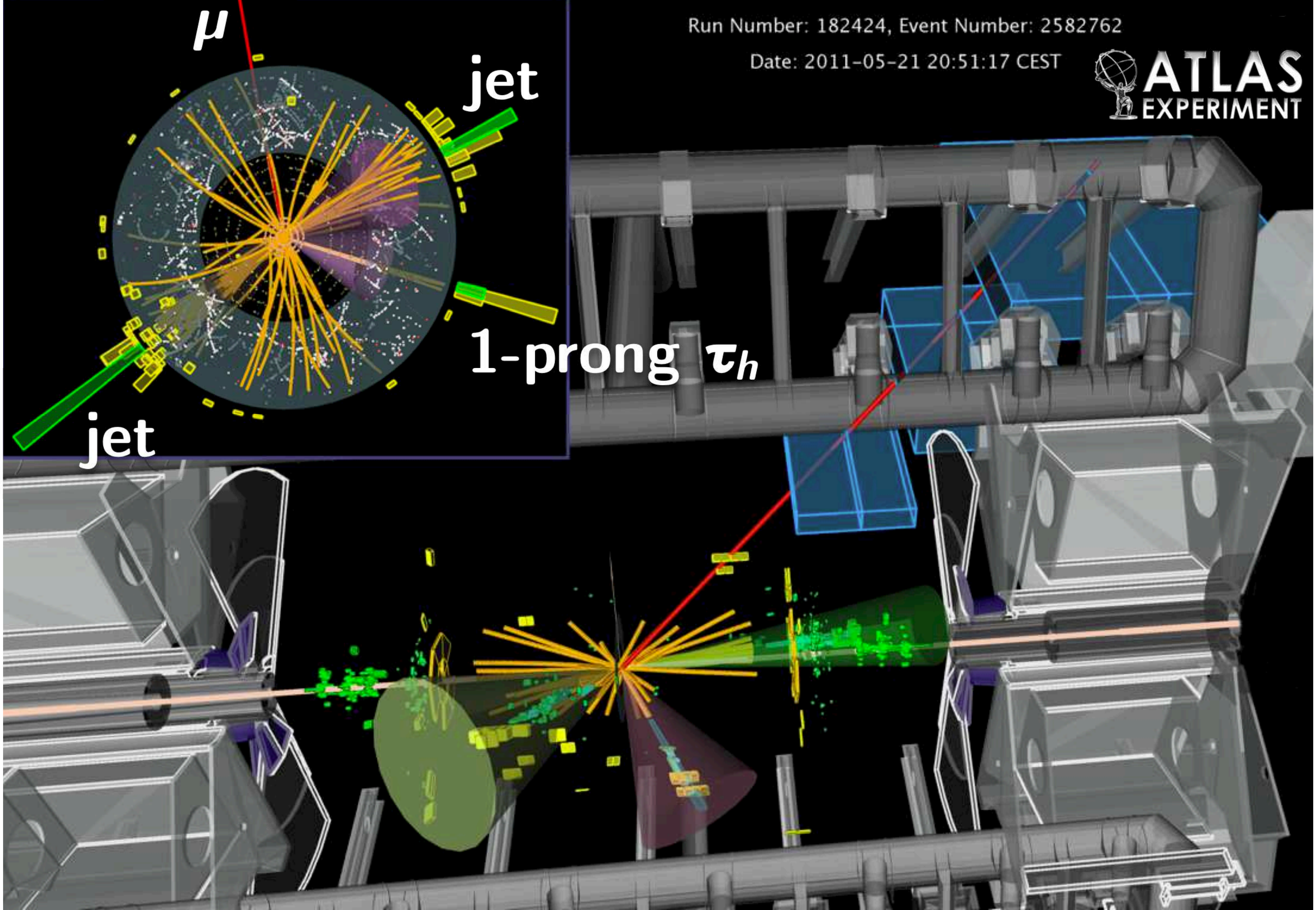
CMS

ATLAS:

- 2T solenoid, 4T air-core toroid
- 3-layer Pb-LAr samp. EM-cal

CMS:

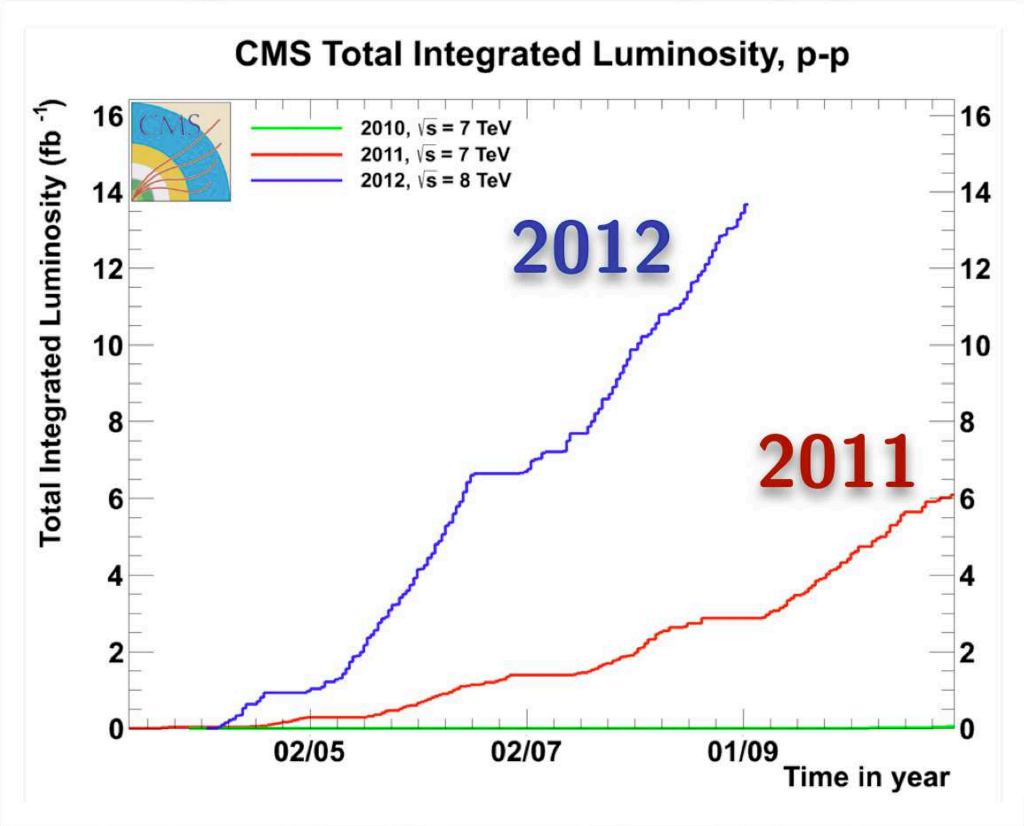
- 3.8T solenoid
- $PbWO_4$ crystal EM-cal



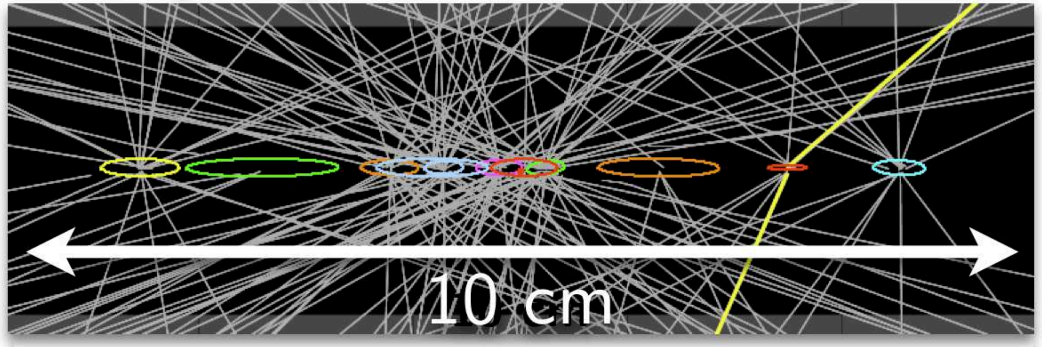
$t\bar{t} \to b\bar{b}(\mu\nu)(\tau_{\mathrm{h}}\nu)$ candidate

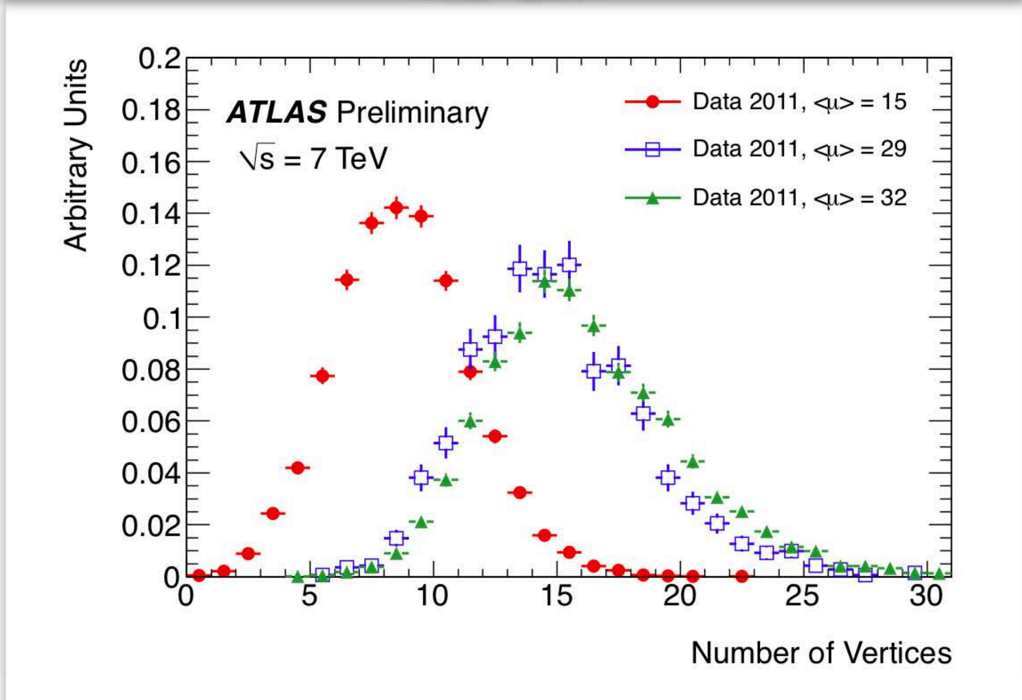
Datasets

Integrated luminosity by year



1-30 pile-up interactions / crossing

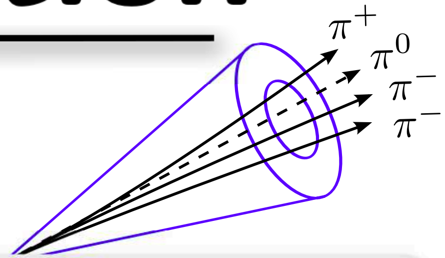




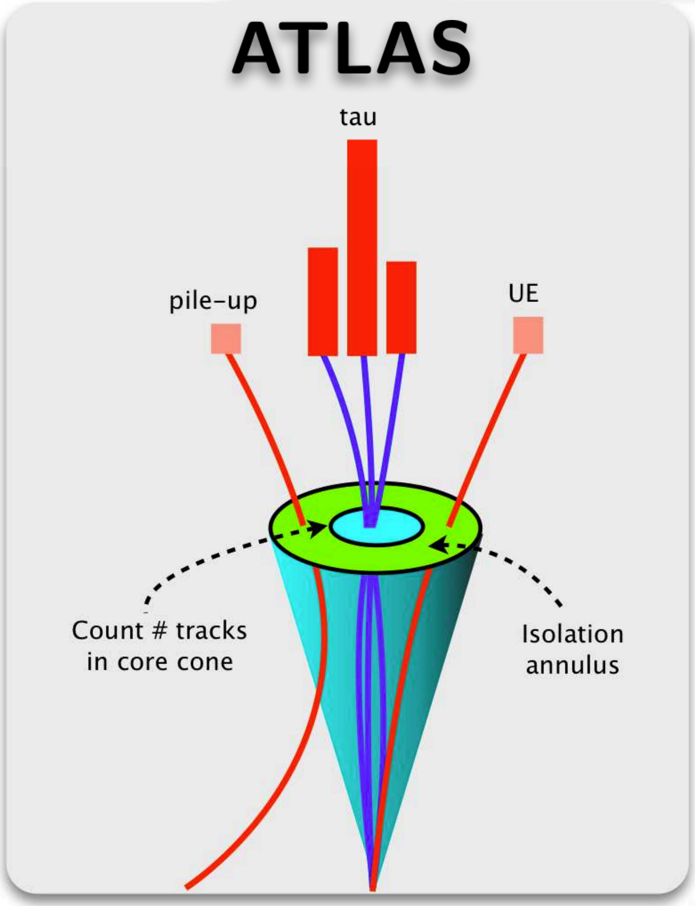
- Analyses reported here use **2-5 fb^{-1}** of the data collected in **2011** at $\sqrt{s} = 7$ **TeV**.
- In 2012, ATLAS and CMS each have collected over 14 fb^{-1} so far at $\sqrt{s} = 8$ TeV.

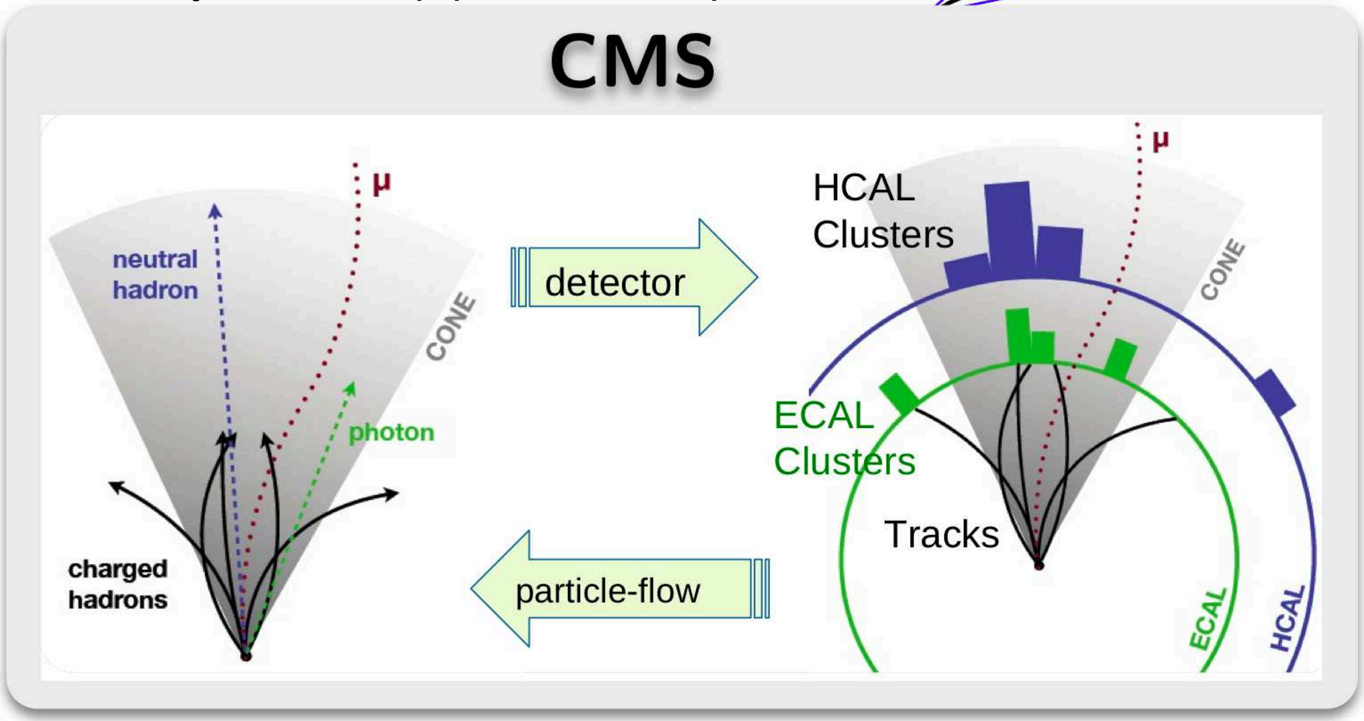
 [TWiki:CMSPublic/LumiPublicResults, ATLAS-CONF-2012-042]

High-p_T τ_h reconstruction



- Hadronic decays dominantly to 1 or 3 $\pi^\pm$ and possibly a few additional π^0s
- Decay in beam-pipe: $c\tau \approx 90$ μm



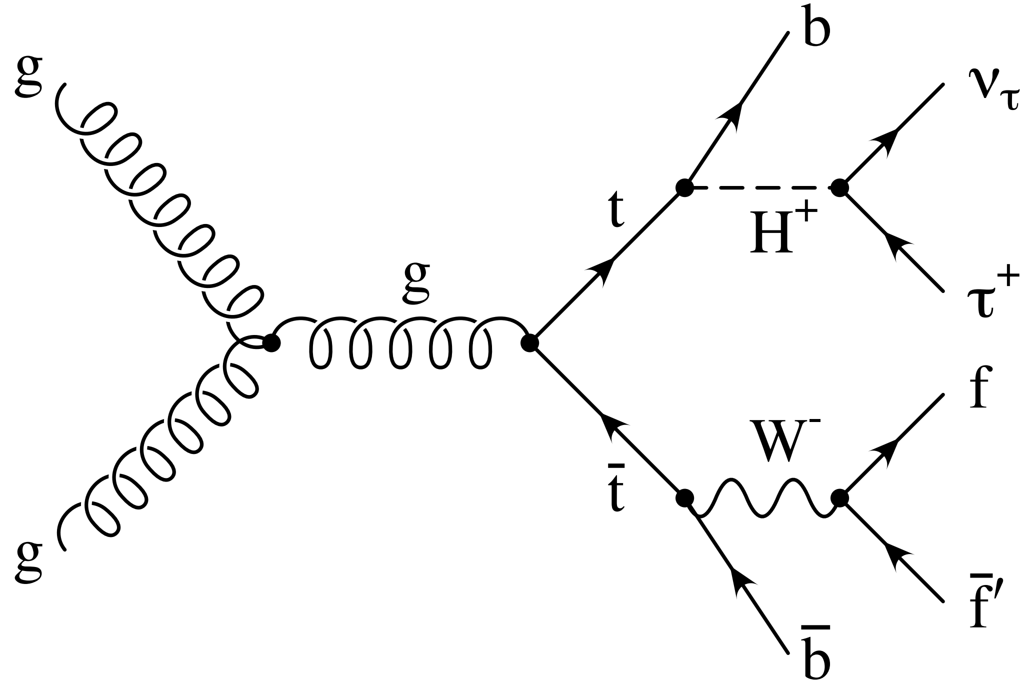


- τ_h reco seeded by calorimeter jets
- associate tracks in $\Delta R < 0.2$, select 1 or 3
- combine calorimeter and tracking information in a BDT or likelihood discriminant, preferring narrow clustering, hadronic activity

- particle-flow reconstructs constituent 4-vectors
- τ_h reco seeded by particle-flow hadrons
- Hadron Plus Strip (HPS) algorithm for counting π^0s
- isolation cone for rejecting QCD jets

[ATLAS-CONF-2011-152, CMS PAS TAU-11-001]

Charged Higgs

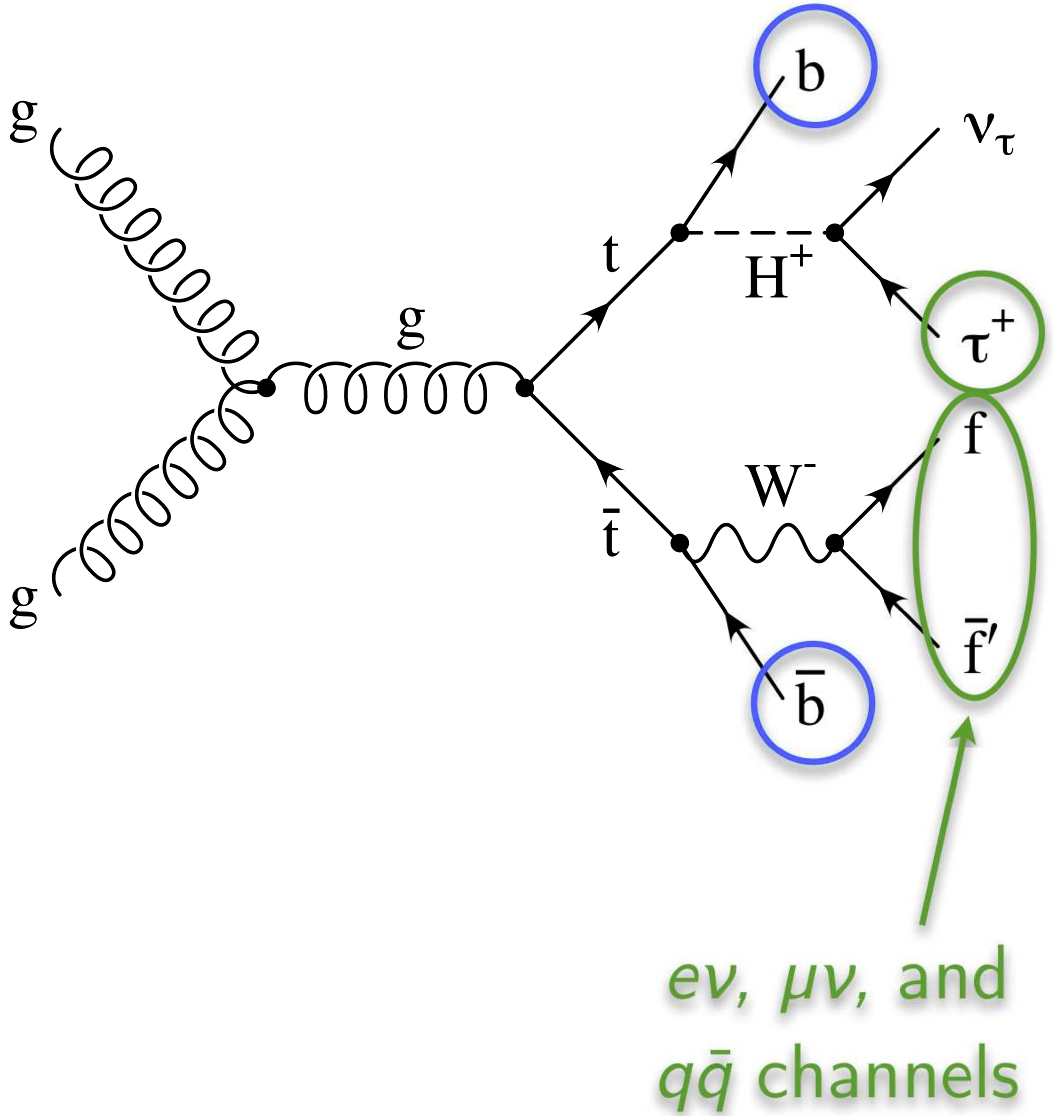


Charged Higgs

- 2HDM, five spin-0 states:

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

- Necessary for MSSM
- $\tan\beta = v_u/v_d$
- For $\tan\beta > 2$, $H^{+} \rightarrow \tau\nu$ dominant decay
- Produced through top decays: $t \rightarrow bH^{+}$ (for $m_{H^{+}} < m_t$)
- Look for $t\bar{t}$ with enhanced τ.



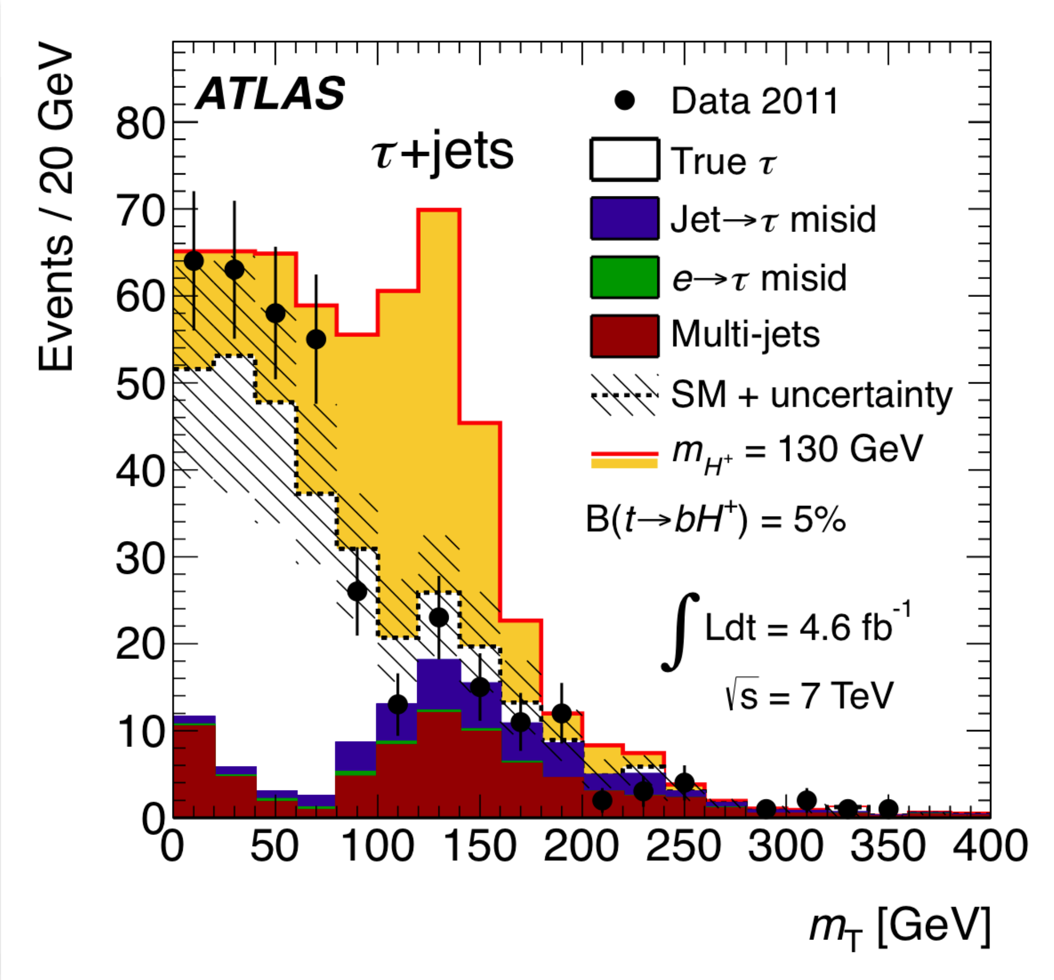
Charged Higgs: $bbqq\tau_h$

ATLAS

$$t\bar{t} \rightarrow b\bar{b}W^{\mp}H^{\pm} \rightarrow b\bar{b}(q\bar{q})(\tau_h\nu)$$

Event selection

- trigger: $p_T(\tau_h) > 29$ GeV + $E_T^{miss} > 35$ GeV
- N(jets) ≥ 4, p_T(jet) > 20 GeV, at least one jet b-tagged
- exactly one τ_h, $p_T(\tau_h) > 40$ GeV
- no other τ_h or leptons
- m(jjb) ∈ [120, 240] GeV - consistent top
- $E_T^{miss} > 65$ GeV
- $$\frac{E_T^{miss}}{0.5\ \mathrm{GeV}^{1/2} \cdot \sqrt{\sum p_T}} > 13$$

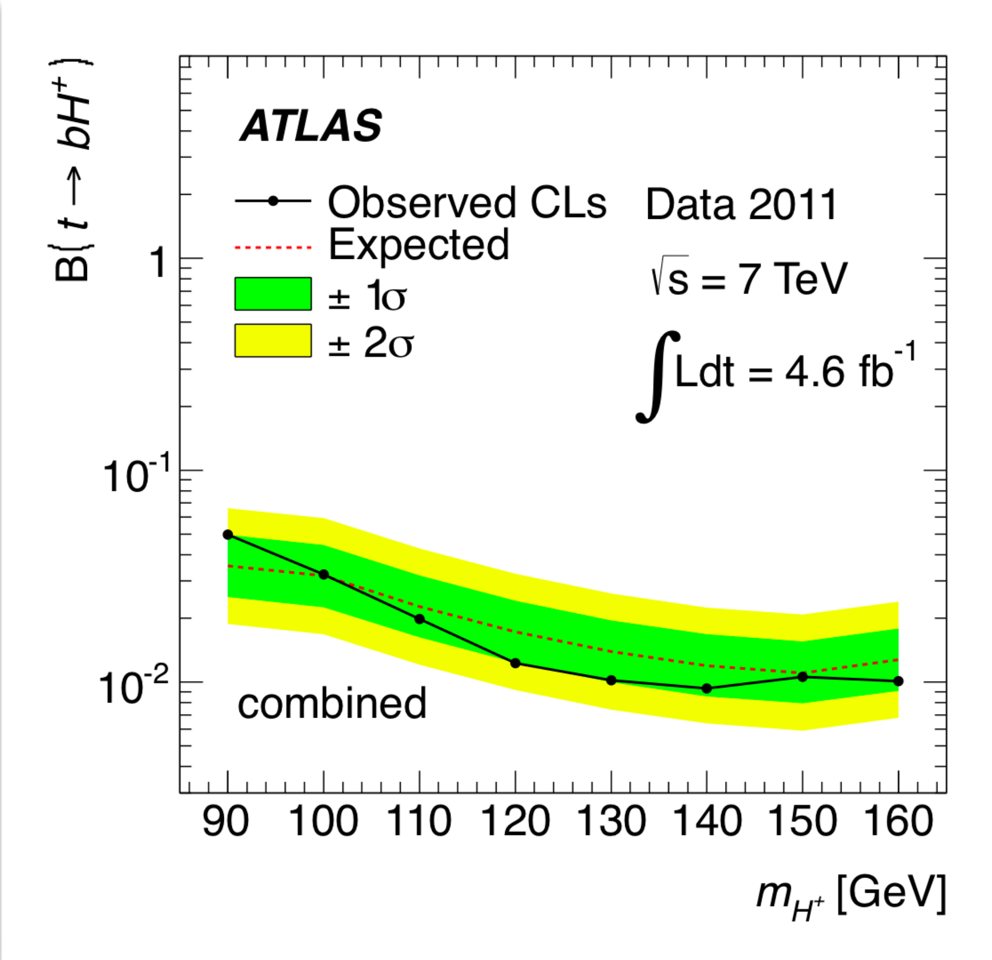


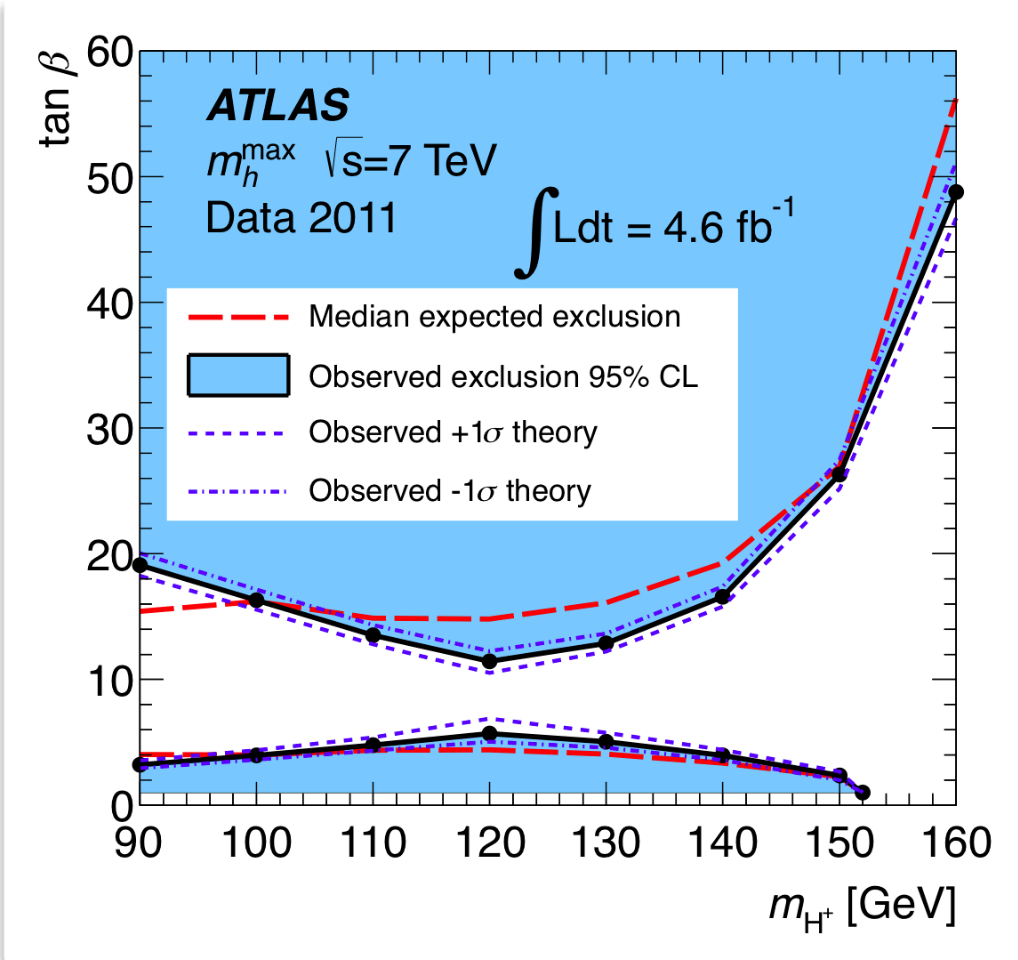
- Suppress multijet fake E_T^{miss} with significance cut.
- Multijet background fit in E_T^{miss} with template from failing tau ID.

[arxiv:1204.2760]

Charged Higgs

ATLAS

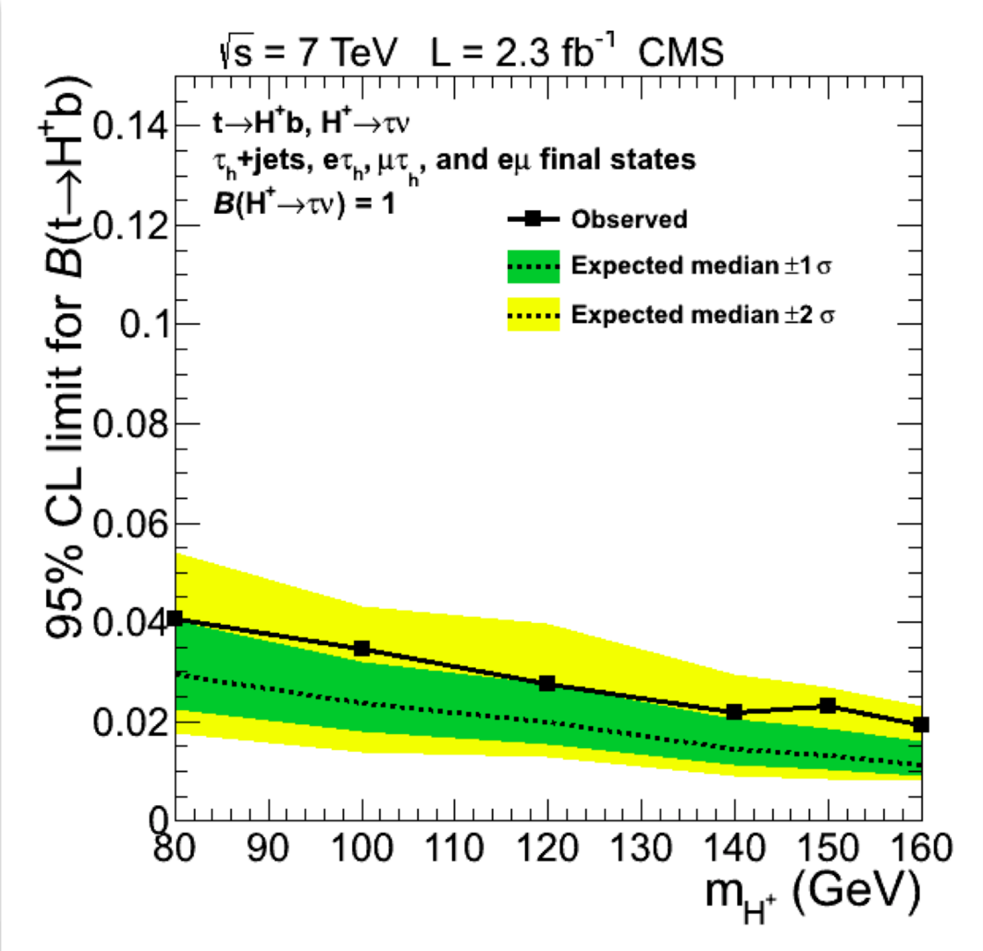


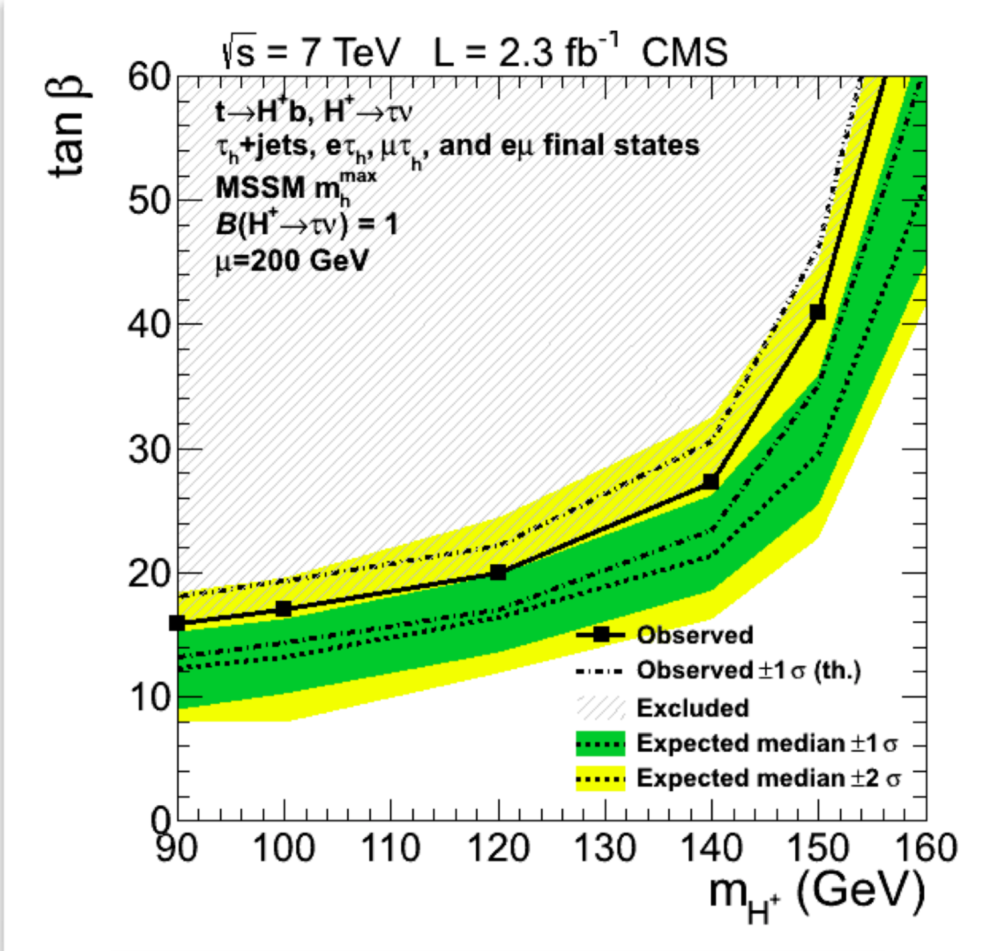


- Combine searches in $bb(qq)(\tau_h\nu)$, $bb(l\nu)(\tau_h\nu)$, $bb(qq)(l\nu)$ channels.
- $B(t\rightarrow bH^{+}) < 1\text{-}5\%$
- Especially exclude high tan $\beta \gtrsim 10\text{-}20$

Charged Higgs

CMS

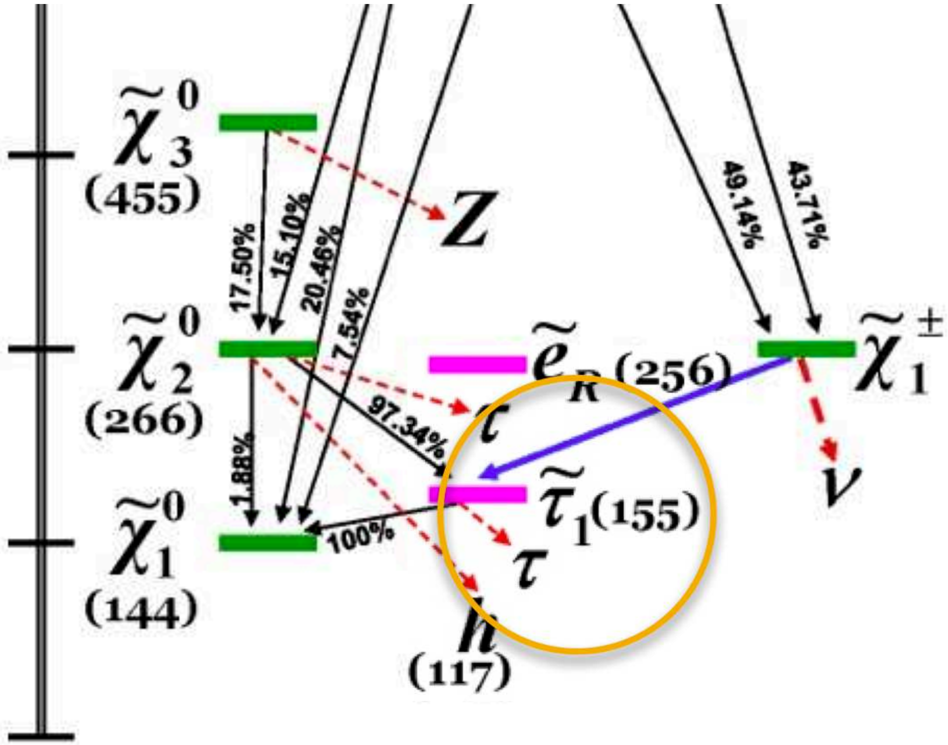




- Combine searches in $bb(qq)(\tau_h\nu)$, $bb(l\nu)(\tau_h\nu)$, $bb(l\nu)(\tau_l\nu)$ channels.
- $B(t\to bH^+) < 2$-4%
- Similar result to ATLAS

[arvix:1205.5736]

SUSY



$\widetilde{\chi}_3^0$
(455)
Z
17.50%
15.10%
20.46%
7.54%
49.14%
43.71%
$\widetilde{\chi}_2^0$
(266)
$\widetilde{e}_R$ (256)
$\widetilde{\chi}_1^\pm$
97.34%
τ
1.88%
$\widetilde{\tau}_1$ (155)
ν
$\widetilde{\chi}_1^0$
(144)
100%
τ
h
(117)

Supersymmetry

- The ***only*** possible consistent extension to the symmetries of 4-D QFT from **Poincaré** $\otimes$ **internal symmetry groups**.
  [Haag–Lopuszanski–Sohnius theorem, 1975]
- No observed SUSY partners yet $\Rightarrow$ SUSY is broken at a high energy scale.

fermions $\longleftrightarrow$ bosons

FERMIONS			BOSONS		
spin	Name	Symbols	Name	Symbols	spin
½	leptons	e, ν_{eL}	sleptons	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_{eL}$	0
		$\mu, \nu_{\mu L}$		$\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_{\mu L}$	
		$\tau, \nu_{\tau L}$		$\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_{\tau L}$	
½	quarks	u, d	squarks	$\tilde{u}_L, \tilde{d}_L, \tilde{u}_R, \tilde{d}_R$	0
		c, s		$\tilde{c}_L, \tilde{s}_L, \tilde{c}_R, \tilde{s}_R$	
		t, b		$\tilde{t}_L, \tilde{b}_L, \tilde{t}_R, \tilde{b}_R$	
½	gluinos	$\tilde{g}$	gluons	g	1
½	charginos	$\tilde{\chi}^{\pm}_1, \tilde{\chi}^{\pm}_2$	EW bosons	$\gamma, Z^0, W^{\pm}$	1
½	neutralinos	$\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4$	higgs	$h^0, H^0, A^0, H^{\pm}$	0

SM particles (observed)	SM particles (not yet observed)	Super Partners (not yet observed)

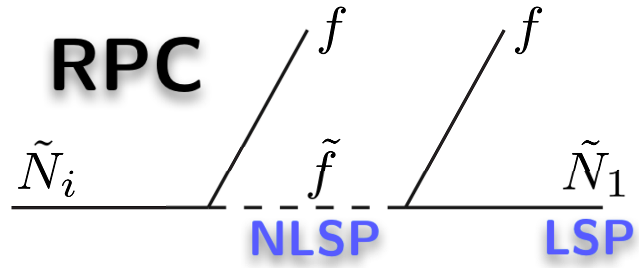
- Could help explain: *observed* ***dark matter***, ***hierarchy problem***, ***fits well with GUTs***, …
- Especially interesting large parameter space when the **lightest** $\tilde{\tau}$ is the *Next-to-Lightest-Supersymmetric-Particle* (**NLSP**)

$$\Rightarrow \tau + E_T^{\text{miss}}$$

SUSY signatures

- **R-parity-conserving:** require **high-E_T^{miss}** and **high-H_T**

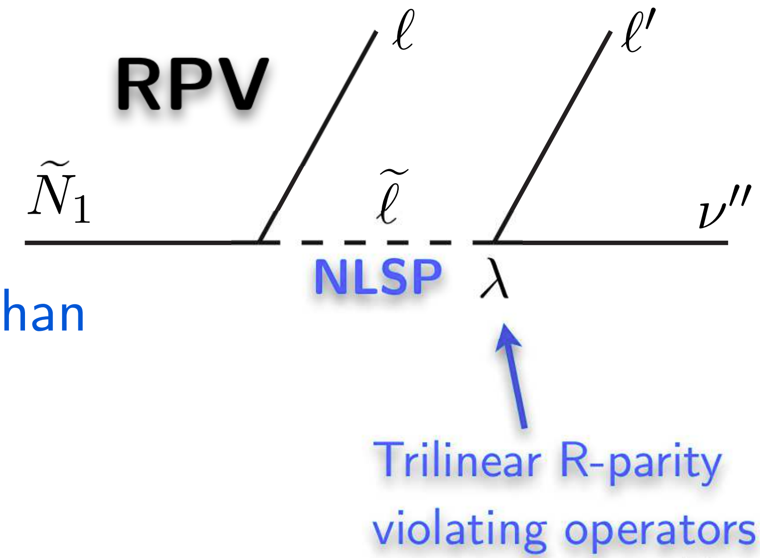
  $H_T = \sum p_T(\text{jets})$



- **R-parity-violating:** require **high-S_T**

  no stable LSP $\Rightarrow$ less E_T^{miss} discrim.

  $S_T = H_T + \sum p_T(\text{isolated leptons}) + E_T^{miss}$



$$\lambda_{ijk} L_i L_j \bar{E}_k$$

- ***Why add taus?***
  - $B(\tilde{N}_2 \to \tau\tau\tilde{N}_1)$ or $B(\tilde{C}_1 \to \tau\nu\tilde{N}_1)$ can be higher than other flavors when $\tan\beta$ is high.
  - Improve stats even without enhancement
  - Constrain all couplings λ_{ijk}
- CMS incorporates taus into their general multi-lepton search.
- ATLAS and CMS perform dedicated searches with taus.

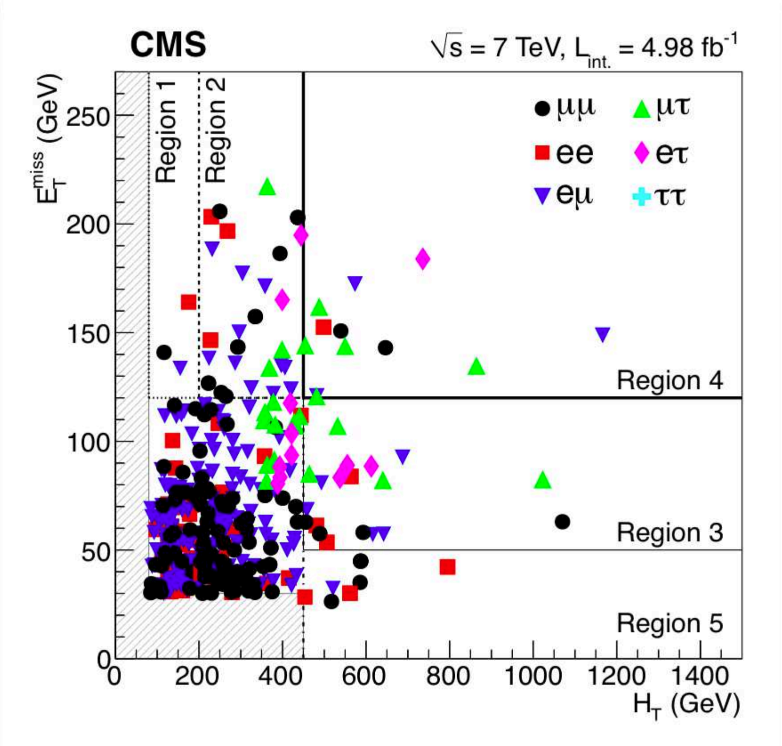
SUSY: Same-sign dileptons + jets + E_T^{miss}

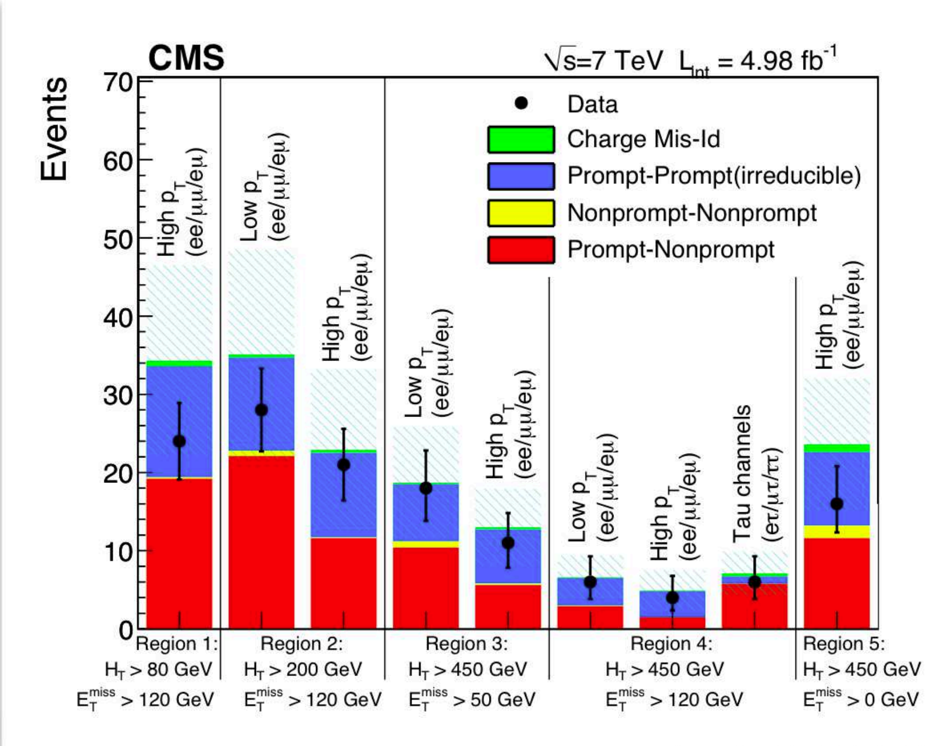
CMS

Event selection

- H_T trigger
- SS ee, $e\mu$, $\mu\mu$, $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$
- signal kin. depend strongly on mass spectrum ⇒ 5 signal regions depending on E_T^{miss} and H_T.

- target R-parity-conserving SUSY
- 5% background from charge mis-ID estimated with Z→ee/ττ tag-and-probe
- τ_h fake factor method for predicting W+jets
- irreducibles from MC: ttW, ttZ, SS WW/ZZ
- combined to set exclusion in the CMSSM

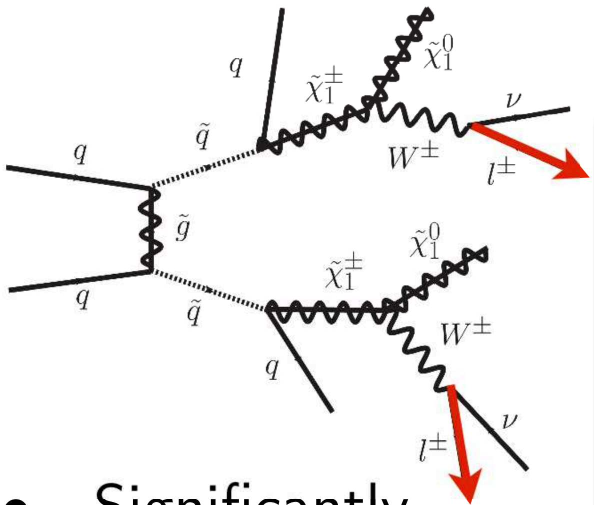




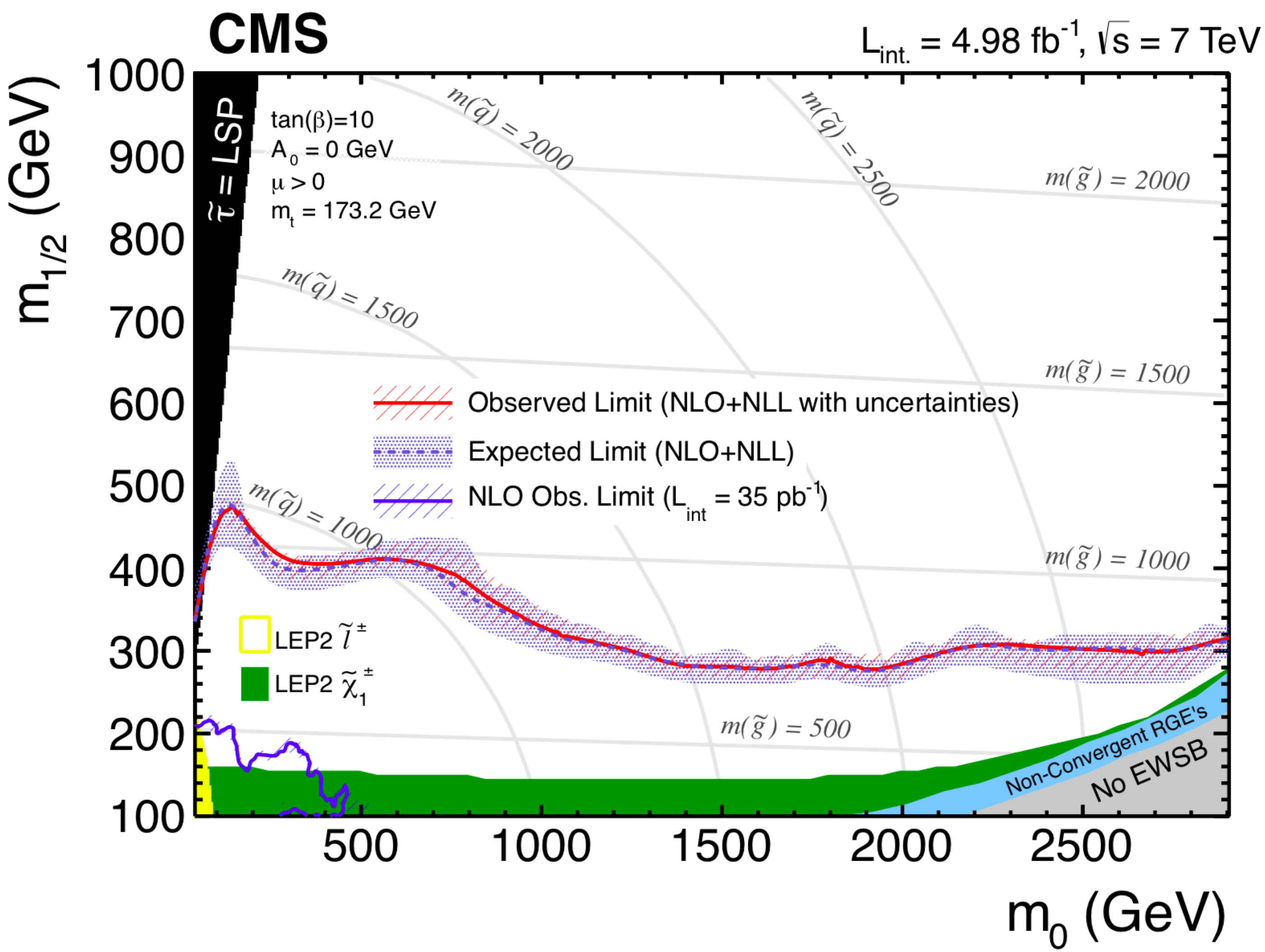
[arxiv:1206.3949]

SUSY: Same-sign dileptons + jets + E_T^{miss}

CMS



CMSSM exclusion



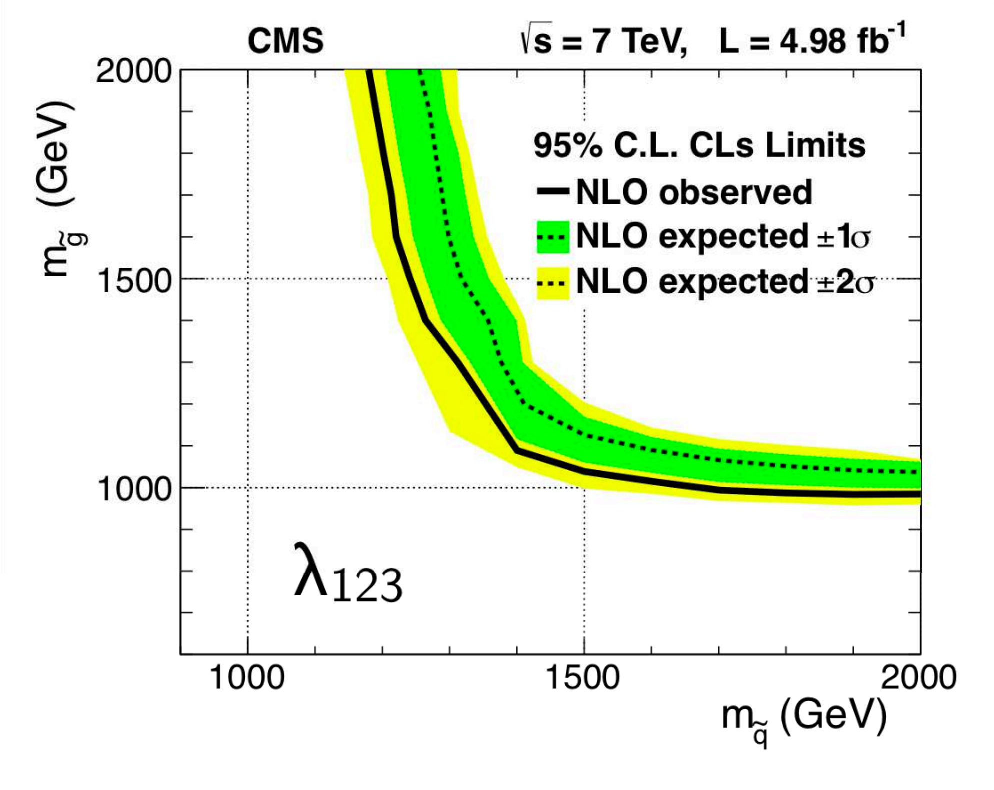
- Significantly extends LEP and CMS 2010 results.
- Gluino masses 500-1000 GeV excluded.
- Similar result in opposite-sign (in back up).

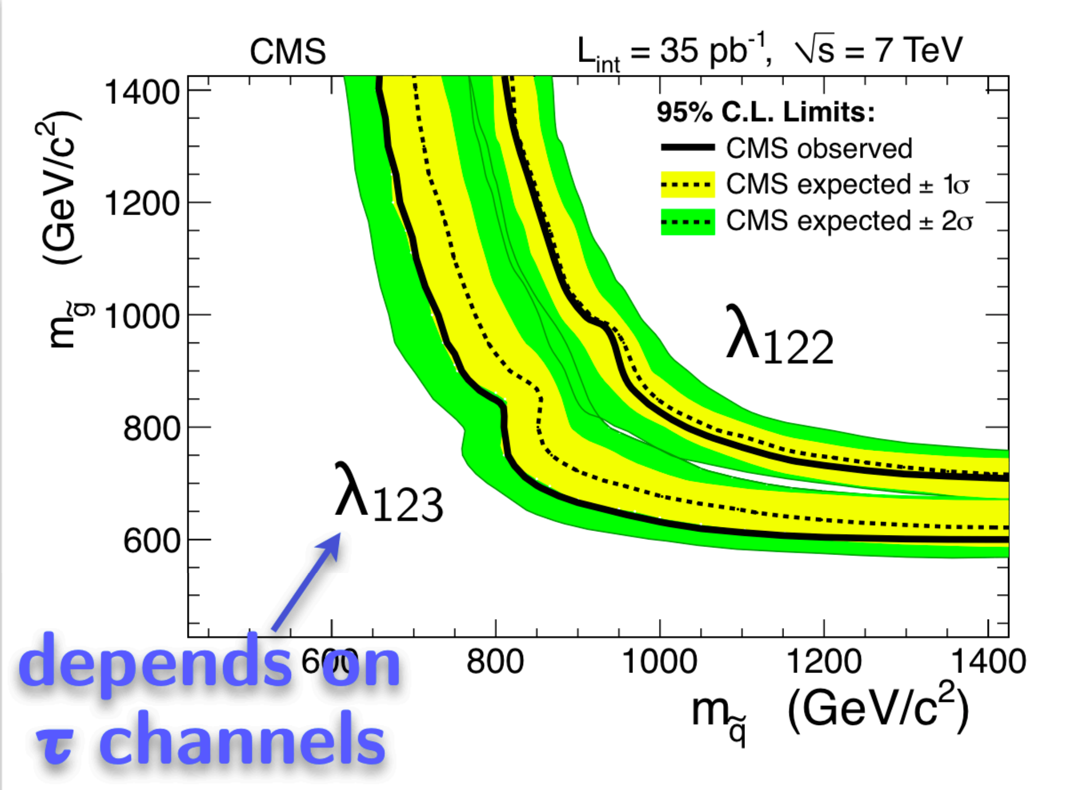
[arxiv:1206.3949]

SUSY: multi-lepton

CMS

- Categorize all events with 3-4 leptons, binning in N(lep), N(τ_h), E_T^{miss} , H_T, Z/no-Z, no-OSSF, S_T $\Rightarrow$ 114 signal regions





- Harder to exclude couplings to 3rd gen. because of tau ID.
- Exclude squark and gluino masses in 1 TeV range in models with neutralino LSP decaying through RPV.

[arxiv:1106.0933, CMS PAS SUS-11-013, arvix:1204.5341]

SUSY: E_T^{miss} + jets + taus

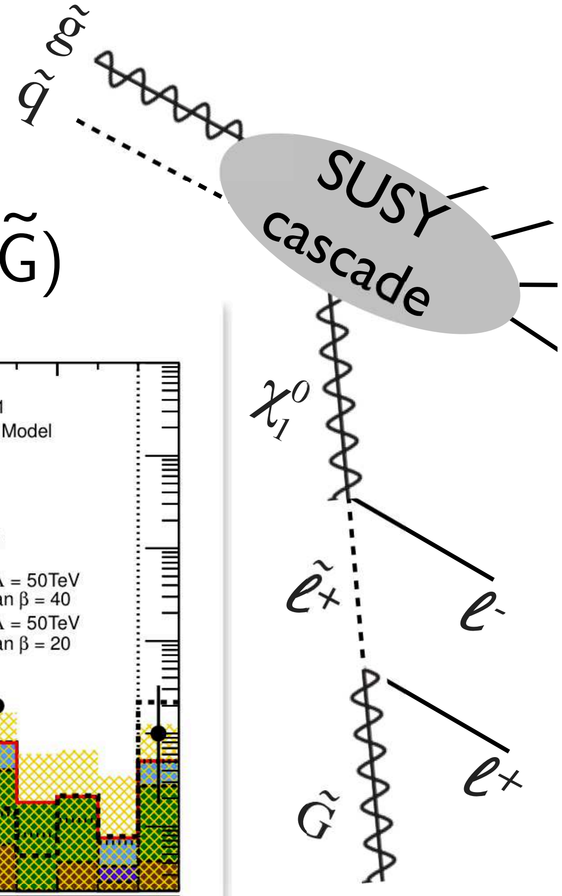
ATLAS

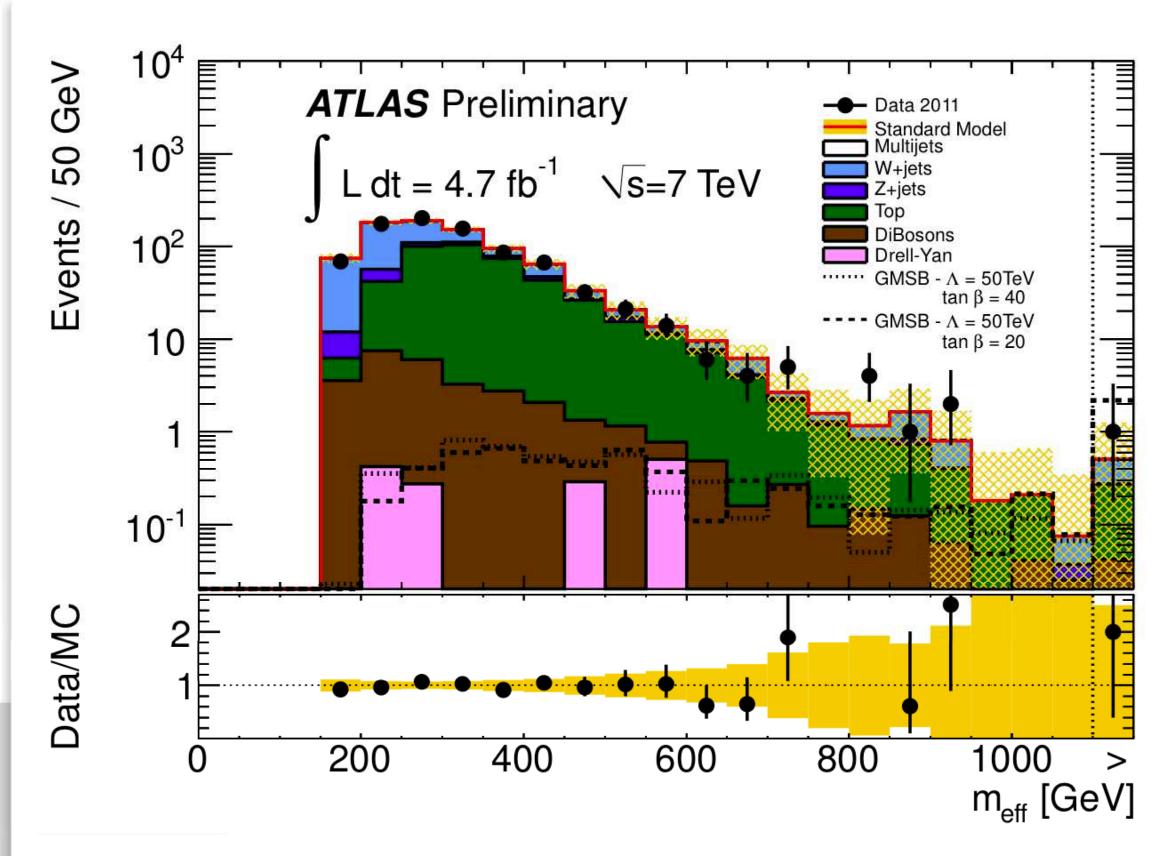
Event selection

$\tau+\mu$
trig: muon/muon+jet
$p_T^{\mu} > 18$ GeV
$p_T^{jet} > 10$ GeV
≥ 1 jet (50 GeV)
—
1 μ (20 GeV)
≥ 1 med. (20 GeV)
$m_T^{e,\mu} > 100$ GeV
$m_{eff} > 1000$ GeV

Gauge-Mediated Supersymmetry Breaking (GMSB) motivated

LSP: very light (~keV) gravitino ($\tilde{G}$)





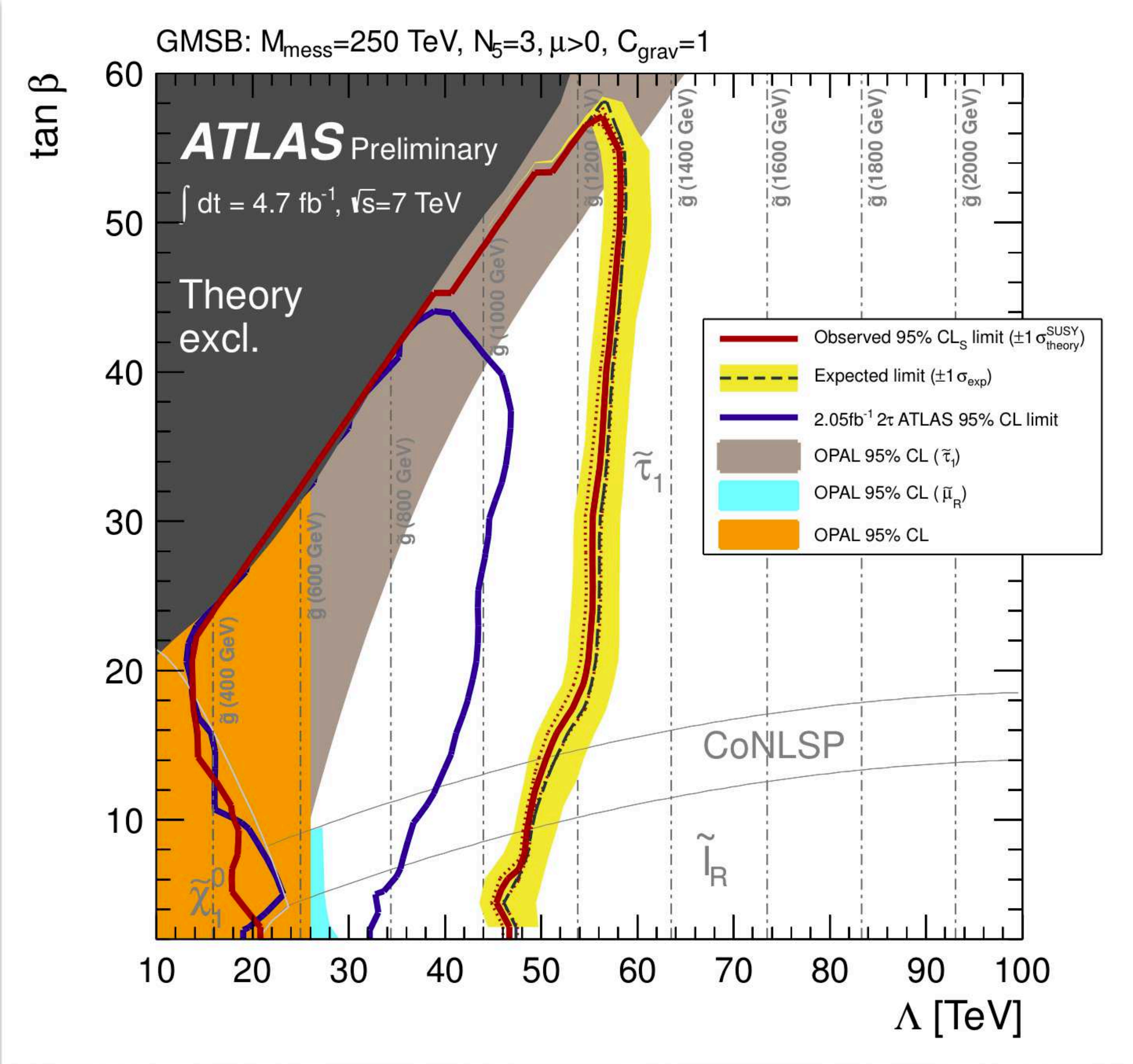
$$m_{eff} = S_T$$
$$= H_T + \sum p_T(\ell,\tau) + E_T^{miss}$$

[arvix:1203.6580, arvix:1204.3852]

SUSY: E_T^{miss} + jets + taus

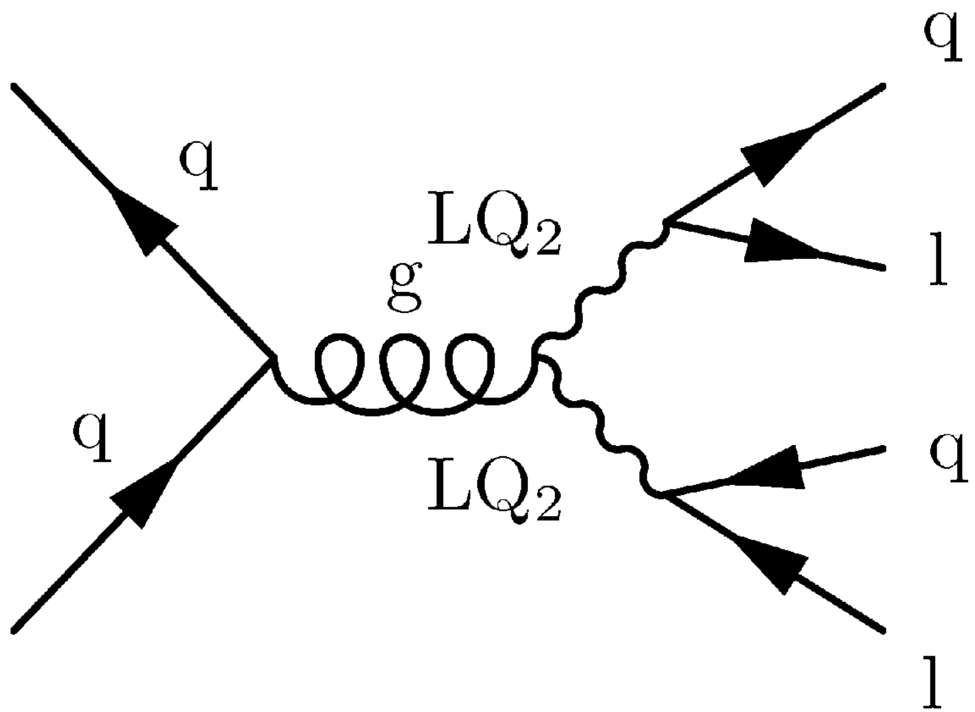
ATLAS

- Combine channels:
  $1\tau_h$+ℓ+jets,
  $1\tau_h$+jets, $\geq 2\tau_h$+jets
- Interpret with GMSB
- Λ = "SUSY breaking scale"
- OPAL:
  $\Lambda > 26$ TeV
- ATLAS:
  $\Lambda >$ 47-58 TeV



[arvix:1203.6580, arvix:1204.3852]

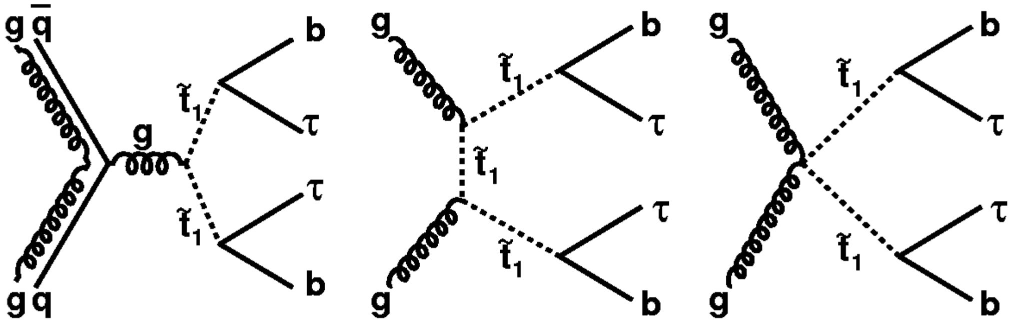
Exotica



3rd generation leptoquarks

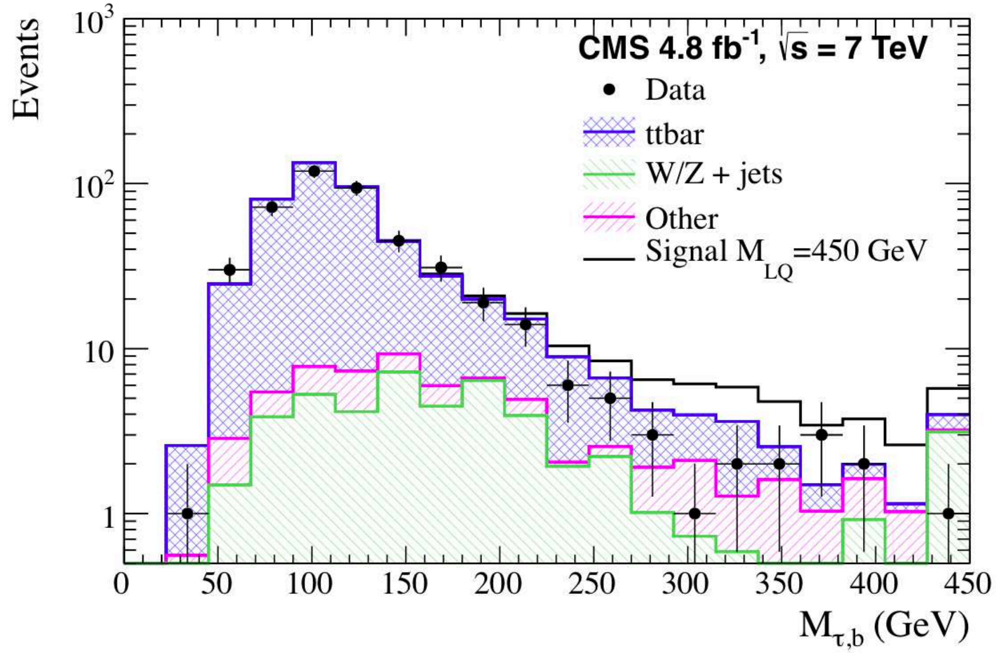
CMS

- Leptoquarks - new bosons predicted in GUTs
- Carry color, lepton, and baryon quantum numbers
- Decay to a quark and a lepton



Event selection

- trigger: $\tau_h + l$
- $p_T(e \text{ or } \mu) > 30$ GeV
- OS $p_T(\tau_h) > 50$ GeV
- $N(\text{b-jets}) \geq 2$, $p_T > 30$ GeV
- $M(\tau_h, b) > 170$ or 190 GeV
- $S_T = p_T(\tau_h) + p_T(l) + p_T(b_1) + p_T(b_2)$

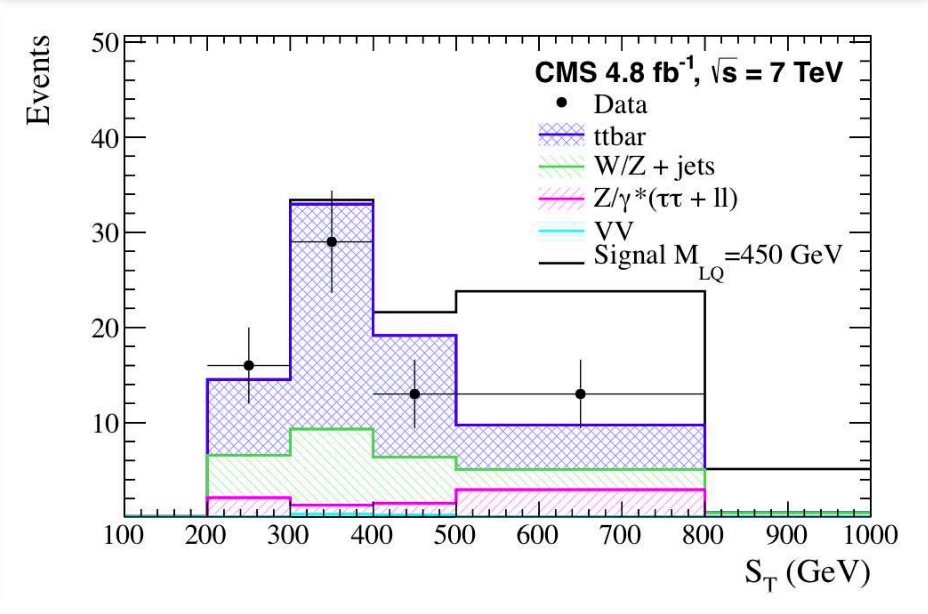


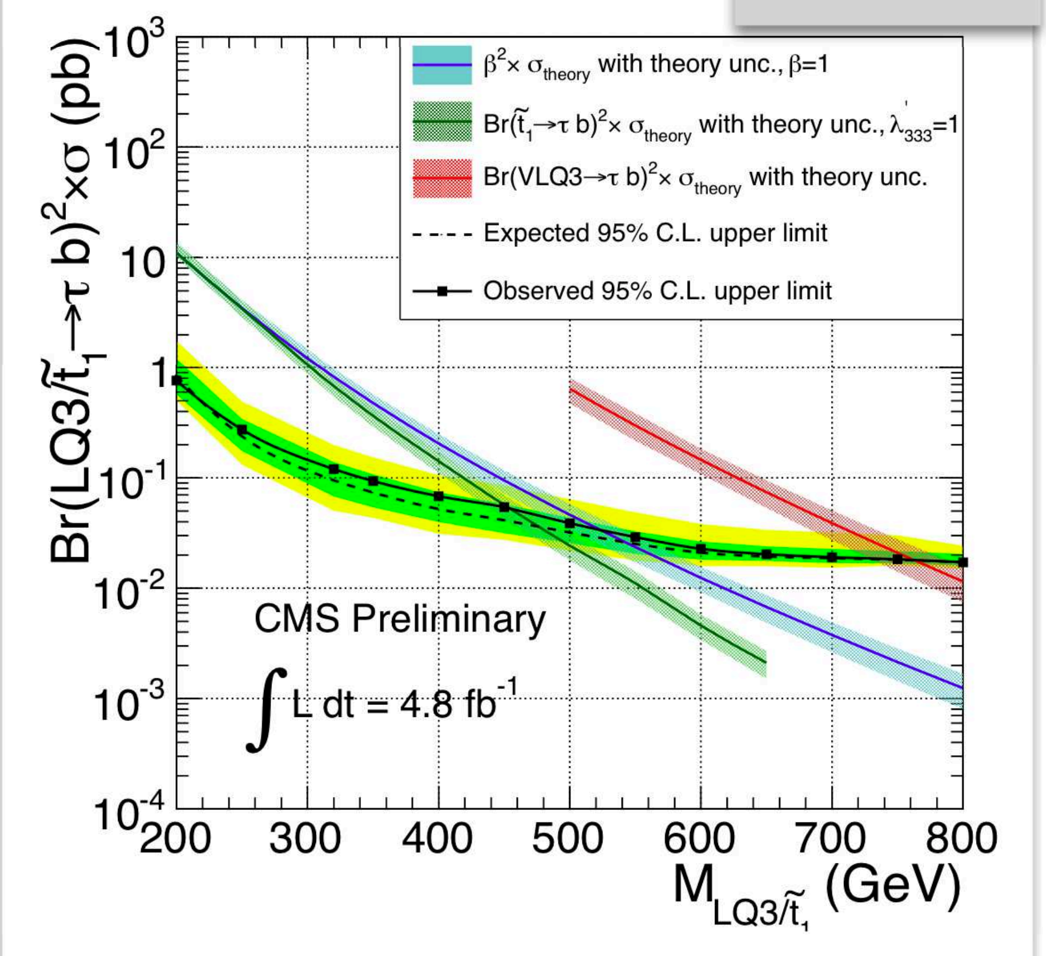
[CMS PAS EXO-12-002]

3rd generation leptoquarks

CMS

- Tau mis-ID probabilities are measured in data using W+jets events, and then applied to fake τ_h in simulation.
- Same production mechanism for SUSY stop ⇒ sensitive to LQ or $\tilde{t}_1$





- m(LQ3) > 525 GeV, for B(LQ→τb)=1
- m(VLQ3) > 760 GeV @ 95% CL
- $m(\tilde{t}_1)$ > 453 GeV

[CMS PAS EXO-12-002]

$Z' \to \tau\tau \to \tau_h\tau_h$

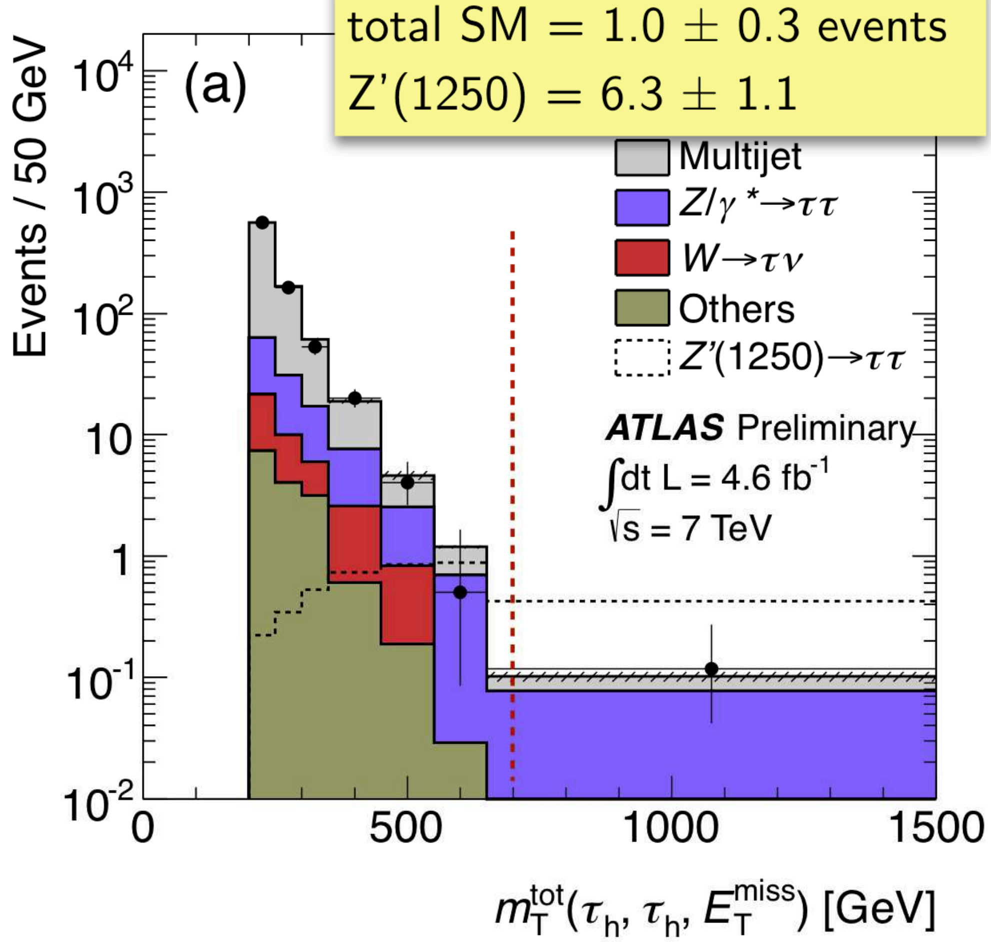
ATLAS

- New gauge bosons predicted in many GUTs with additional U(1).
- Best limit on $m(Z' \to ee/\mu\mu) > 2.3$ TeV from CMS [arxiv:1206.1849].
- Important to test the couplings to all lepton flavors.

Event selection

- 2 BDT loose 1 or 3-prong taus with $p_T(\tau_h) > 50$ GeV
- opposite sign
- $|\Delta\phi(e, \tau_h)| > 2.7$
- $m_T(\tau_h, \tau_h, E_T^{miss}) > 700$ GeV

total SM $= 1.0 \pm 0.3$ events
Z'(1250) $= 6.3 \pm 1.1$



- Tau ID efficiency uncert. $\approx$ 11% on the signal. (4% from $Z \to \tau\tau$ tag-and-probe)
- Jet/tau energy scale uncert. $\approx$ +22/-11%
- Multijet modeled by fitting the shape of the SS data. uncert. $\approx$ +21/-11%

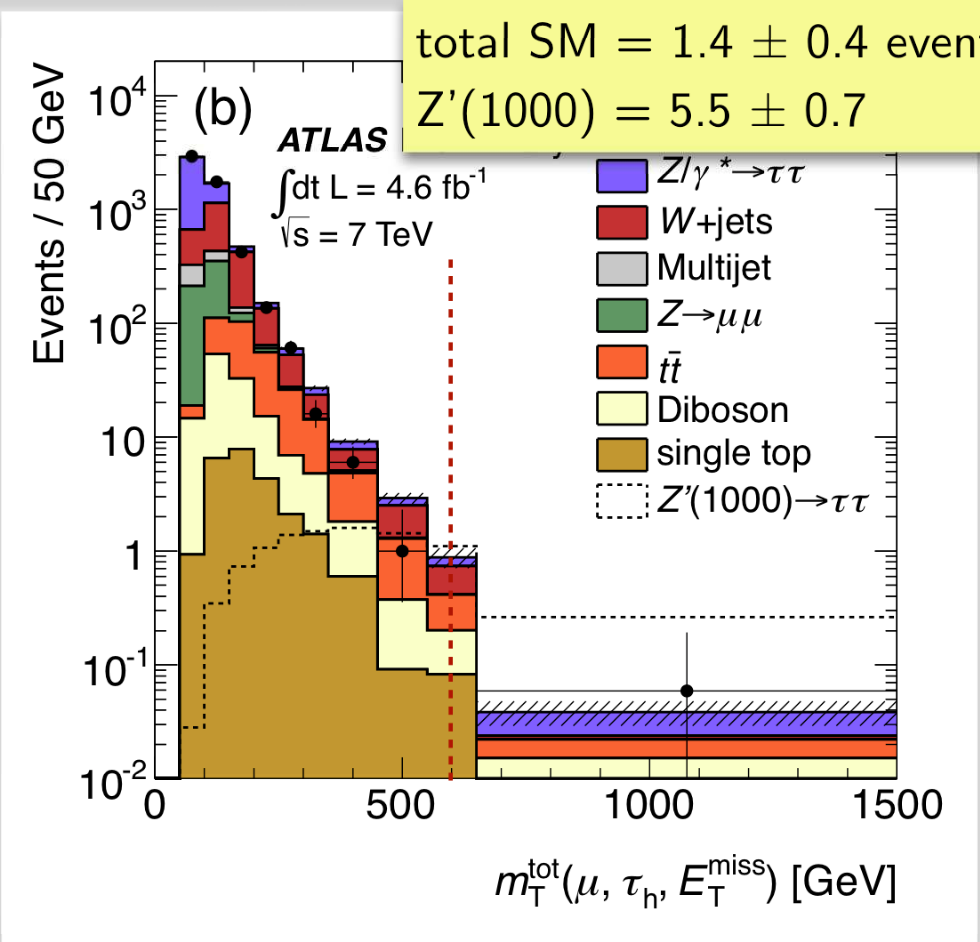
[ATLAS-CONF-2012-067]

$Z' \to \tau\tau \to \mu\tau_h$

ATLAS

Event selection

- $p_T(\mu) > 25$, $p_T(\tau_h) > 35$ GeV
- 1-prong τ_h
- $|\Delta\phi(e, \tau_h)| > 2.7$
- opposite sign μ and τ_h
- $m_T(e, \tau_h, E_T^{miss}) > 600$ GeV



total SM = 1.4 ± 0.4 events

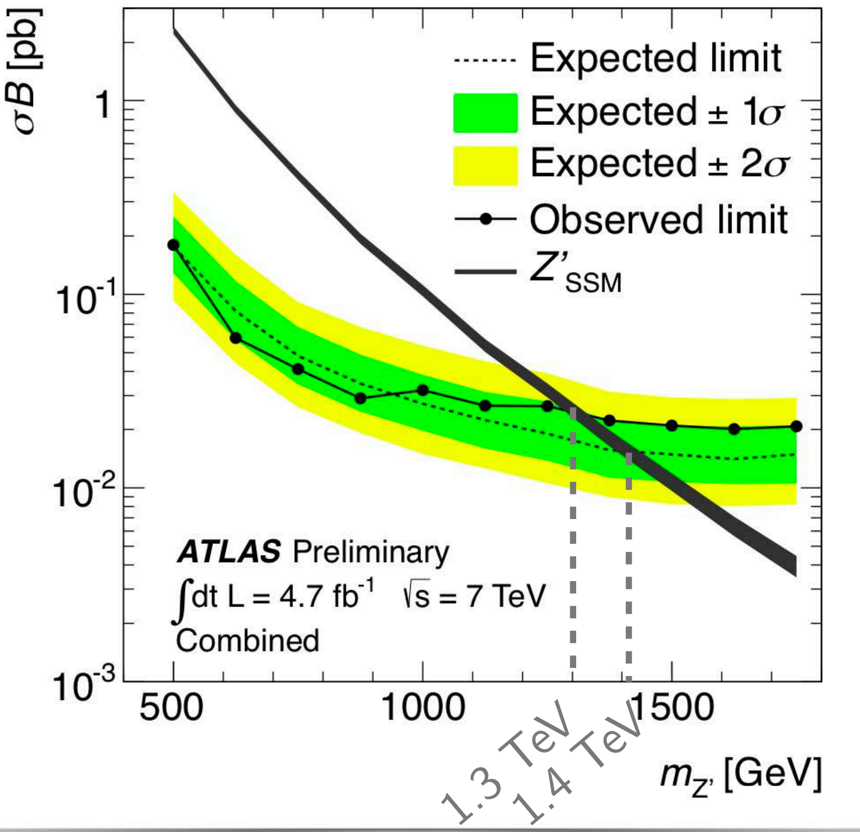
Z'(1000) = 5.5 ± 0.7

- Fake factor methods used to model multijet and W+jet backgrounds
- Need to be modeled in data-driven ways to trace them to the high mass tail, and because the jet$\to$ τ_h fake rate is mis-modeled in Monte Carlo.
- *Statistical* uncert. in the modeling dominates the background uncertainty (71% for W+jets).

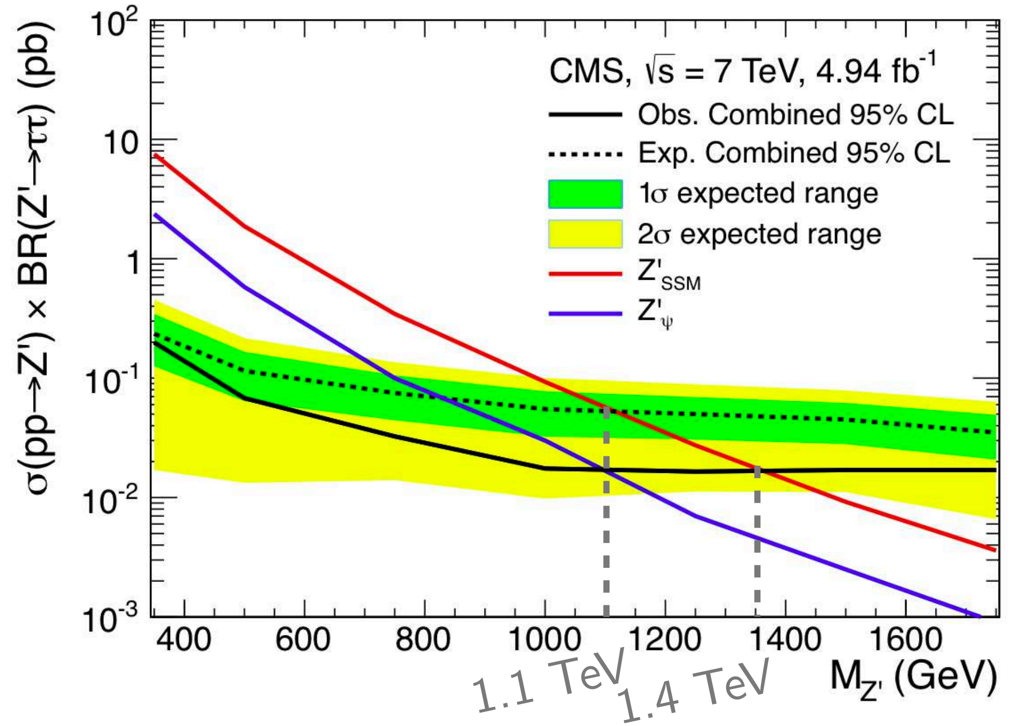
[ATLAS-CONF-2012-067]

Combined limit

ATLAS



CMS



ATLAS Z' SSM Exclusions: observed (expected) @ 95% CL

- $\tau_h\tau_h$: 1.25 (1.35) TeV
- $\mu\tau_h$: 1.00 (1.05) TeV
- $e\mu$: 0.75 (0.80) TeV

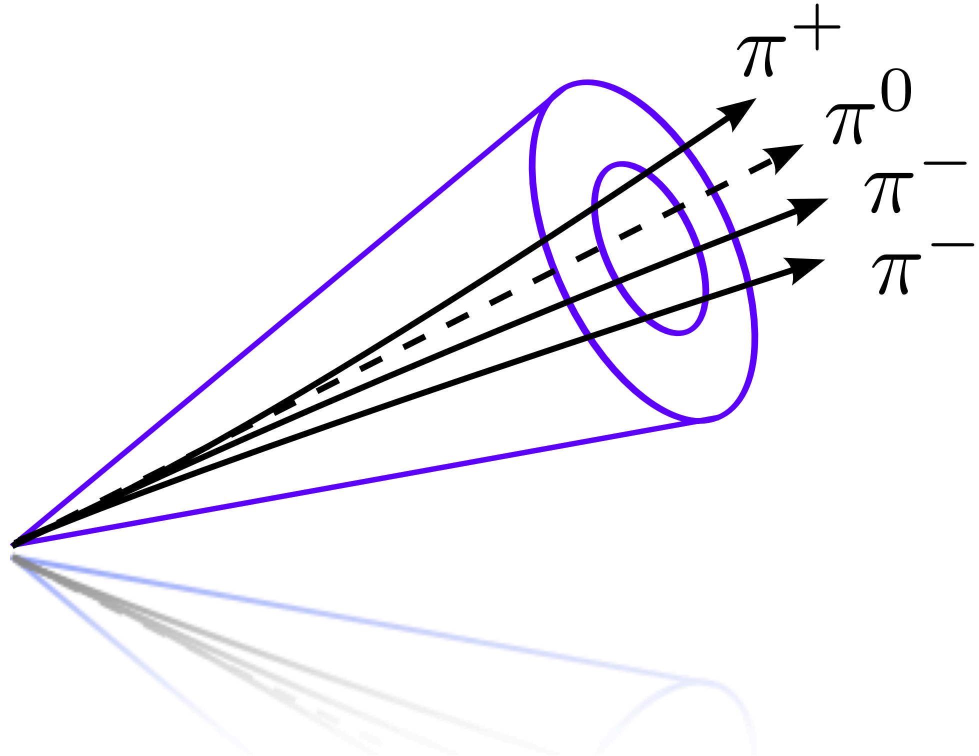
- ATLAS combined of 1.3 (1.4) TeV
- CMS combined: 1.4 (1.1) TeV

[ATLAS-CONF-2012-067]

Conclusions

- The performance of the LHC, and the ATLAS and CMS experiments have ***extended many exclusions*** for new physics.
- Many searches ***will be improved with the 2012*** dataset and further their reach with increases in luminosity and energy after the coming long shutdown.
- Unification and supersymmetry remain hidden.
- A ***new boson is in grasp*** consistent with the SM Higgs with a mass of 126 GeV, and ***taus*** will play an important role determining its ***couplings to fermions!***

References



General references

- J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).
- U. Amaldi, W. de Boer, and H. Furstenau. "Comparison of grand unified theories with electroweak and strong coupling constants measured at LEP." PLB 260 (1991) 447.
- W. de Boer, C. Sander. "Global Electroweak Fits and Gauge Coupling Unification." (2003) [arxiv:0307049]
- S.P. Martin. "A Supersymmetry Primer" [arxiv:9709356]

Charged Higgs

- ATLAS
  - "Search for charged Higgs bosons decaying via $H^{\pm} \rightarrow \tau^{\pm}\nu$ in $t\bar{t}$ events using pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS detector" [arxiv:1204.2760]
- CMS
  - "Search for a light charged Higgs boson in top quark decays in pp collisions at $\sqrt{s} = 7$ TeV" [arvix:1205.5736]

SUSY

- ATLAS
  - "Search for events with large missing transverse momentum, jets, and at least two tau leptons in 7 TeV proton-proton collision data with the ATLAS detector" [arxiv: 1203.6580]
  - "Search for supersymmetry with jets, missing transverse momentum and at least one hadronically decaying τ lepton in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector" [arxiv:1204.3852]
- CMS
  - "Search for anomalous production of multilepton events in pp collisions at $\sqrt{s} = 7$ TeV" [arvix:1204.5341]
  - "Search for new physics with same-sign isolated dilepton events with jets and missing transverse energy" [arxiv:1205.6615]
  - "Search for new physics in events with opposite-sign leptons, jets, and missing transverse energy in pp collisions at $\sqrt{s} = 7$ TeV" [arxiv:1206.3949]

Exotics

- ATLAS
  - "A search for high-mass resonances decaying to $\tau^+\tau^-$ in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector" [ATLAS-CONF-2012-067]
- CMS
  - "Search for high-mass resonances decaying into τ-lepton pairs in pp collisions at $\sqrt{s} = 7$ TeV" [arvix:1206.1725]
  - "Search for pair production of third generation leptoquarks and stops that decay to a tau and a b quark" [CMS PAS EXO-12-002]

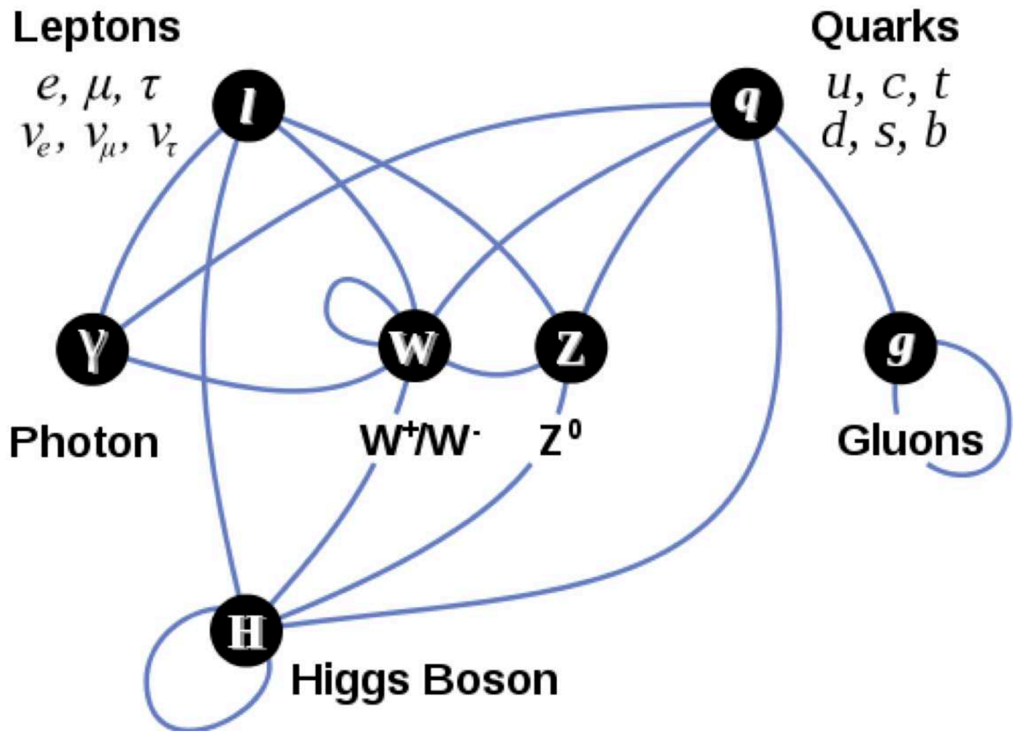
Tau performance

- ATLAS
  - "Reconstruction, Energy Calibration, and Identification of Hadronically Decaying Tau Leptons" [ATLAS-CONF-2011-077]
  - "Performance of the Reconstruction and Identification of Hadronic Tau Decays with ATLAS" [ATLAS-CONF-2011-152]
  - "$Z \rightarrow \tau\tau$ cross section measurement in proton-proton collisions at 7 TeV with the ATLAS experiment" [ATLAS-CONF-2012-006]

Tau performance

- CMS
  - "Performance of τ-lepton reconstruction and identification in CMS" [arvix:1109.6034, CMS PAS TAU-11-001]
  - "CMS Strategies for tau reconstruction and identification using particle-flow techniques" [CMS PAS PFT-08-001]
  - "Particle–Flow Event Reconstruction in CMS and Performance for Jets, Taus, and $E_{\mathrm{T}}^{\mathrm{miss}}$" [CMS PAS PFT-09-001]
  - "Commissioning of the Particle-Flow Reconstruction in Minimum-Bias and Jet Events from pp Collisions at 7 TeV" [CMS PAS PFT-10-002]
  - "Commissioning of the particle-flow event reconstruction with leptons from J/Psi and W decays at 7 TeV" [CMS PAS PFT-10-003]
  - "Study of tau reconstruction algorithms using pp collisions data collected at $\sqrt{s} = 7$ TeV" [CMS PAS PFT-10-004]

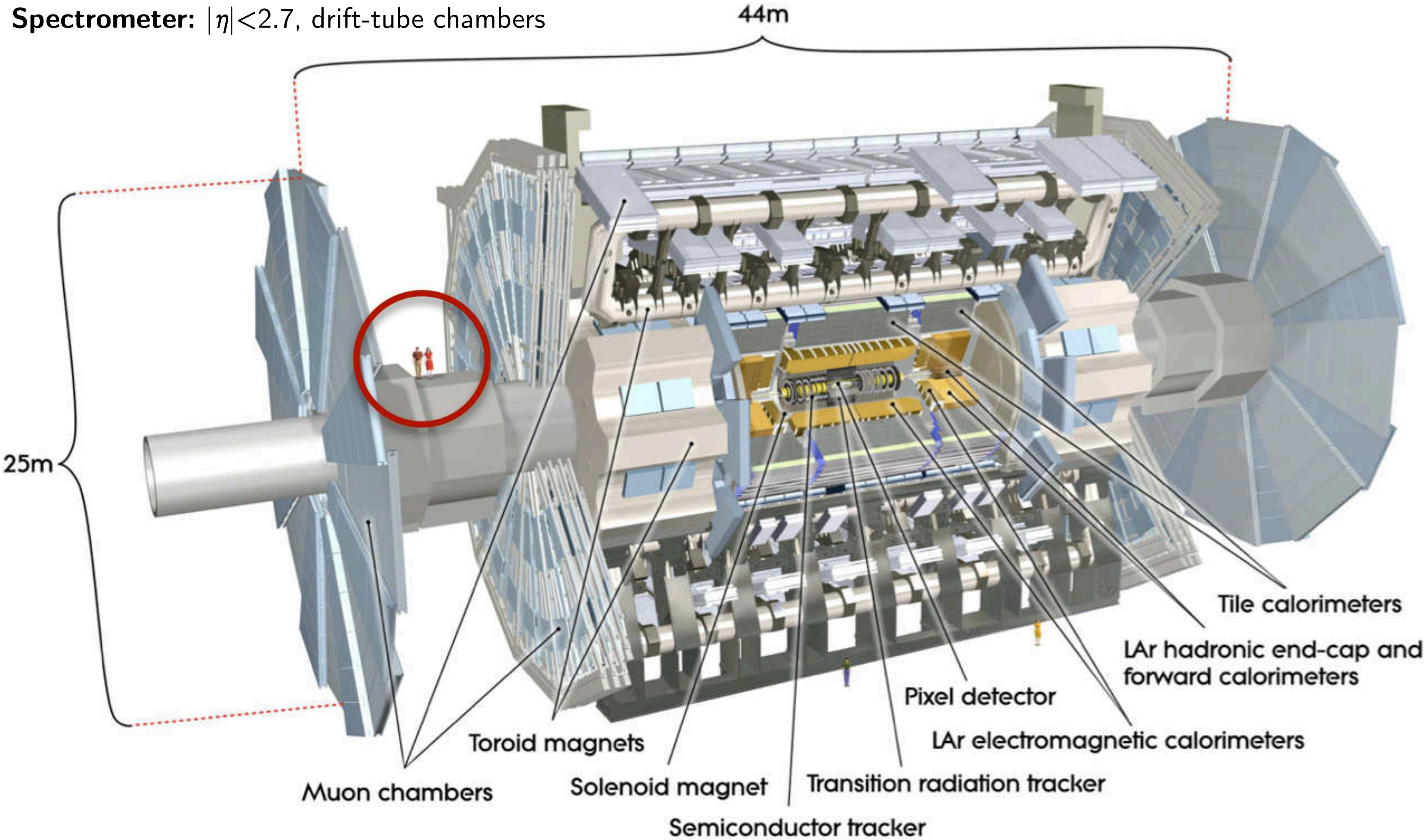
Back up: general



ATLAS Detector

Magnets: 5 tonne central solenoid, 2T in inner detector, 4T toroid system

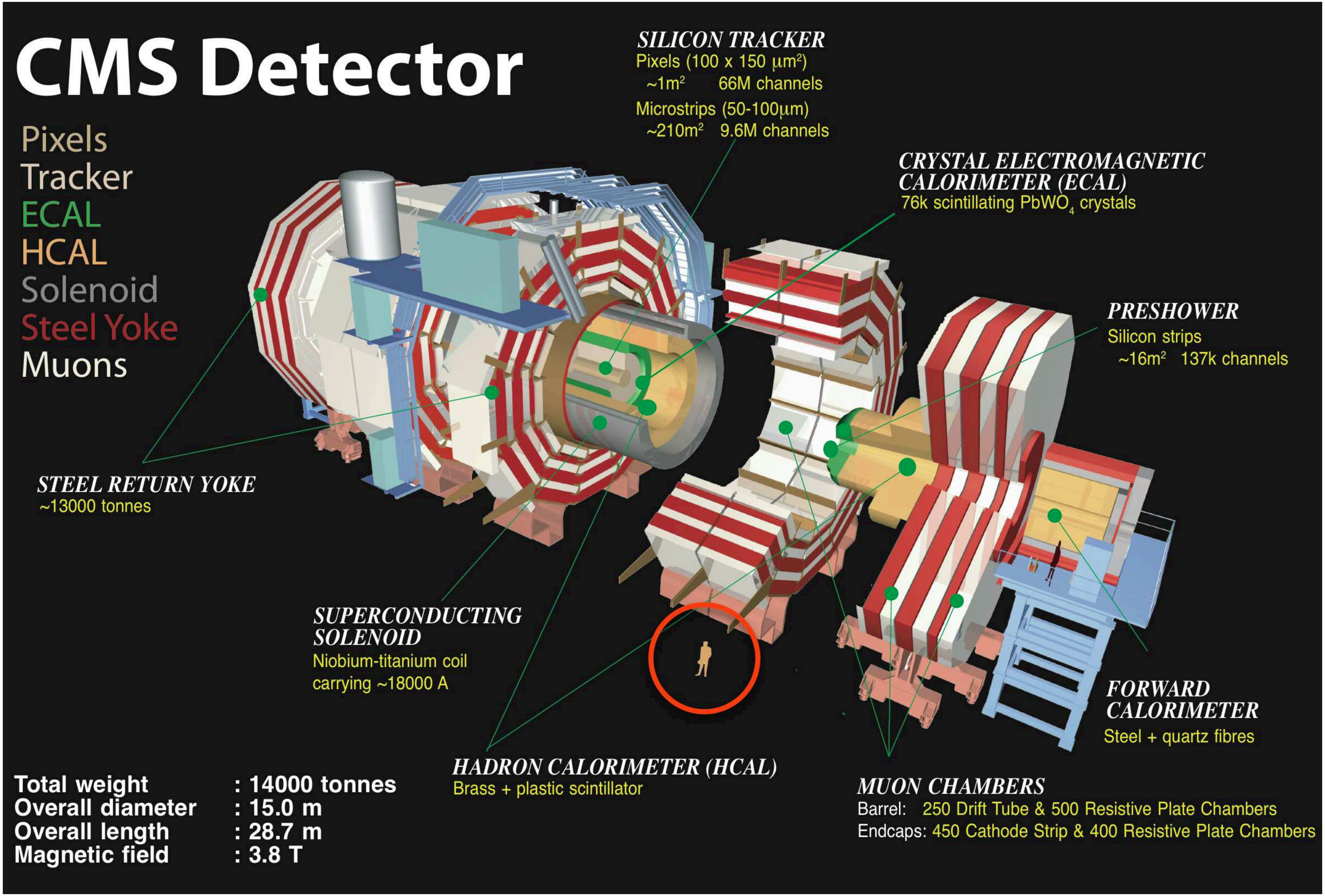
Muon Spectrometer: $|\eta|<2.7$, drift-tube chambers



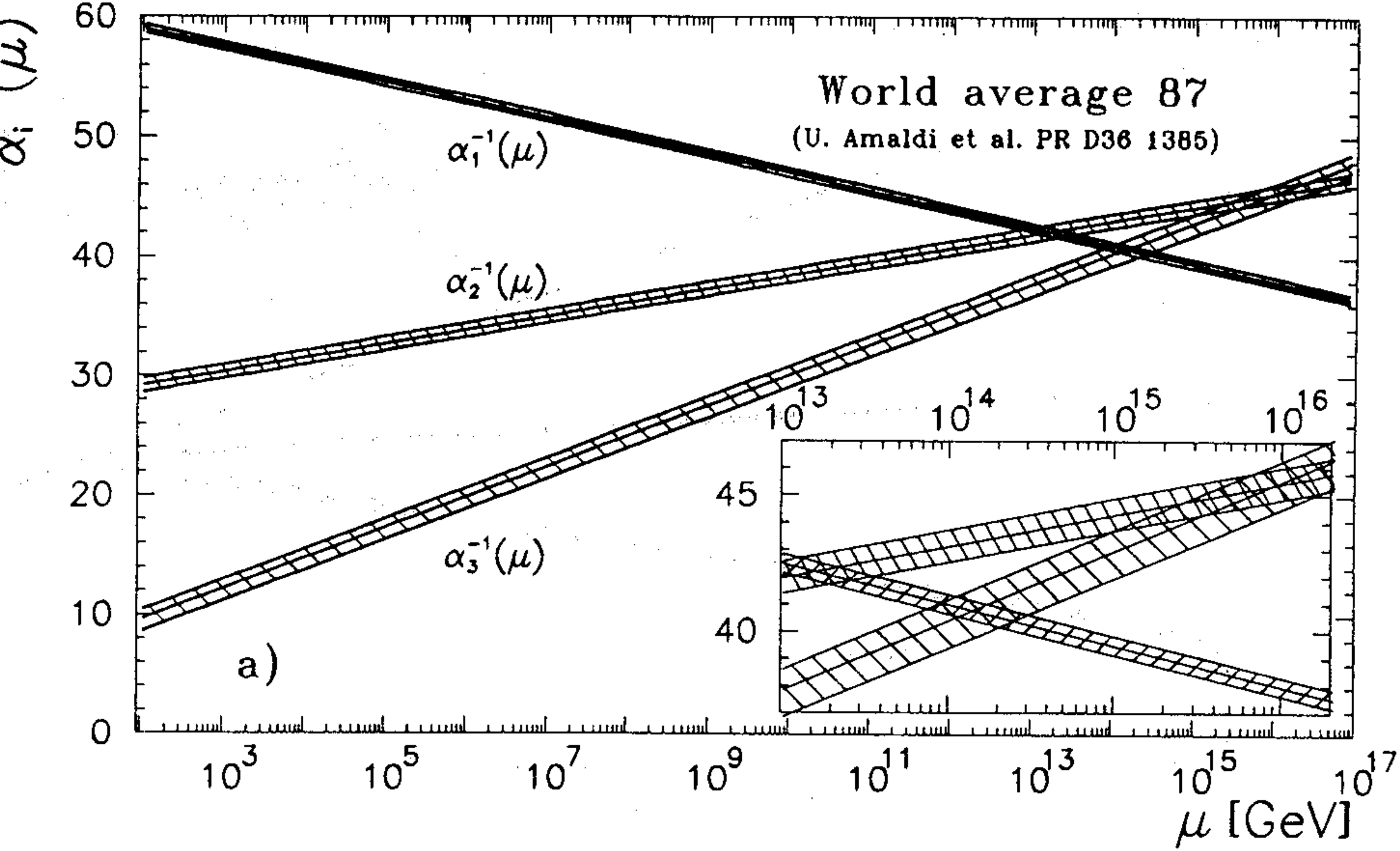
Tracking: $|\eta|<2.5$, B=2T, precise tracking and vertexing, Si pixels, strips, and TRT straws, TR electron ID

Electromagnetic Calorimeter: $|\eta|<3.2$, 3+1 layers corrugated layers of lead and LAr

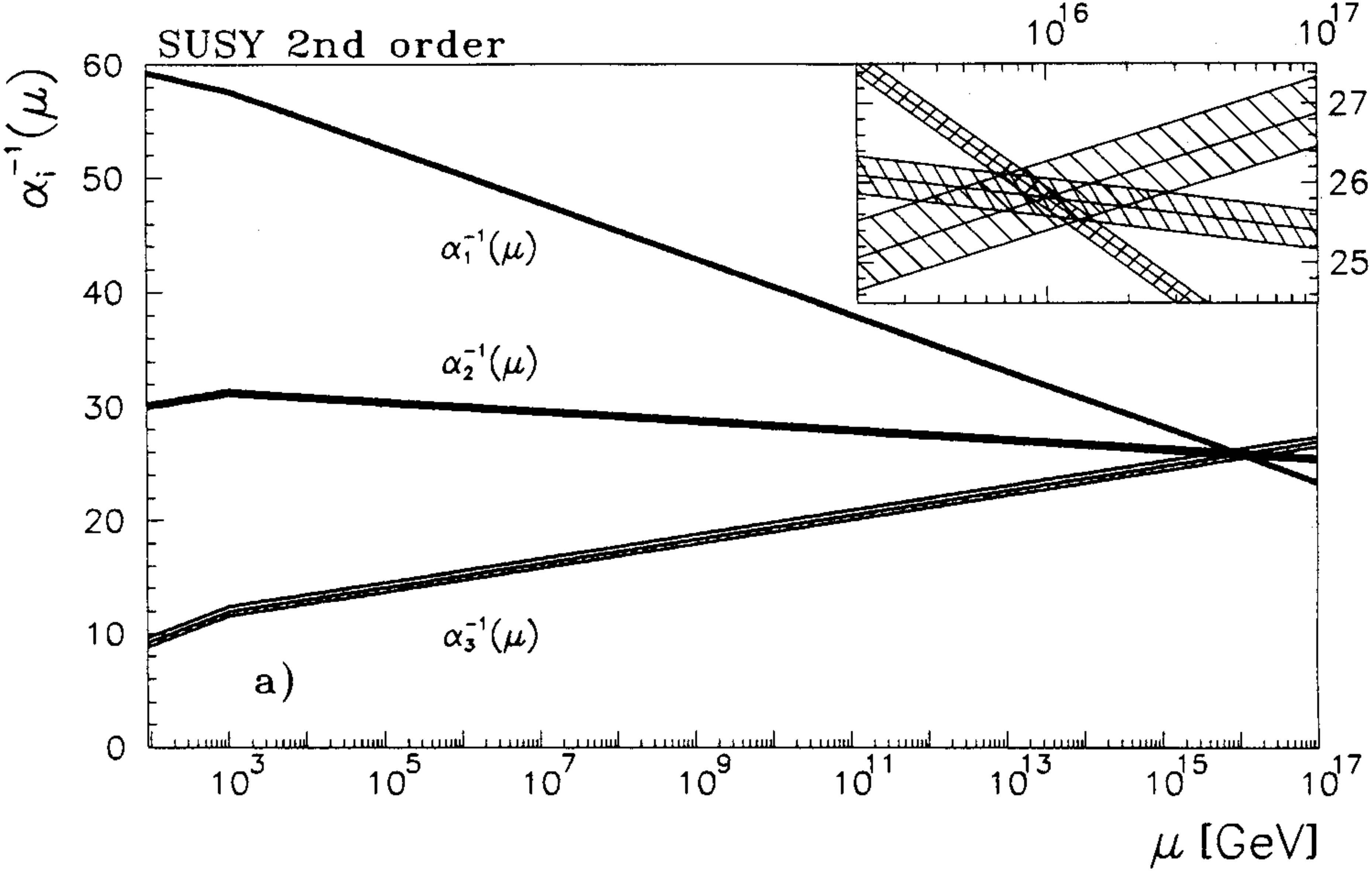
Hadronic Calorimeter: $|\eta|<5$, Central: iron/scintillator tiles, Forward: copper/tungsten-LAr


CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² 137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
FORWARD CALORIMETER
Steel + quartz fibres
MUON CHAMBERS
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Gauge coupling unification

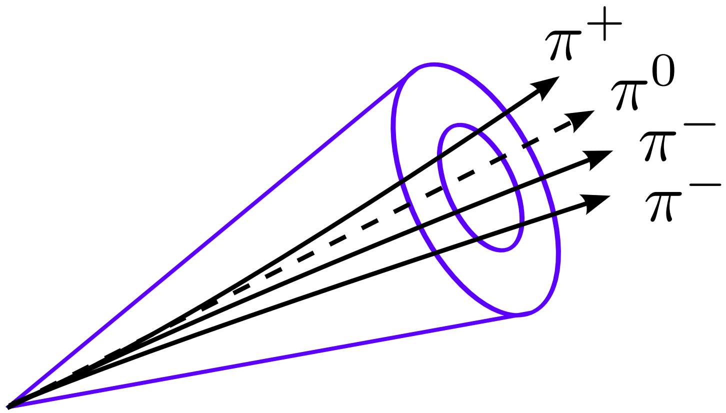


Gauge coupling unification

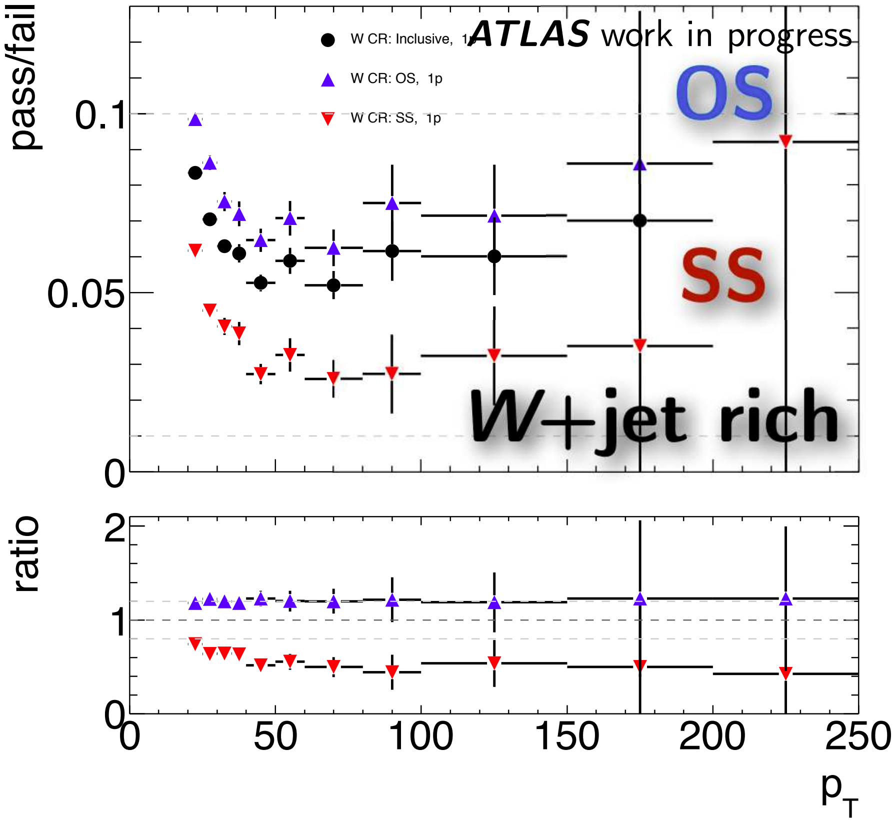


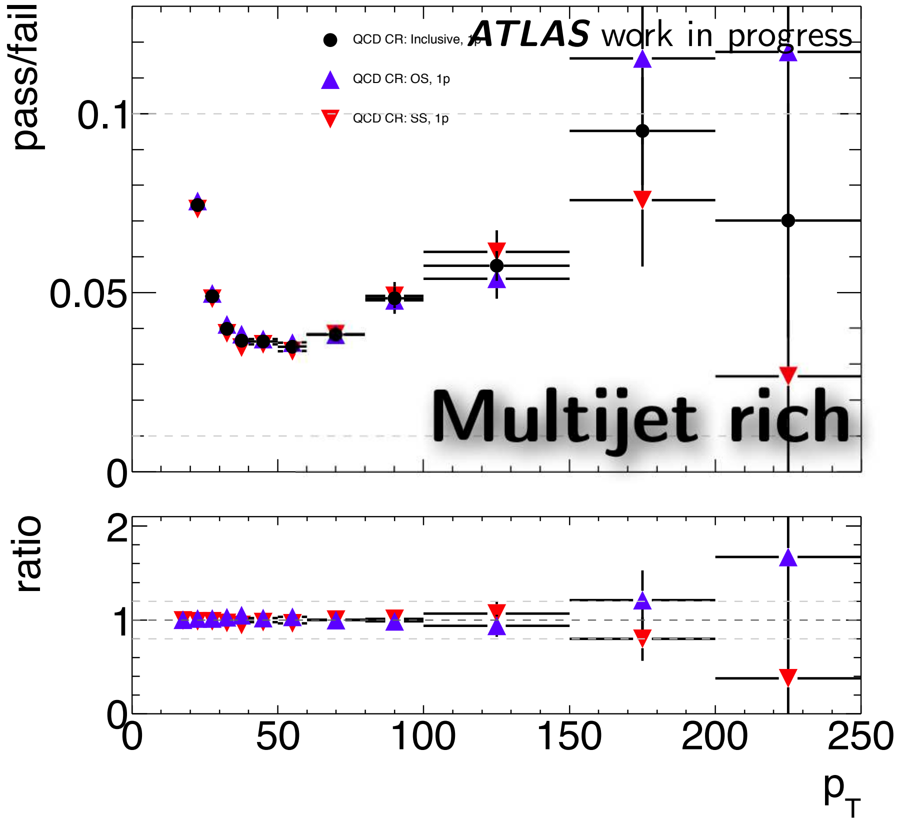
Phenomenology of tau decays

$\tau^- \to$	$e^- \, \bar{\nu}_e \, \nu_\tau$	17.8%	leptonic 35.2%
	$\mu^- \, \bar{\nu}_\mu \, \nu_\tau$	17.4%	
	$\pi^- \, \pi^0 \, \nu_\tau$	25.5%	1 prong 49.5%
	$\pi^- \, \nu_\tau$	10.9%	
	$\pi^- \, 2\pi^0 \, \nu_\tau$	9.3%	
	$K^- \, (N\pi^0) \, (NK^0) \, \nu_\tau$	1.5%	
	$\pi^- \, 3\pi^0 \, \nu_\tau$	1.0%	
	$\pi^- \, \pi^- \, \pi^+ \, \nu_\tau$	9.0%	3 prong 15.2%
	$\pi^- \, \pi^- \, \pi^+ \, \pi^0 \, \nu_\tau$	4.6%	



Observed variance in fake-rates





(BDTMedium)

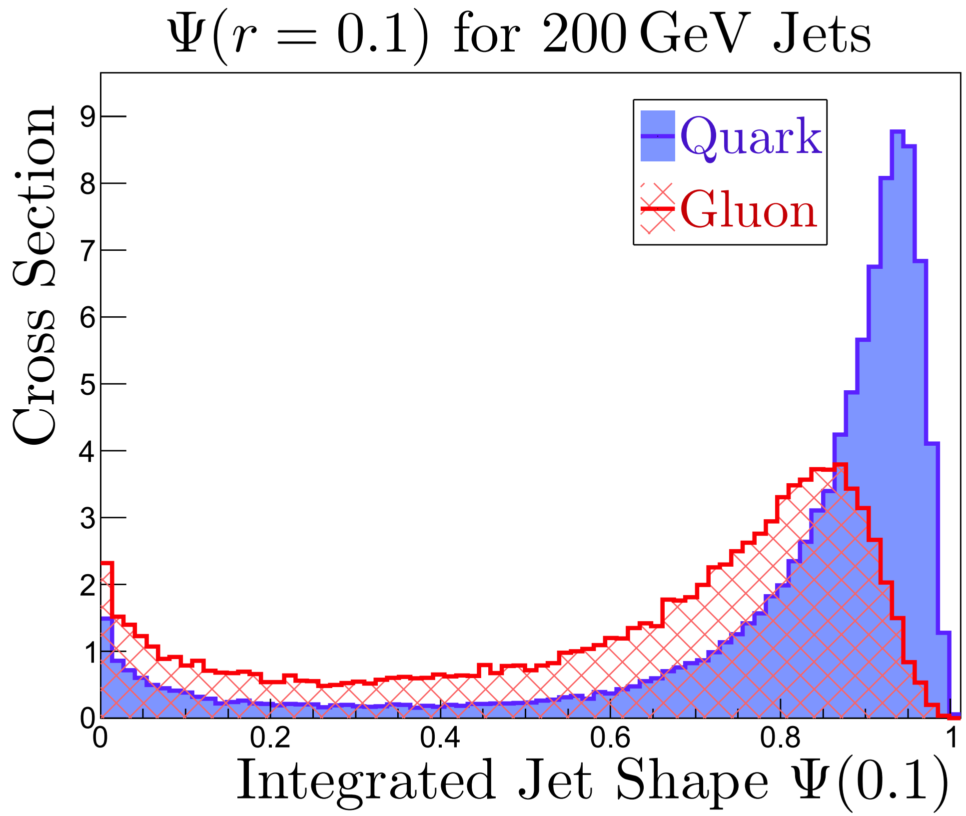
- Hypothesis: quarks vs gluons
- Divide the issue into two questions:

1. *Why do quarks and gluons have different tau fake-rates?*
2. *How does the quark/gluon fraction vary among samples?*

Jet width for quark/gluons

Why do quarks and gluons have different tau fake-rates?

- $\Psi(r)$ = fraction of jet energy within $\Delta R < r$.
- Quark jets are more narrow than gluon jets of the same energy.
- Tau identification prefers narrow candidates.



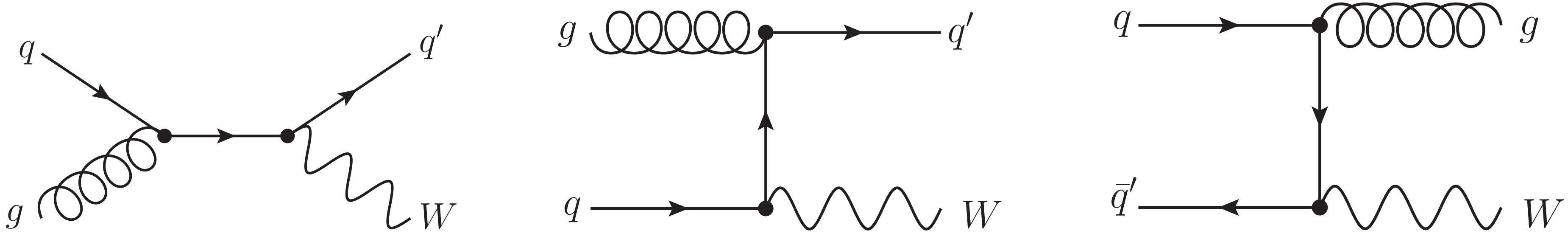
- This is consistent with samples of quark-enriched jets, like W+jet, having higher fake-rates.

J. Gallicchio, M. Schwartz. "Quark and Gluon Tagging at the LHC". arXiv:1106.3076.

OS vs SS W+jet

How does the quark/gluon fraction vary among samples?

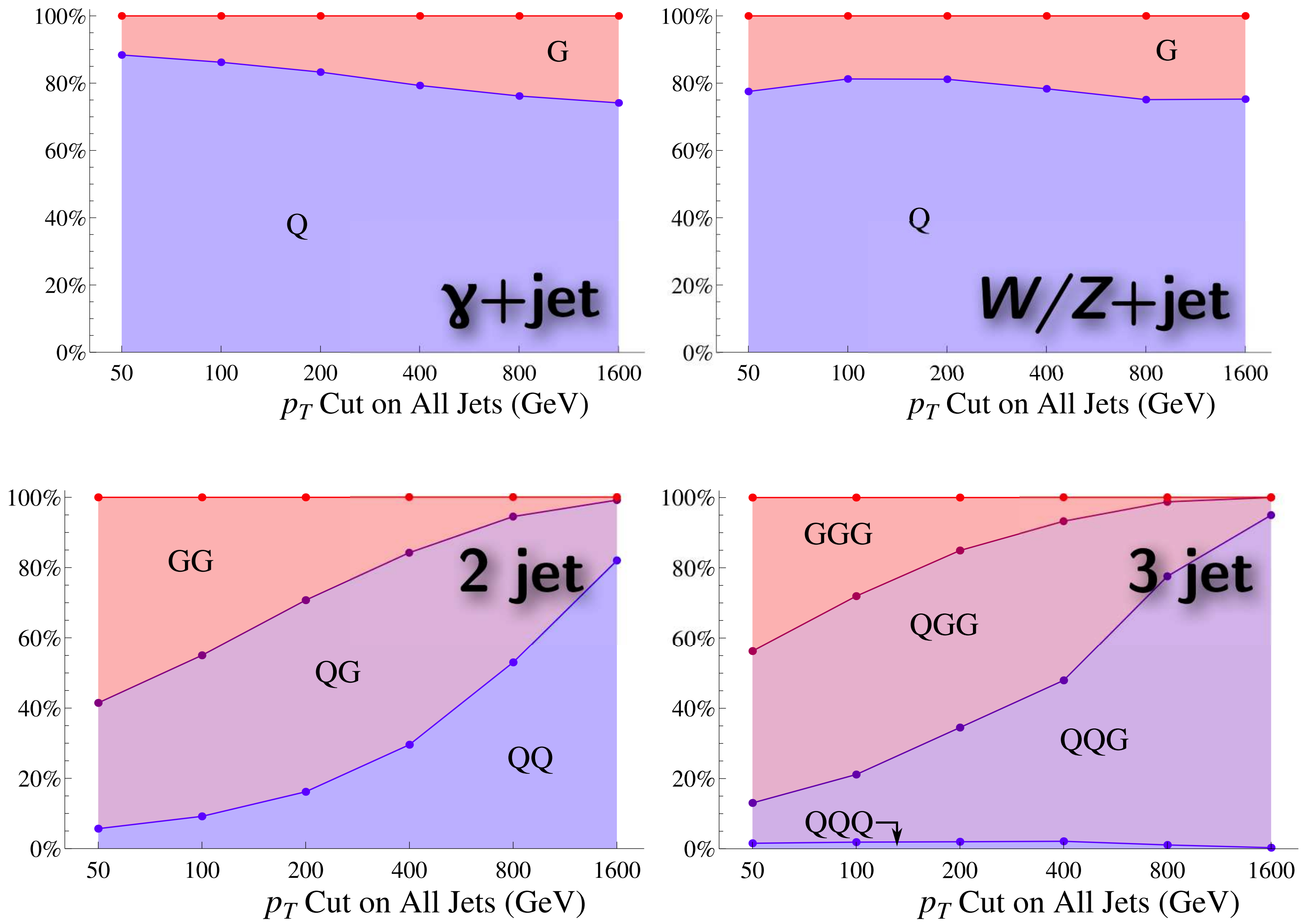
Leading order W+jet production:



(a) (b) (c)

- The charge of the quark should correlate with the reconstructed charge of the tau candidate, therefore (a) and (b) preferably produce opposite sign W+jet events.
- OS and SS will have different quark/gluon fractions.

Madgraph predicted Quark/Gluon



J. Gallicchio, M. Schwartz. “Pure Samples of Quark and Gluon Jets at the LHC”. arXiv:1104.1175

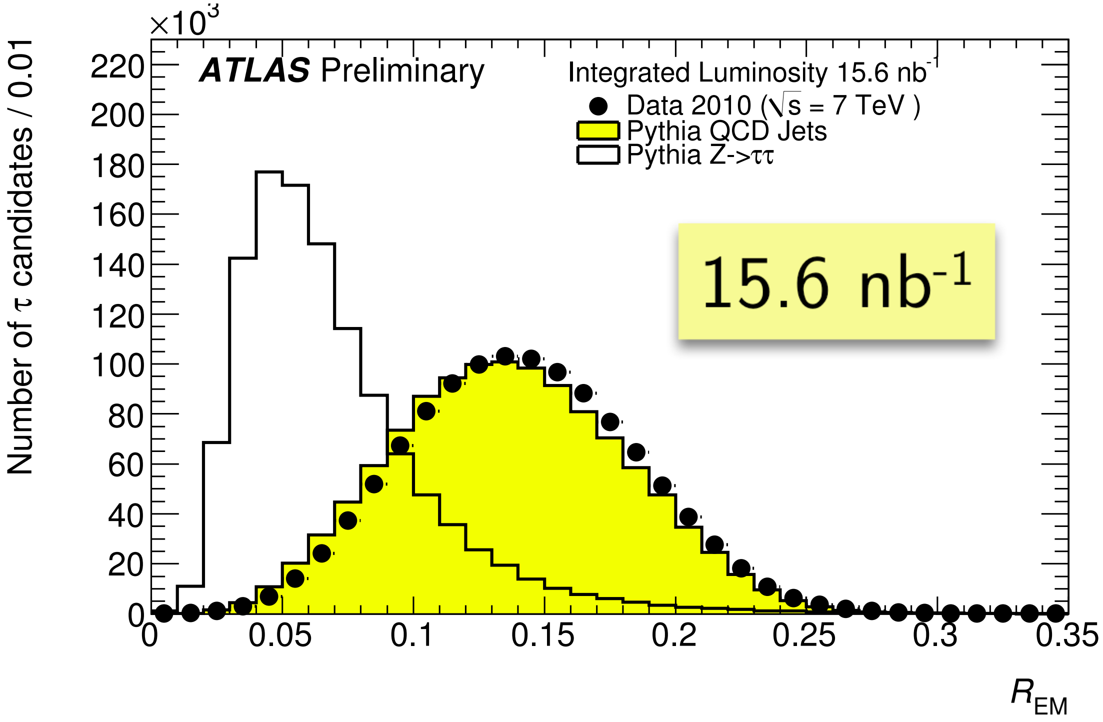
Back up: ATLAS tau identification

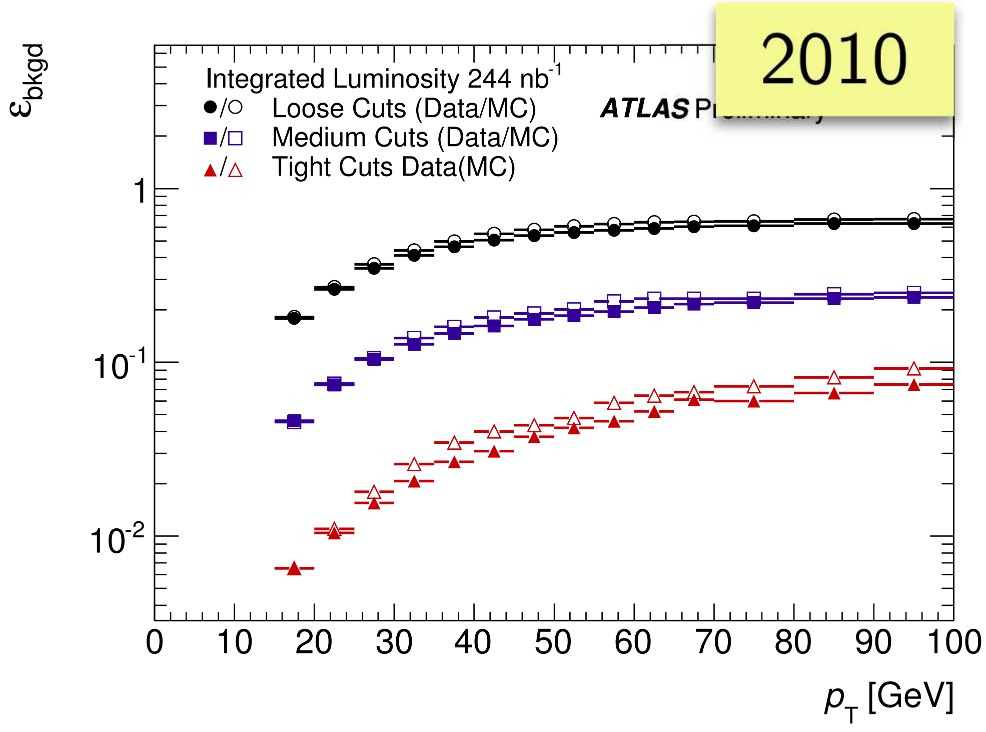
Tau identification variables

- Electrmagnetic radius: $R_{\mathrm{EM}} = \frac{\sum_{i \in \{\mathrm{EM}\ 0-2\}}^{\Delta R_i < 0.4} E_{\mathrm{T},i}^{\mathrm{EM}} \Delta R_i}{\sum_{i \in \{\mathrm{EM}\ 0-2\}}^{\Delta R_i < 0.4} E_{\mathrm{T},i}^{\mathrm{EM}}}$
- Track radius: $R_{\mathrm{track}} = \frac{\sum_{i}^{\Delta R_i < 0.4} p_{\mathrm{T},i} \Delta R_i}{\sum_{i}^{\Delta R_i < 0.4} p_{\mathrm{T},i}}$
- Leading track momentum fraction: $f_{\mathrm{track}} = \frac{p_{\mathrm{T},1}^{\mathrm{track}}}{p_{\mathrm{T}}^{\tau}}$
- Core energy fraction: $f_{\mathrm{core}} = \frac{\sum_{i \in \{\mathrm{all}\}}^{\Delta R_i < 0.1} E_{\mathrm{T},i}^{\mathrm{EM}}}{\sum_{i \in \{\mathrm{all}\}}^{\Delta R_i < 0.4} E_{\mathrm{T},i}^{\mathrm{EM}}}$
- Electromagnetic fraction: $f_{\mathrm{EM}} = \frac{\sum_{i \in \{\mathrm{EM}\ 0-2\}}^{\Delta R_i < 0.4} E_{\mathrm{T},i}^{\mathrm{EM}}}{\sum_{j \in \{\mathrm{all}\}}^{\Delta R_j < 0.4} E_{\mathrm{T},j}^{\mathrm{EM}}}$
- Cluster mass: m_{clusters}, invariant mass clusters at the EM energy scale.
- Track mass: m_{tracks}, invariant mass of the track system.
- Transverse flight path significance: $S_{\mathrm{T}}^{\mathrm{flight}}$

Motivation: taus tend to be collimated more than jets, have a leading track, and often significant neutral pion deposits in the EM calorimeter.

First data



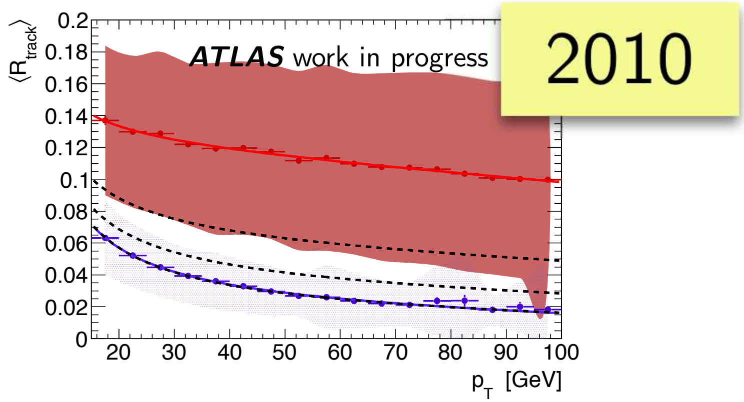


- First comparisons of background distributions and the QCD fake-rate between data and Monte Carlo.

- Already see that MC over-estimates the jet fake-rate. $\Rightarrow k_W \approx 0.5$

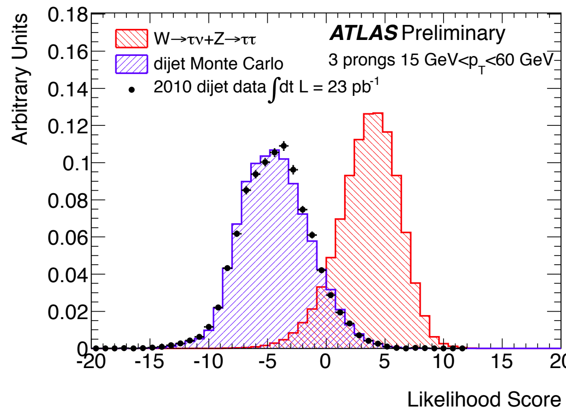
"Reconstruction of hadronic tau candidates in QCD events at ATLAS with 7 TeV pp collisions"
[ATLAS-CONF-2010-059]
"Tau Reconstruction and Identification Performance in ATLAS"
[ATLAS-CONF-2010-086]

Tau discriminants



- **Cuts**

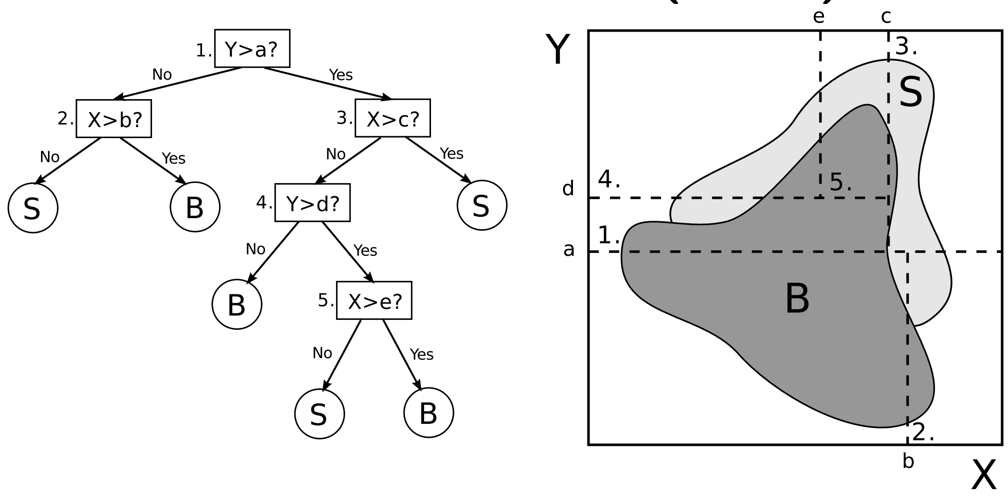
  p_{T}-parametrized cuts on R_{EM} and R_{track}, and a cut on f_{track}.

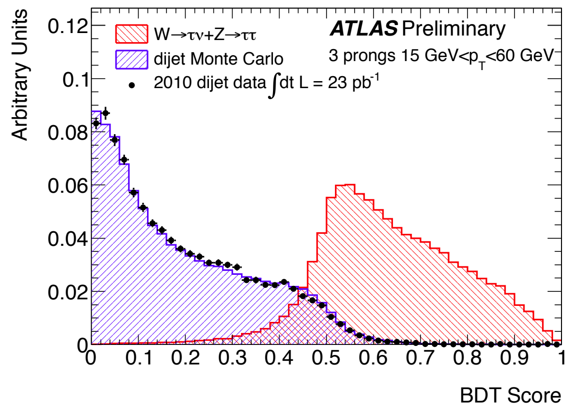


- **Projective likelihood**

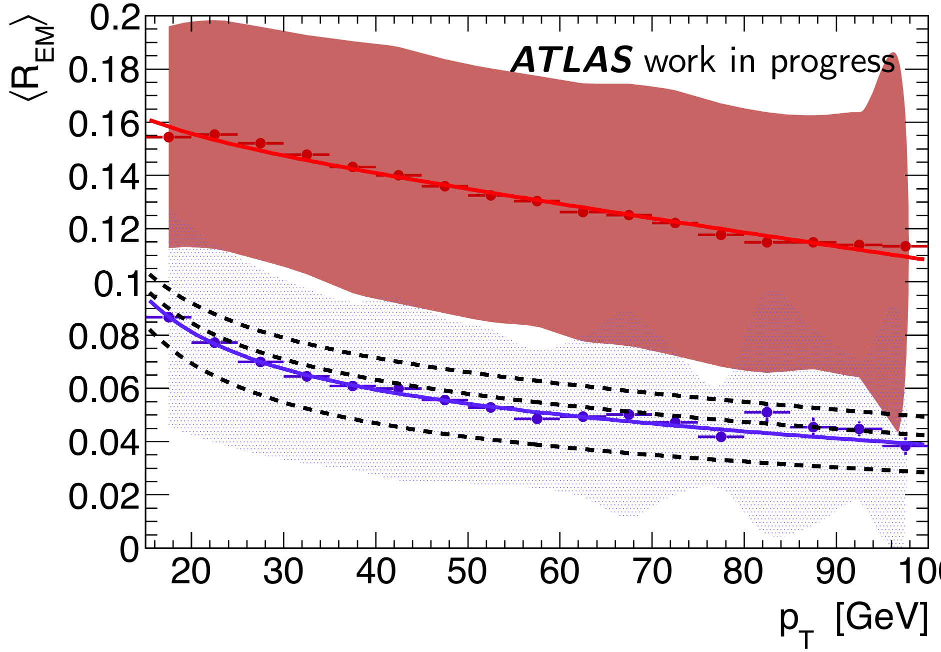
  $$d = \ln\left(\frac{L_S}{L_B}\right) = \sum_{i=1}^{N} \ln\left(\frac{p_i^S(x_i)}{p_i^B(x_i)}\right)$$

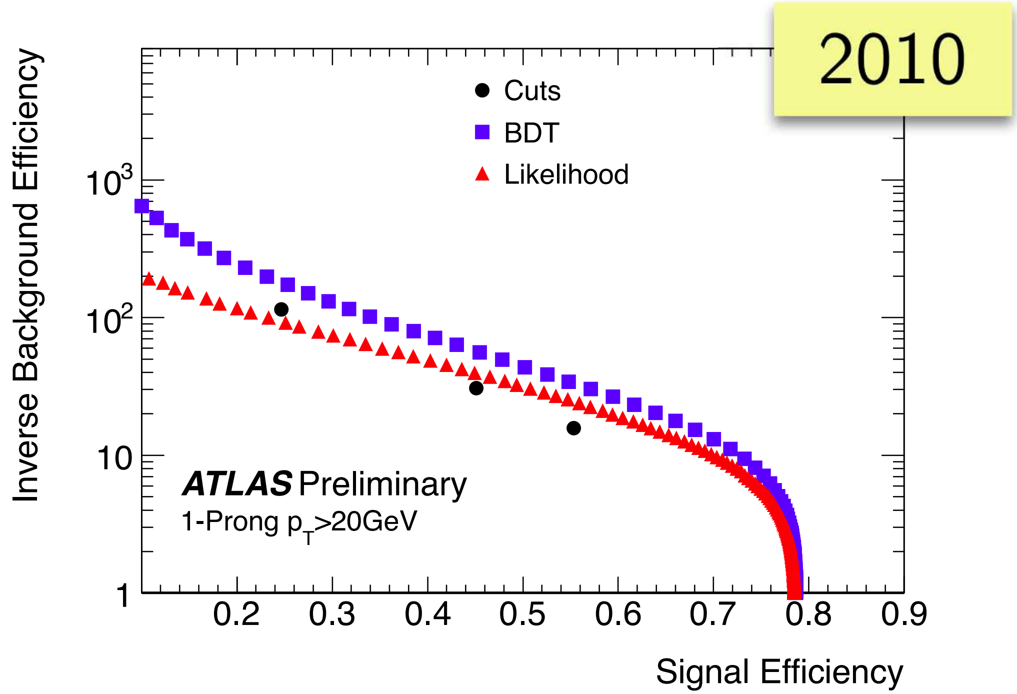
- **Boosted decision trees (BDT)**





Maturing of discriminants



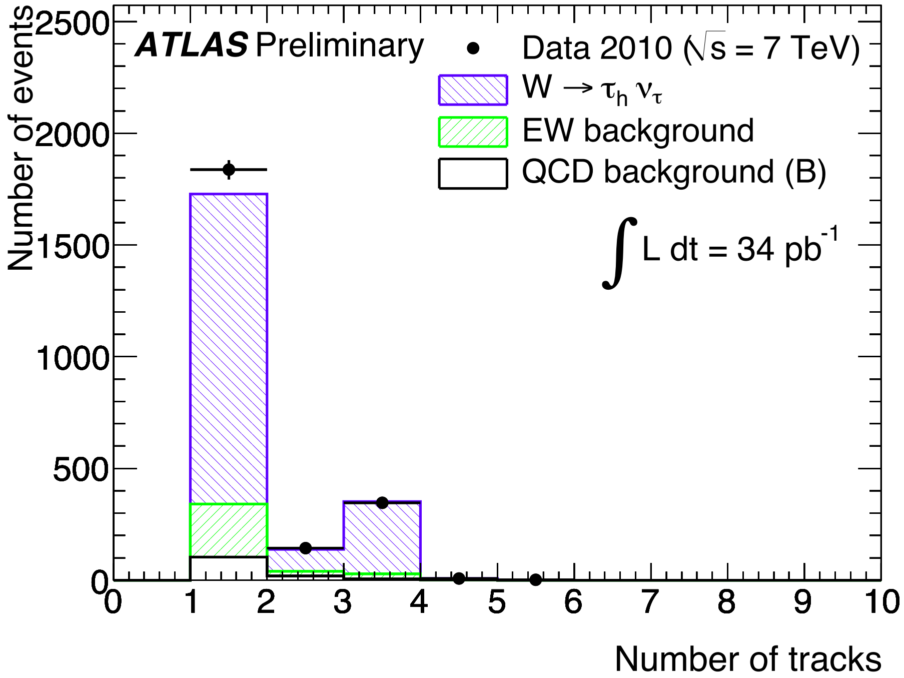


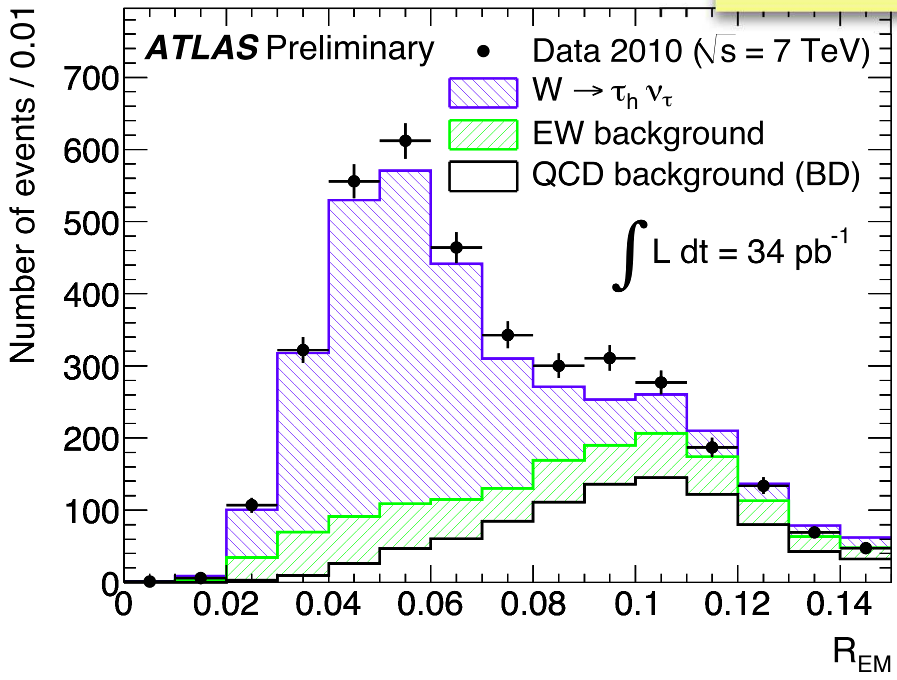
- Cuts are pt-parametrized to account for the Lorentz collimation of boosted taus.
- Experience grows with LLH and BDT discriminants, which become the preferred discriminants in 2011.

"Reconstruction, Energy Calibration, and Identification of Hadronically Decaying Tau Leptons in the ATLAS Experiment" [ATLAS-CONF-2011-077, ATL-PHYS-INT-2011-068]

Seeing first hadronic taus

2010





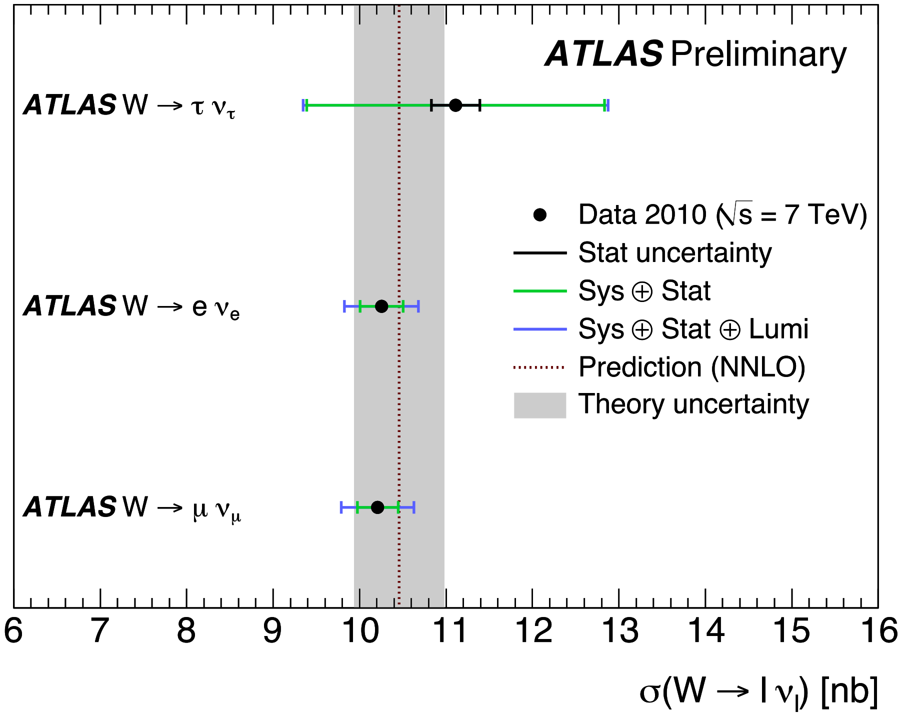
- Nov 2010: Observation of $W \to \tau_h \nu$ [ATLAS-CONF-2010-097]
- Feb 2011: Observation of $Z \to \tau_h \tau_l$ [ATLAS-CONF-2011-010]

$W \to \tau\nu$ cross section

2010

$$\sigma(W \to \tau\nu) = 11.1 \pm 0.3(\text{stat.}) \pm 1.7(\text{sys.}) \pm 0.4(\text{lumi.})\ \text{nb}$$

$$\sigma_{\text{theory}} = 10.46 \pm 0.52\ \text{nb at NNLO}$$



Dominant systematics

- $\tau_{\rm h}$ efficiency 10.3%
- $\tau_{\rm h}$ energy scale 8.0%
- $\tau_{\rm h}$ + MET trigger efficiency 7.0%
- luminosity 3.4%
- acceptance 2.3%

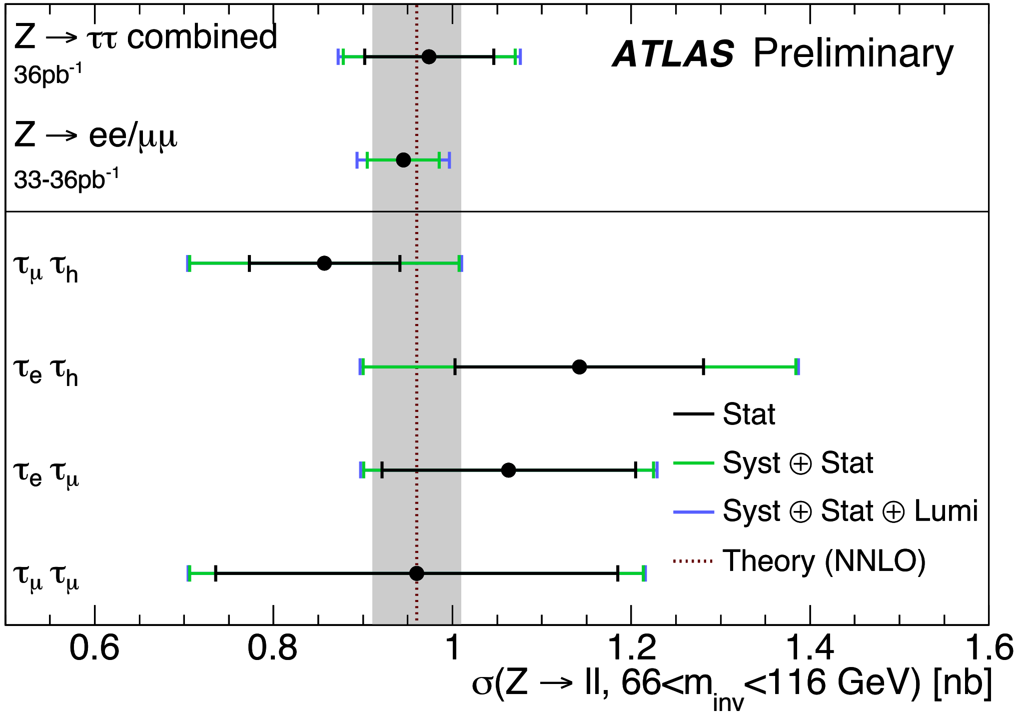
"Measurement of the $W \to \tau\nu$ cross section in pp collisions at sqrt(s)= 7 TeV with the ATLAS experiment" [arXiv:1108.4101]

$Z\to\tau\tau$ cross section

2011

$$\sigma_{\text{combined}} = 0.97 \pm 0.07(\text{stat.}) \pm 0.07(\text{sys.}) \pm 0.03(\text{lumi.})\ \text{nb}$$

$$\sigma_{\text{theory}} = 0.96 \pm 0.05\ \text{nb at NNLO}$$

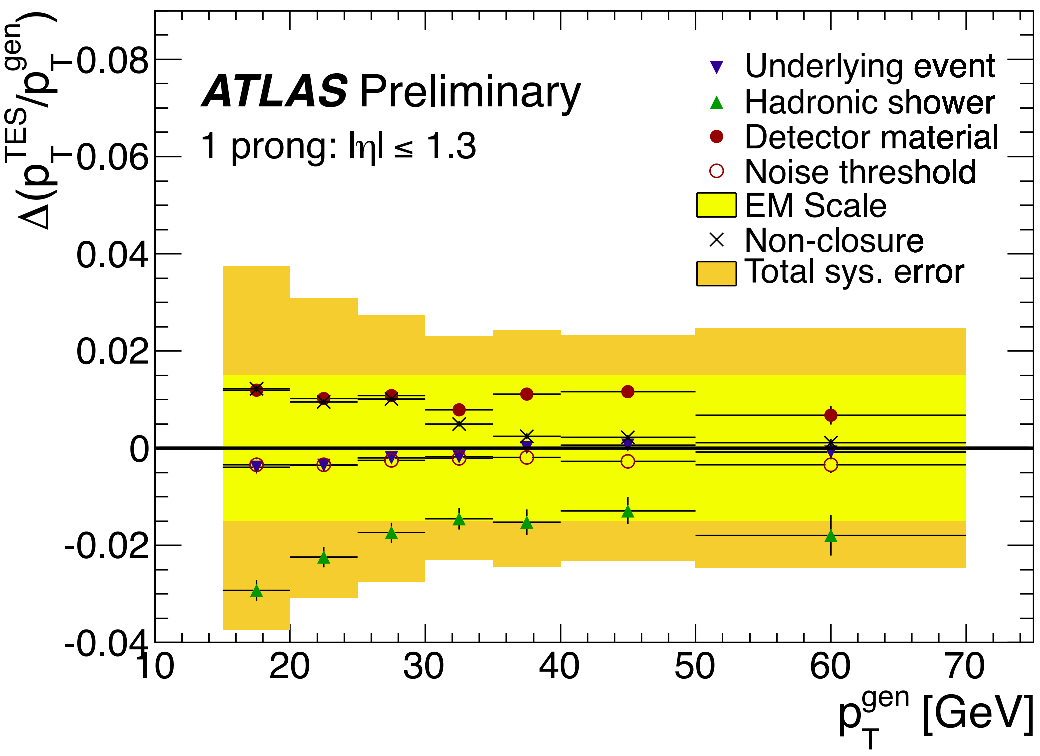


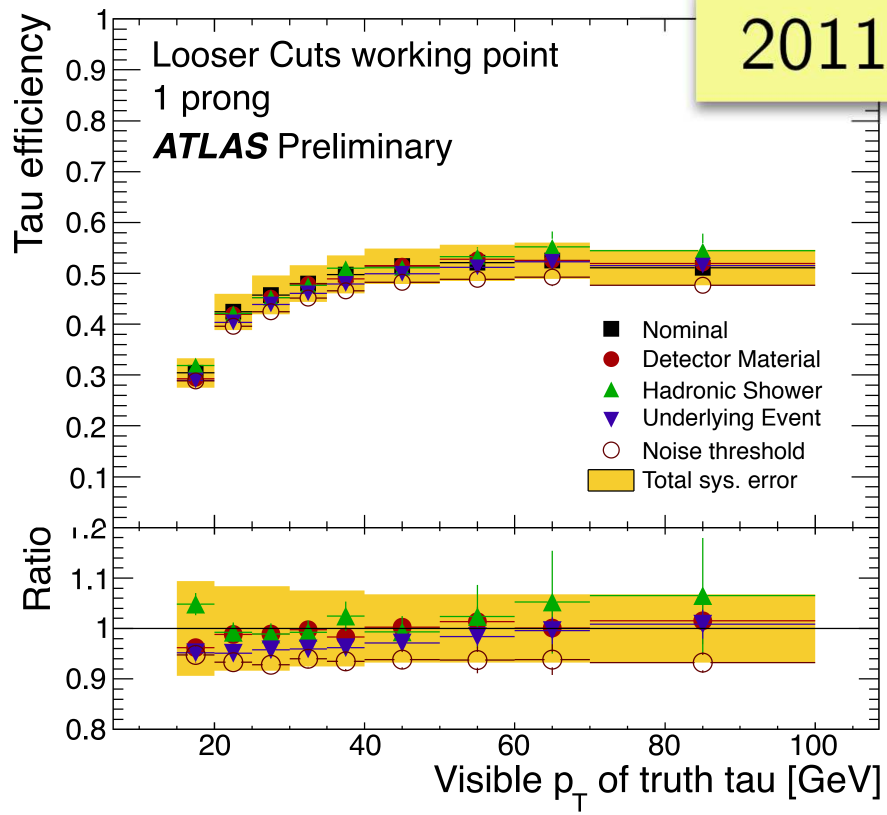
Dominant systematics

- $\tau_{\rm h}$ energy scale 11%
- $\tau_{\rm h}$ efficiency 8.6%
- μ efficiency 8.6%
- e efficiency 3-10%
- acceptance 3%
- luminosity 3.4%

"Measurement of the $Z\to\tau\tau$ cross section in pp collisions at sqrt(s)= 7 TeV with the ATLAS detector" [arXiv:1108.2016]

First systematic recommendations





2011

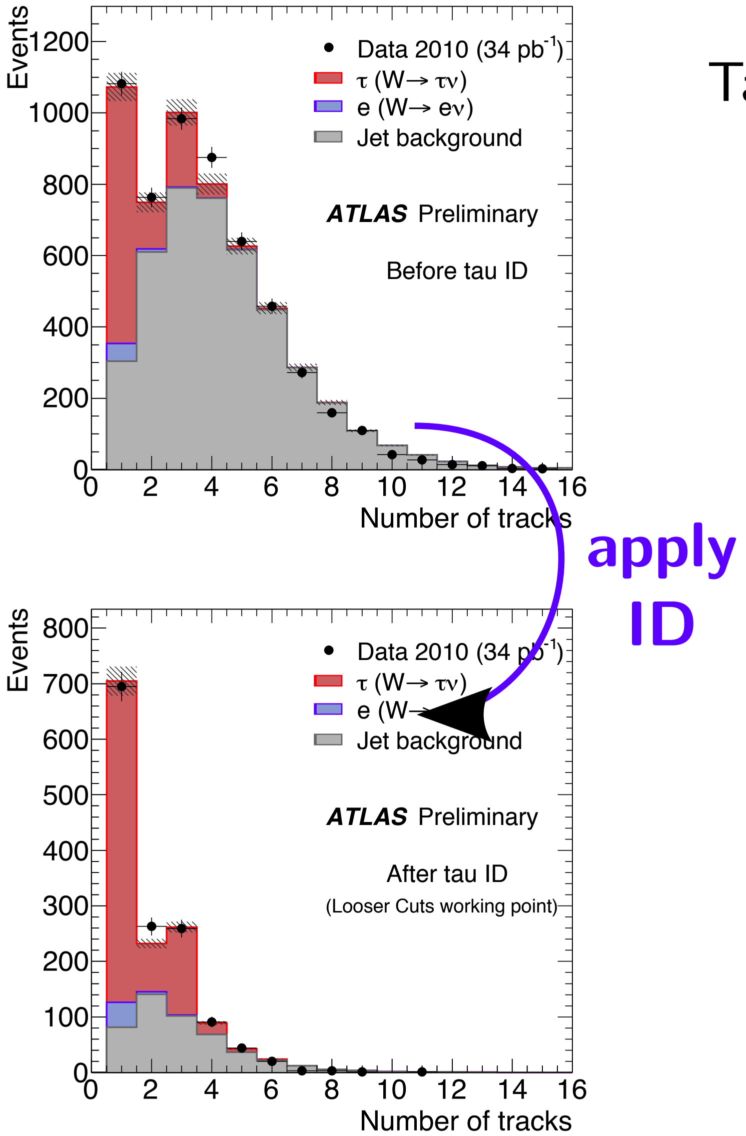
- Systematic uncertainties estimated with dedicated Monte Carlo with shifts in UE, hadronization, and detector-related effects.
- The efficiency measurement has been superseded with data-driven measurements from $Z \rightarrow \tau\tau$ and $W \rightarrow \tau\nu$ tag-and-probe.

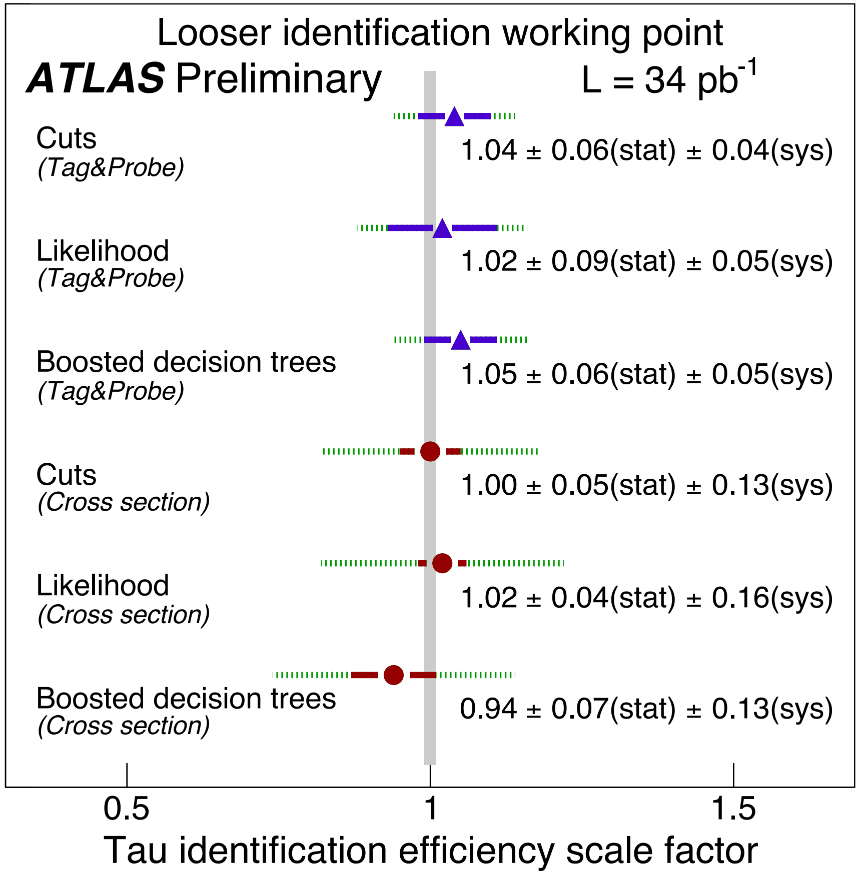
[ATLAS-CONF-2011-077]

$W\to\tau\nu$ tag-and-probe

2011

Tag jet + MET events, probe for tau.

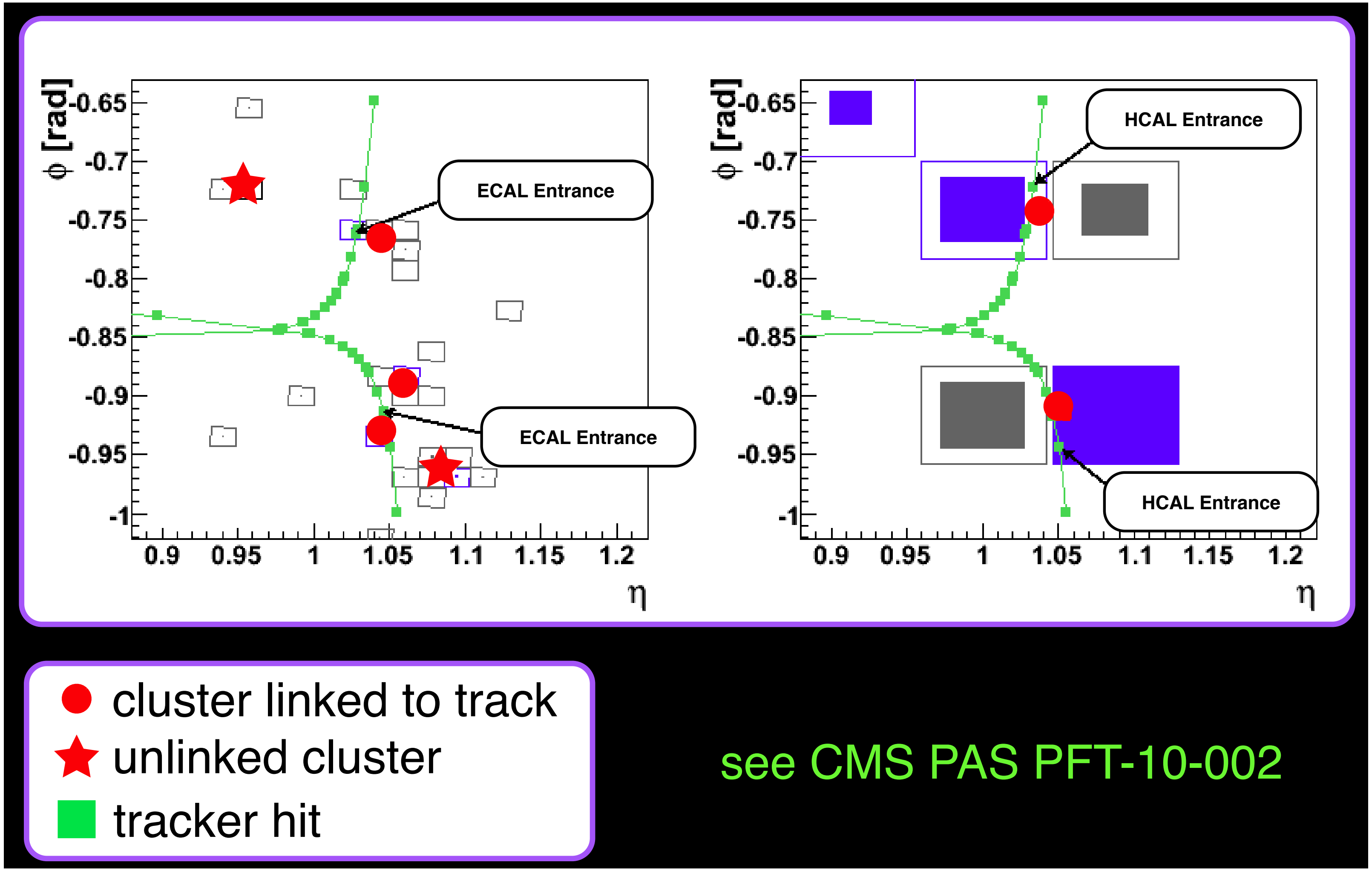




"Measurement of hadronic tau identification efficiency with $W\to\tau\nu$ events" [ATLAS-CONF-2011-093]

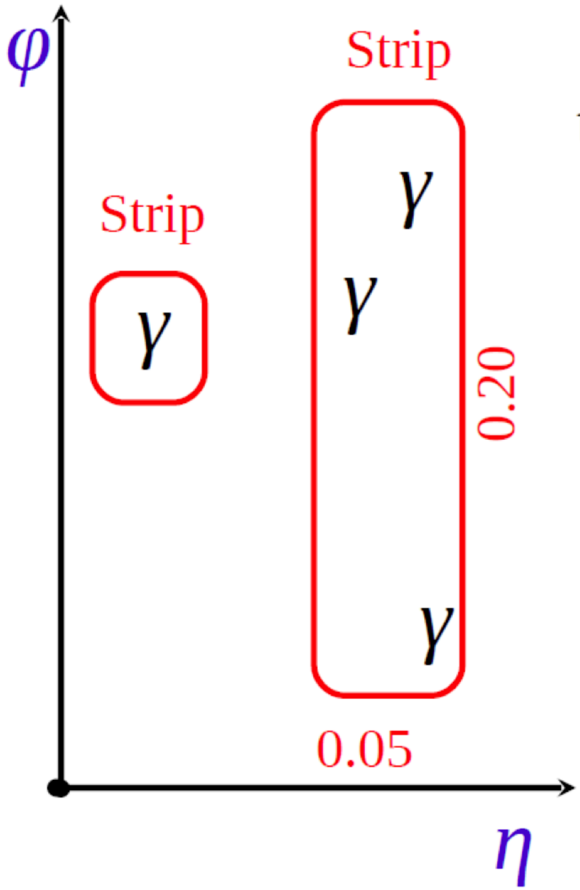
Back up: CMS tau identification

CMS Particle Flow



- Matches track to clusters to form charged and neutral PF objects.
- PF objects are used as input for all CMS tau reconstruction.

CMS: Hadron Plus Strip (HPS)



Build all possible taus
that have a 'tau-like'multiplicity
from the seed jet

π^+

$\pi^+ \pi^0$

$\pi^+ \pi^+ \pi^-$

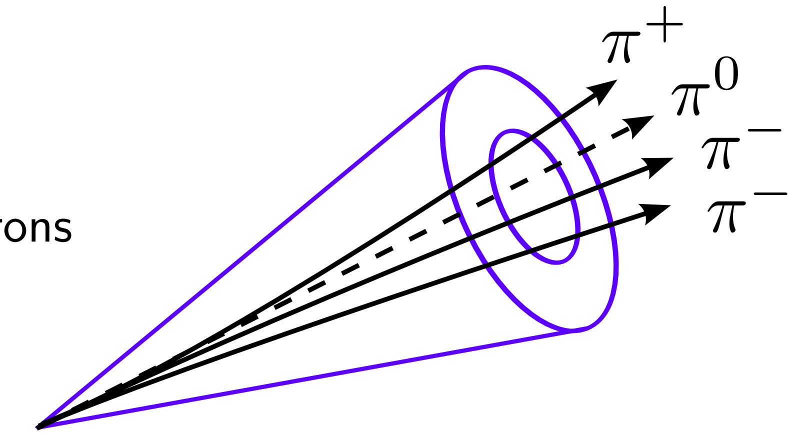
tau that is 'most isolated'
with compatible m_{vis}
is the final tau candidate
associated to the seed jet

Discrimination with calorimeter based isolation $\Delta R < 0.5$.

[CMS PAS TAU-11-001]

CMS: Tau Neural Classifier (TaNC)

- Uses a ***shrinking core-cone***:
  - $\Delta R(\text{photons}) < 0.15$ for photons
  - $\Delta R(\text{charged}) < (5\ \text{GeV})/E_{\text{T}}$ for charged hadrons
  - $\Delta R(\text{charged}) < \Delta R(\text{isolation}) < 0.5$



- Immediately discarded if the candidate doesn't match an expected tau decay mode.

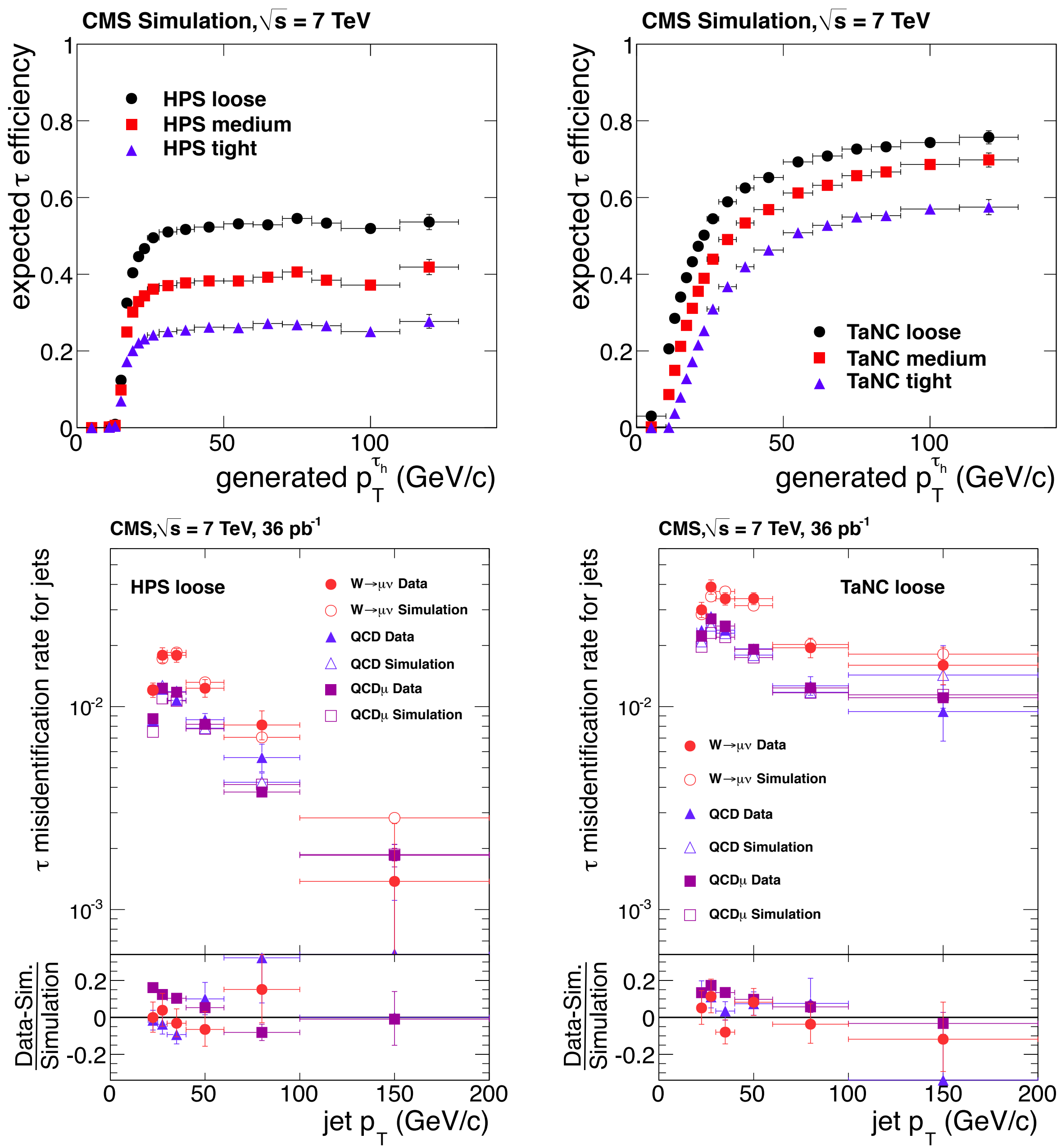
Decay mode	Resonance	Mass (MeV/c^2)	Branching fraction (%)
$\tau^- \to h^- \nu_\tau$			11.6%
$\tau^- \to h^- \pi^0 \nu_\tau$	ρ^-	770	26.0%
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	a_1^-	1200	9.5%
$\tau^- \to h^- h^+ h^- \nu_\tau$	a_1^-	1200	9.8%
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8%

- Dedicated Neural-net classifier for each decay mode

[CMS PAS TAU-11-001]

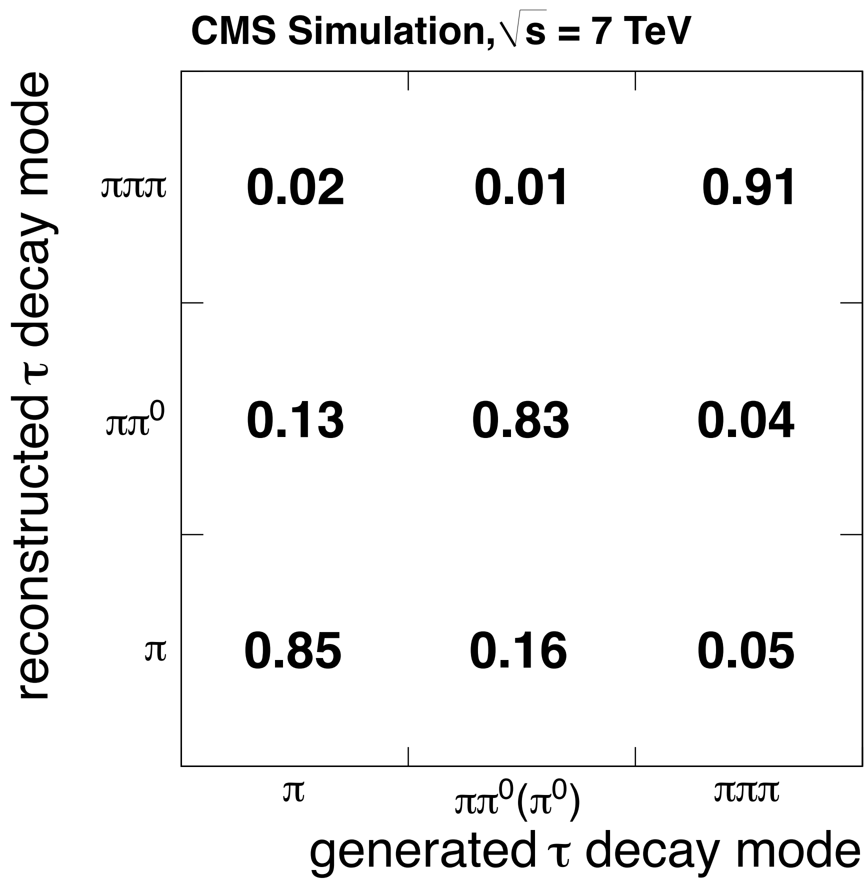
CMS Performance

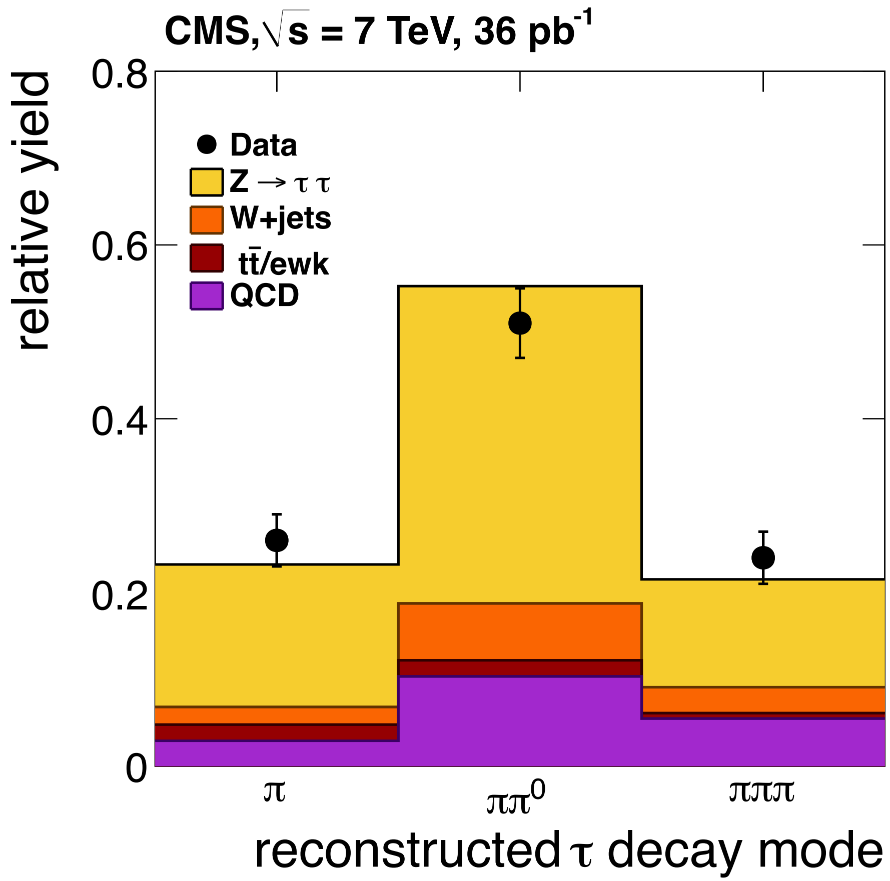
- Not trivial to compare ATLAS and CMS tau performance because we bin fake-rates in N(track) instead of categorizing the decay mode.



[CMS PAS TAU-11-001]

CMS decay mode ID





[CMS PAS TAU-11-001]

Calorimeter granularity

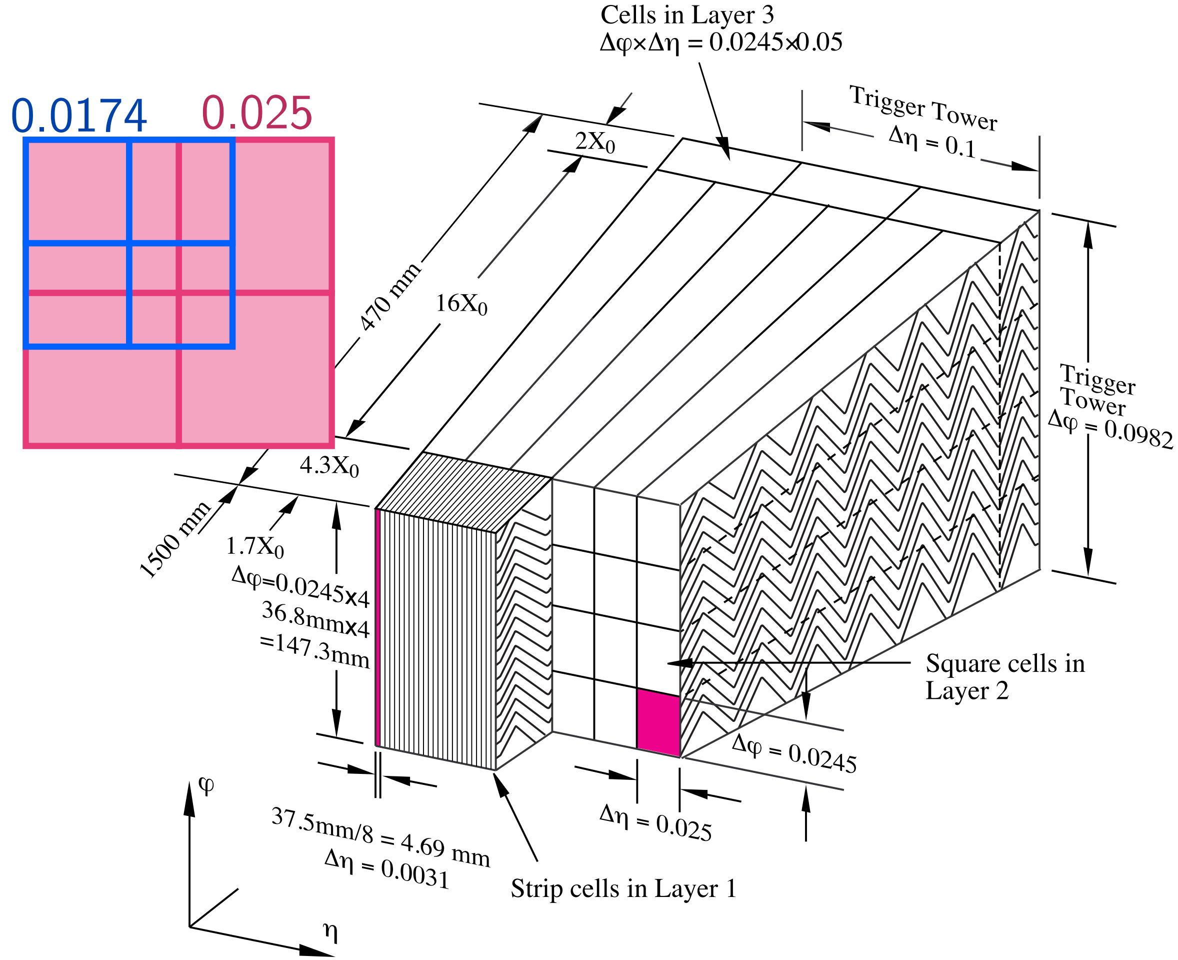
ATLAS

- $B = 2.0$ T
- $\Delta\eta \times \Delta\phi =$ 0.025×0.0245
- R = 0.4 anti-k_{T} topo-jets

CMS

- $B = 3.8$ T
- $\Delta\eta \times \Delta\phi =$ 0.0174×0.0174
- R = 0.5 anti-k_{T} PF-jets

ATLAS Barrel EM Calorimeter



Granularity could fundamentally limit our capacity to reconstruct sub-structure / π^0s.

Back up: ATLAS Charged Higgs

ATLAS

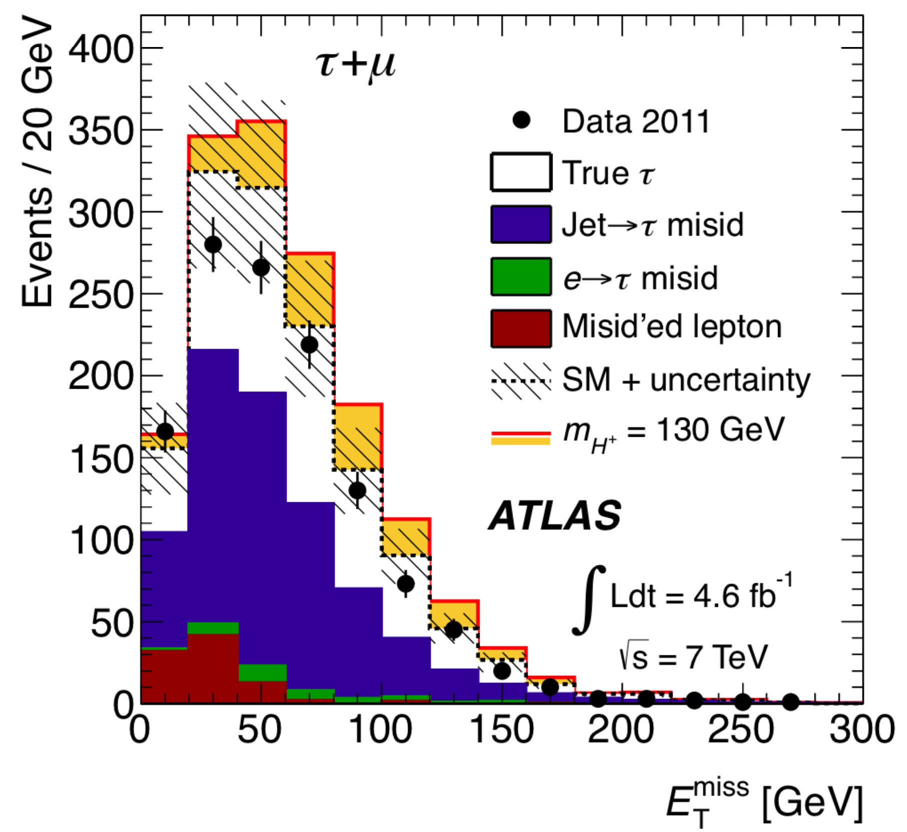
Charged Higgs: $bbl\tau_h$

ATLAS

$$t\bar{t} \rightarrow b\bar{b}W^{\mp}H^{\pm} \rightarrow b\bar{b}(l^{\mp}\nu)(\tau_h\nu)$$

Event selection

- single-lepton trigger
- exactly one isolated electron or muon, $p_{\mathrm{T}}(e) > 25$ GeV, $p_{\mathrm{T}}(\mu) > 20$ GeV
- exactly one τ_h, $p_{\mathrm{T}}(\tau_h) > 20$ GeV
- opposite sign
- N(jets) ≥ 4, $p_{\mathrm{T}}(\text{jet}) > 20$ GeV, at least one jet b-tagged
- $\sum p_{\mathrm{T}}(\text{tracks at PV}) > 100$ GeV



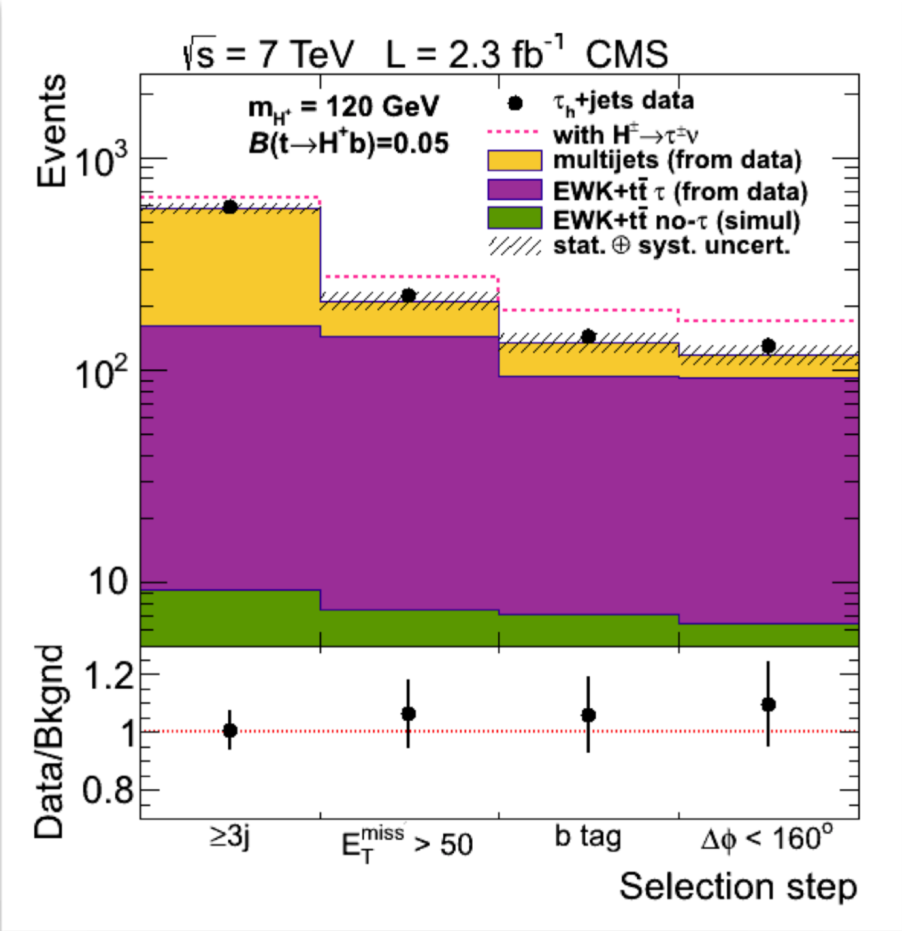
- Cut on $\sum p_{\mathrm{T}}$ is a pile-up robust way to suppress the multijet background.
- Tau mis-ID probabilities are measured in data using W+jets events, and then applied to fake τ_h in simulation.

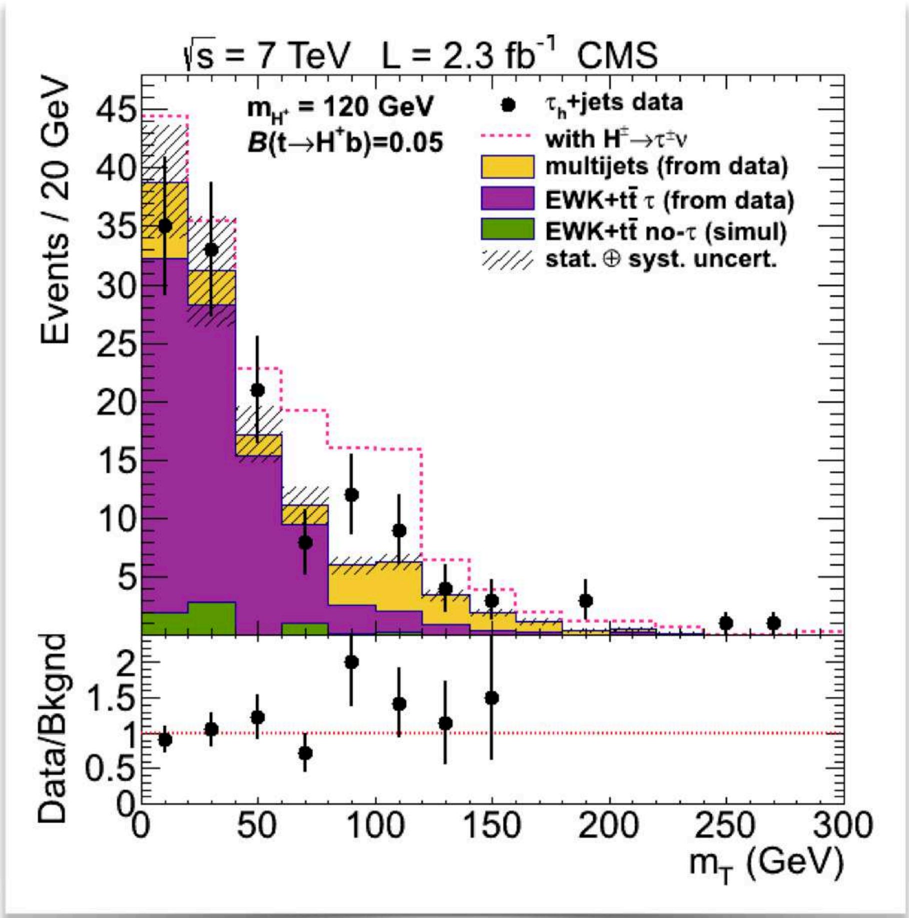
[arxiv:1204.2760]

Back up: CMS Charged Higgs

Charged Higgs

CMS



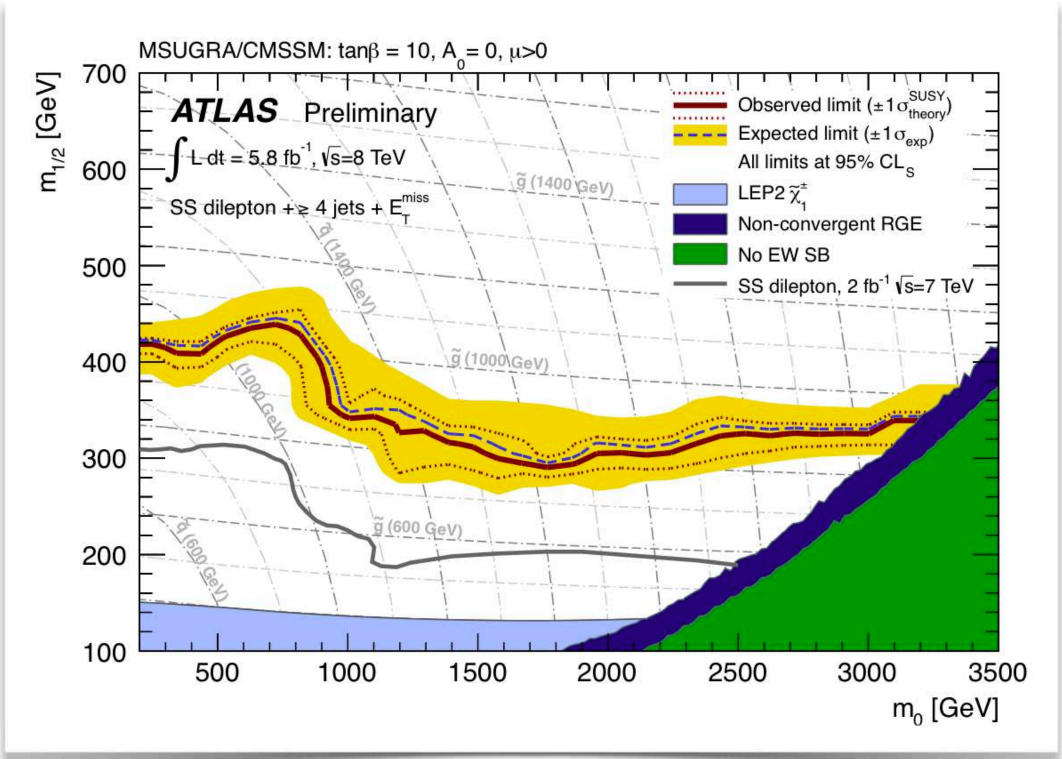


[arvix:1205.5736]

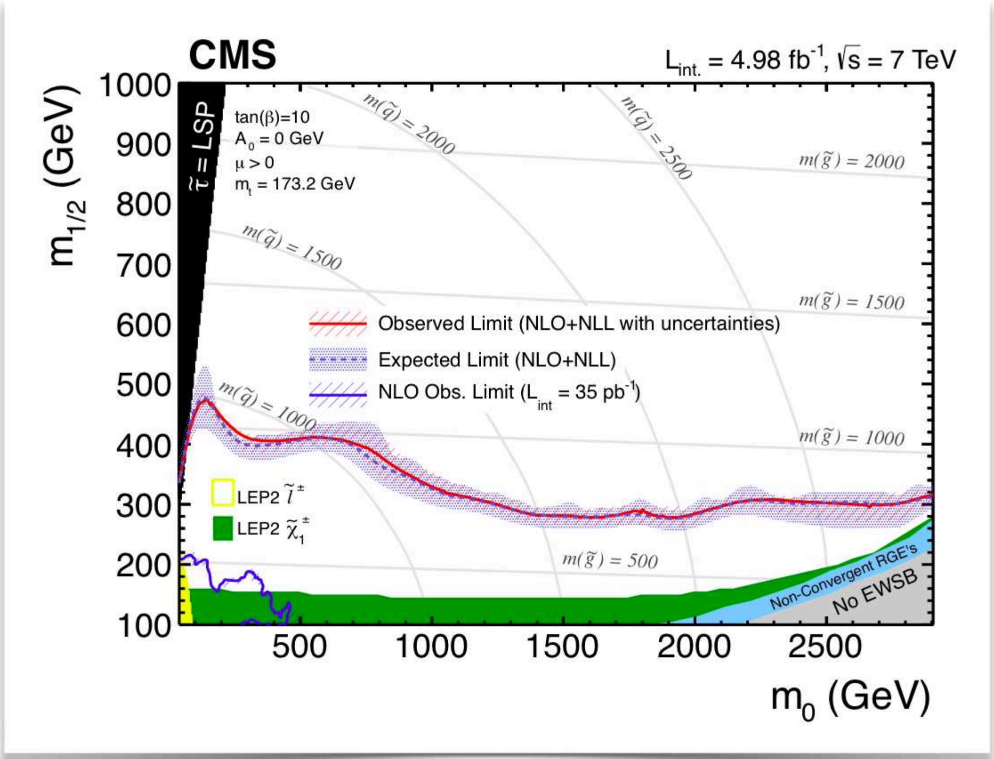
Back up:
ATLAS SUSY

ATLAS: Same-sign dileptons + jets + E_T^{miss}

ATLAS



CMS



- Select SS ee, $\mu\mu$, $e\mu$ + 4 jets + E_T^{miss} > 150 GeV
- ATLAS result does not use hadronic taus.

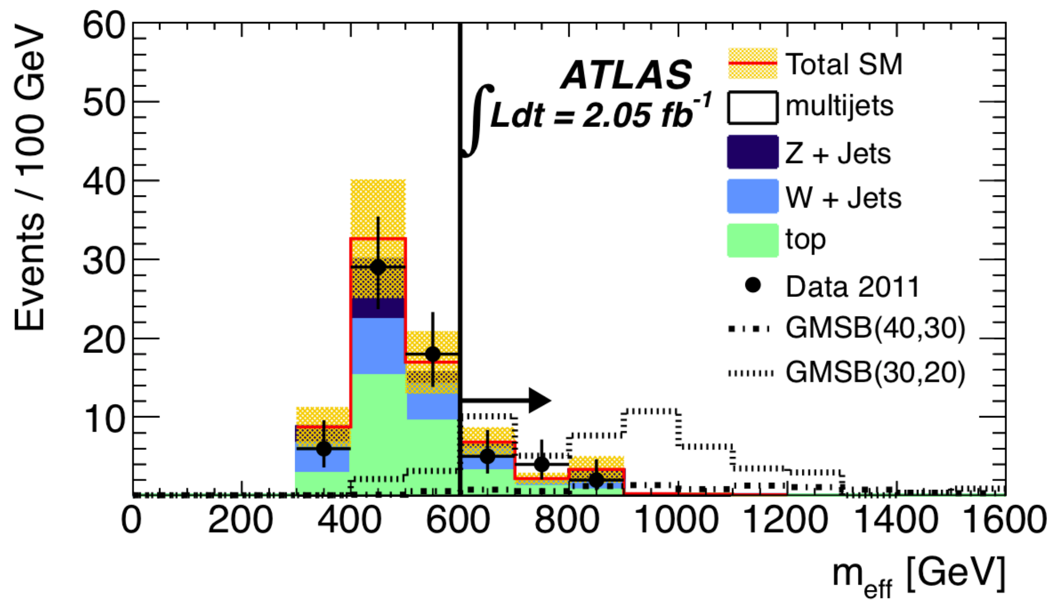
[ATLAS-CONF-2012-105, arxiv:1206.3949]

SUSY: E_T^{miss} + jets + taus

ATLAS

Event selection

- trigger: $p_T(\text{jet}) > 75$ GeV $+ E_T^{miss} > 45$ GeV
- $N(\text{jets}) \geq 2$, $p_T(\text{jet}_1) > 130$ GeV, $p_T(\text{jet}_2) > 30$ GeV
- $E_T^{miss} > 130$ GeV
- $N(\tau_h) = 1$ or 2, $p_T(\tau_h) > 20$ GeV
- no other τ_h or leptons



$\geq 1\tau_h$ channel

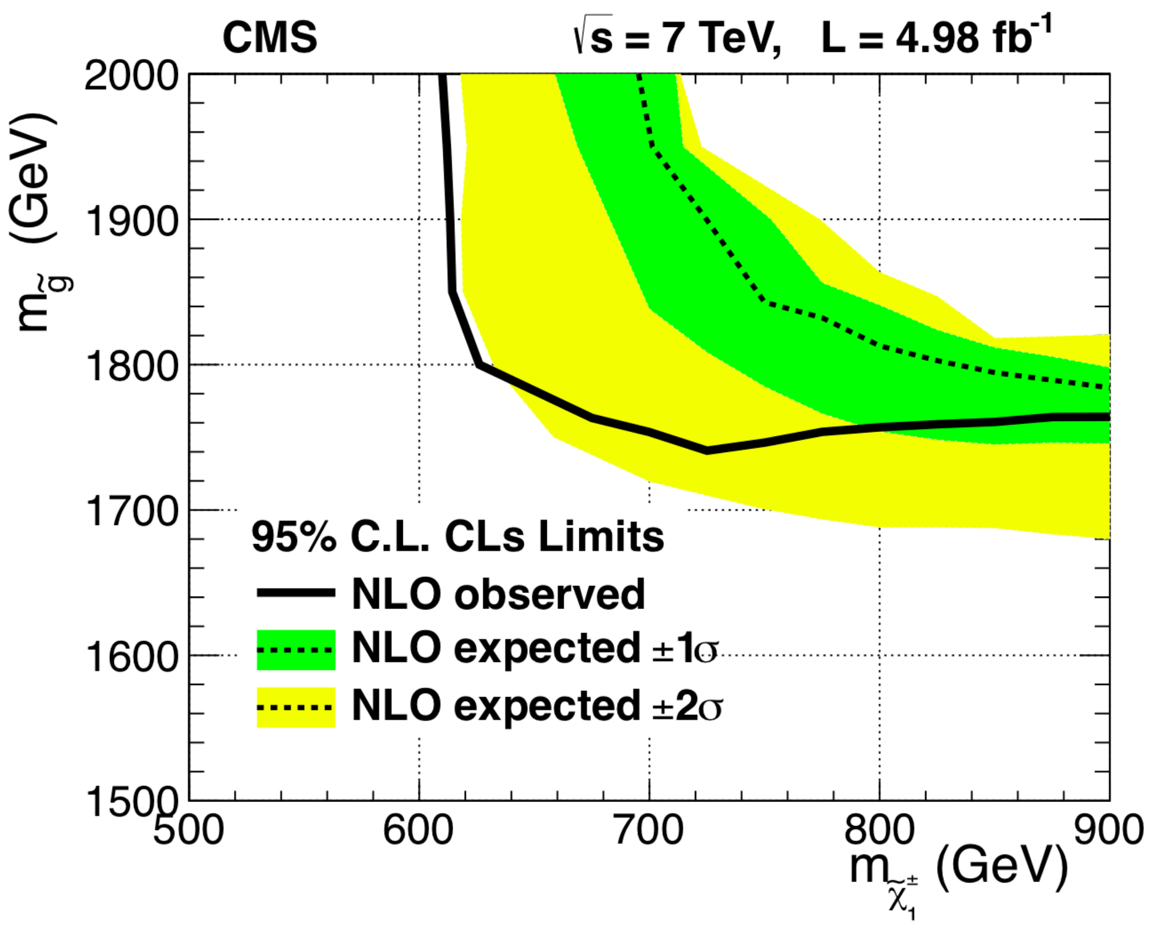
- $\Delta\phi(p_T^{miss}, \text{jet}_{1,2}) > 0.3$
- $m_{\text{eff}} > 600$ GeV
- $E_T^{miss} / m_{\text{eff}} > 0.25$
- $m_T > 110$ GeV

[arvix:1204.3852]

Back up:
CMS SUSY

SUSY: multi-lepton

CMS



- Deviation in obs. limit from slight excess in category:

  4lep($1\tau_h$), $E_T^{miss} > 50$ GeV, $H_T < 200$ GeV, no Z

  Expect 0.59 ± 0.17 and observed 3 events.

[arxiv:1106.0933, CMS PAS SUS-11-013, arvix:1204.5341]

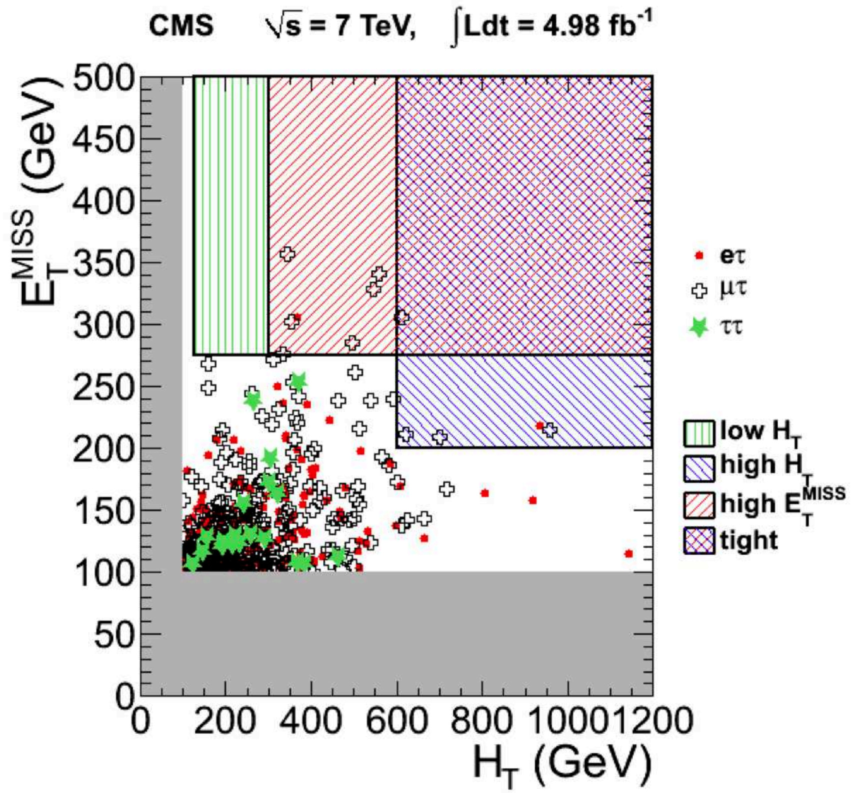
SUSY: Opposite-sign dileptons + jets + E_T^{miss}

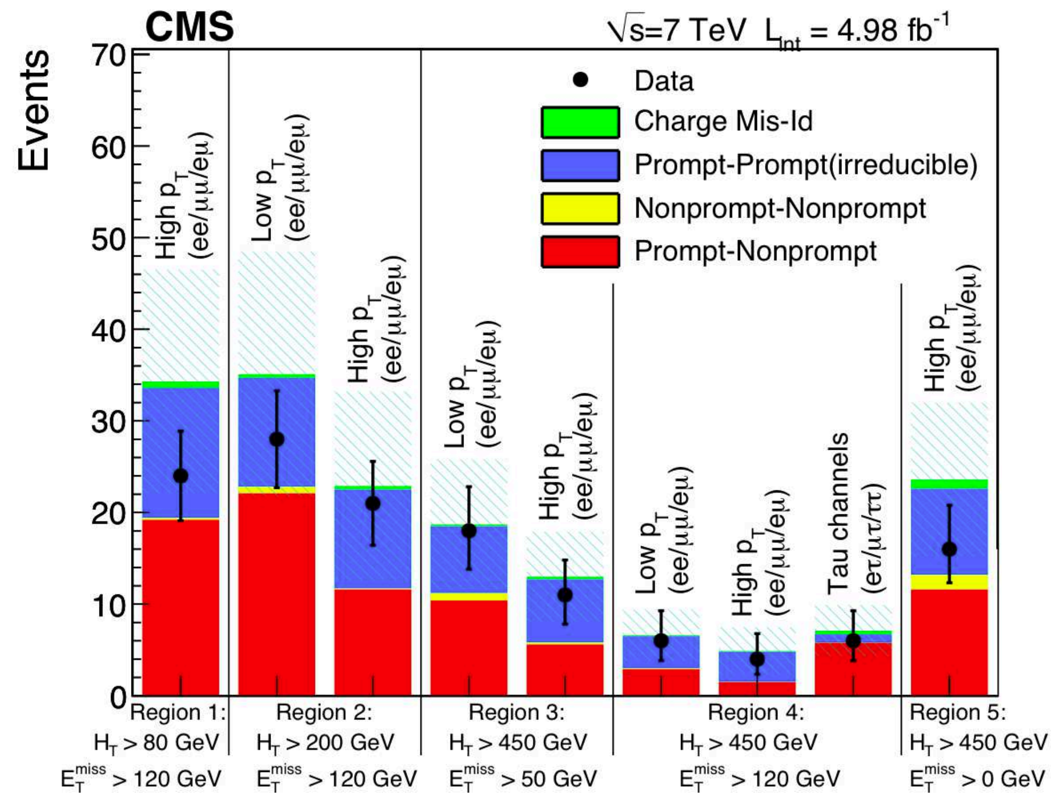
CMS

Event selection

- OS ee, $e\mu$, $\mu\mu$, $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$
- $N(\text{jets}) \geq 2$, $p_T(\text{jet}) > 30$ GeV
- higher H_T and E_T^{miss} thresholds than SS
- for ee, $\mu\mu$, veto if $m_{ll} = 76$-106 GeV

- τ_h fake factor method for predicting W+jets
- sets CMSSM exclusion



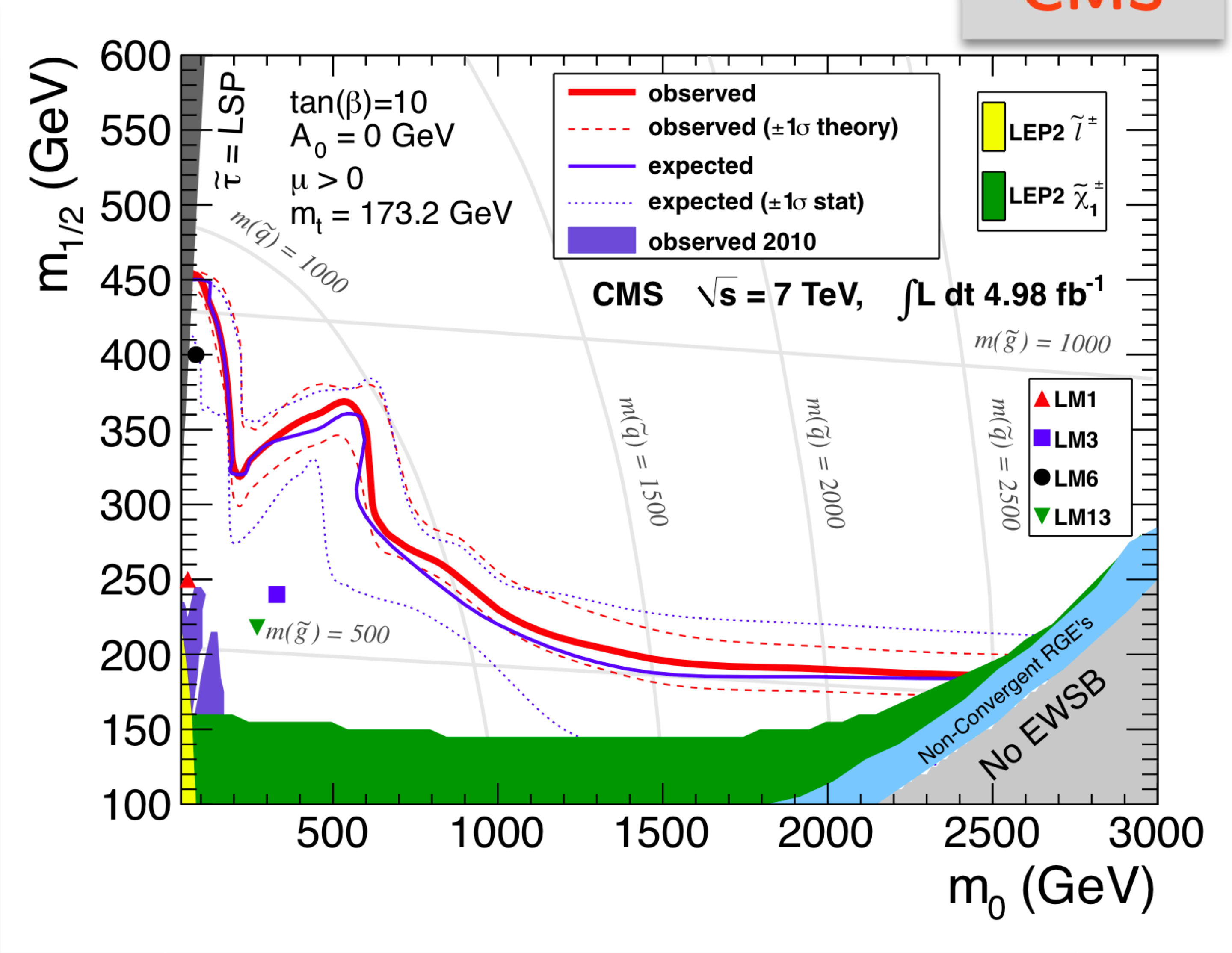


[arxiv:1206.3949]

SUSY: Opposite-sign dileptons + jets + E_T^{miss}

CMS

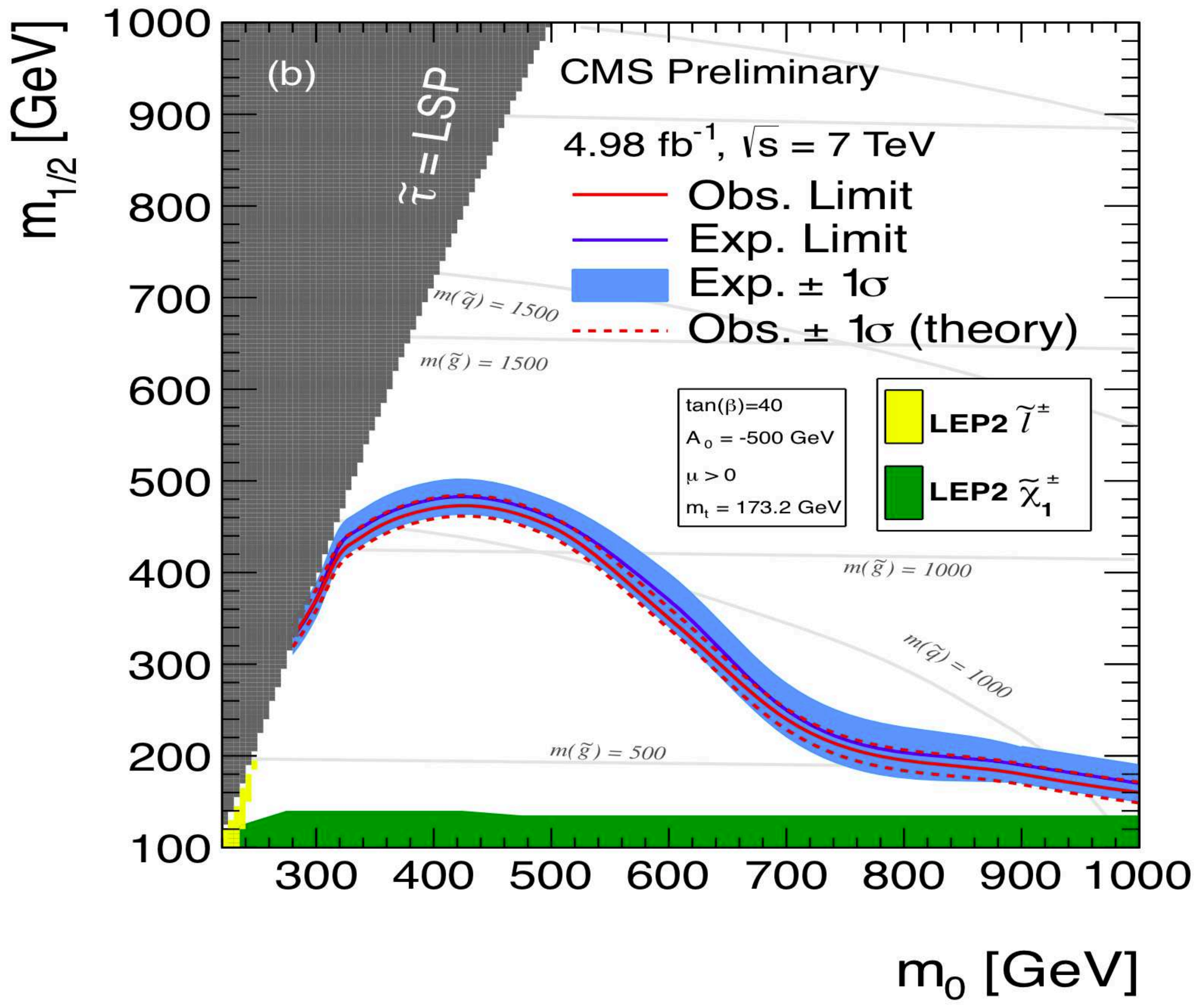
- Similar methods to the same-sign search
- Slightly less sensitive



[arxiv:1206.3949]

SUSY: E_T^{miss} + jets + taus

CMS



[CMS PAS SUS-12-004]

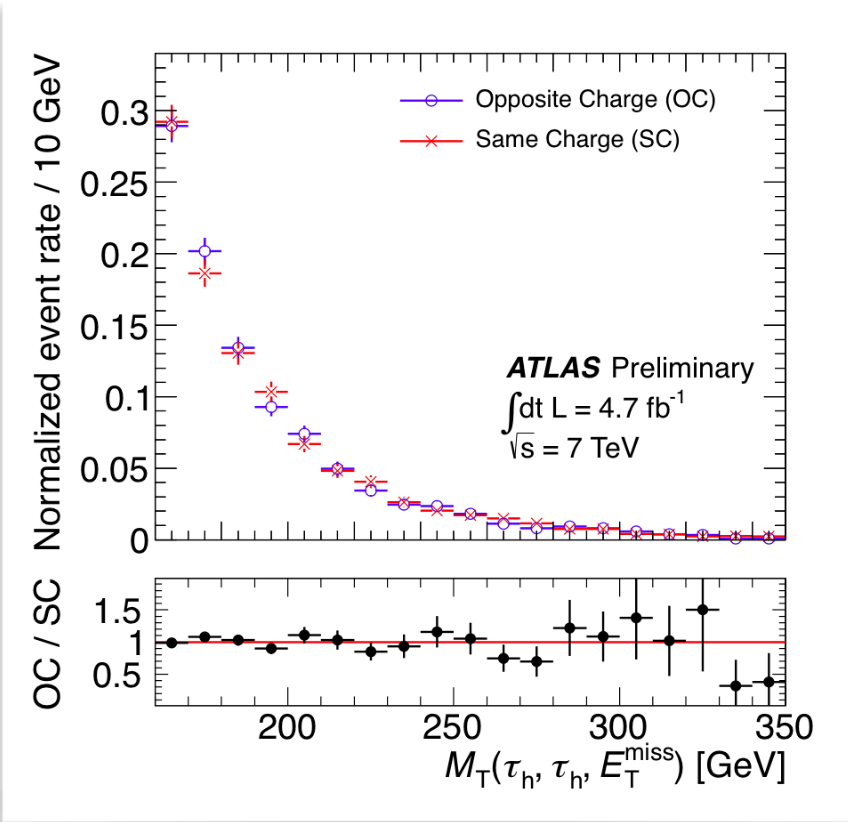
Back up:
ATLAS Exotics

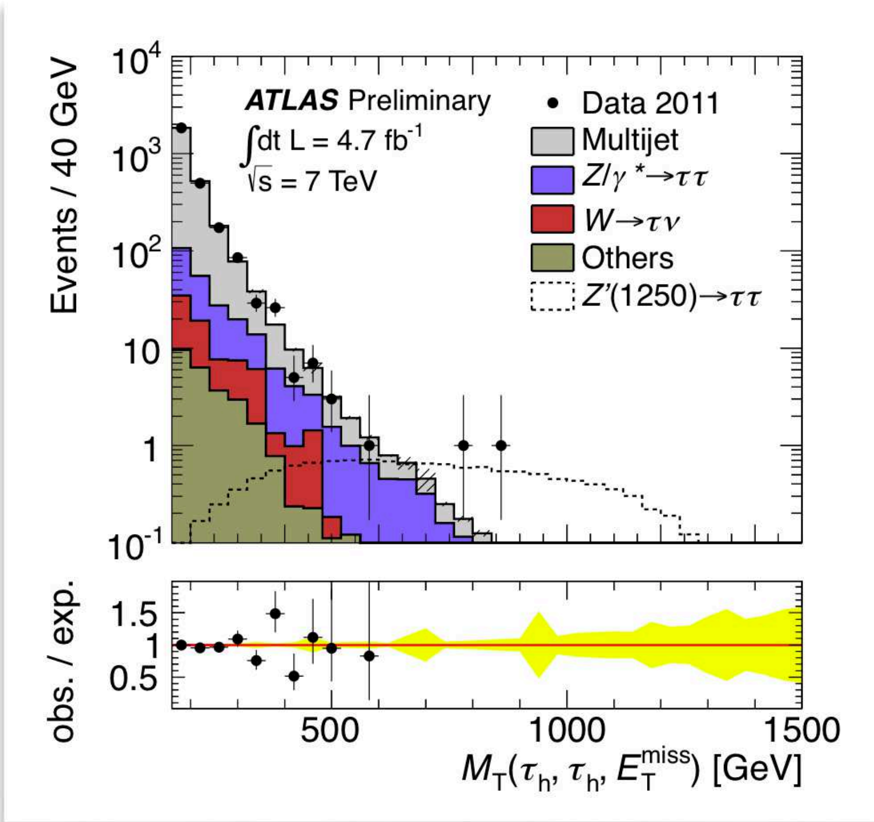
Data-driven multijet

ATLAS

Fit same-sign (SS) data with dijet function:

$$f(M_T|p_0,p_1,p_2) = p_0 \cdot M_T^{\,p_1+p_2 \log M_T}.$$





- OS/SS shapes agree well
- normalize in OS sideband with 200 < M_T < 250 GeV

[ATLAS-CONF-2012-067]

Multijet background estimation

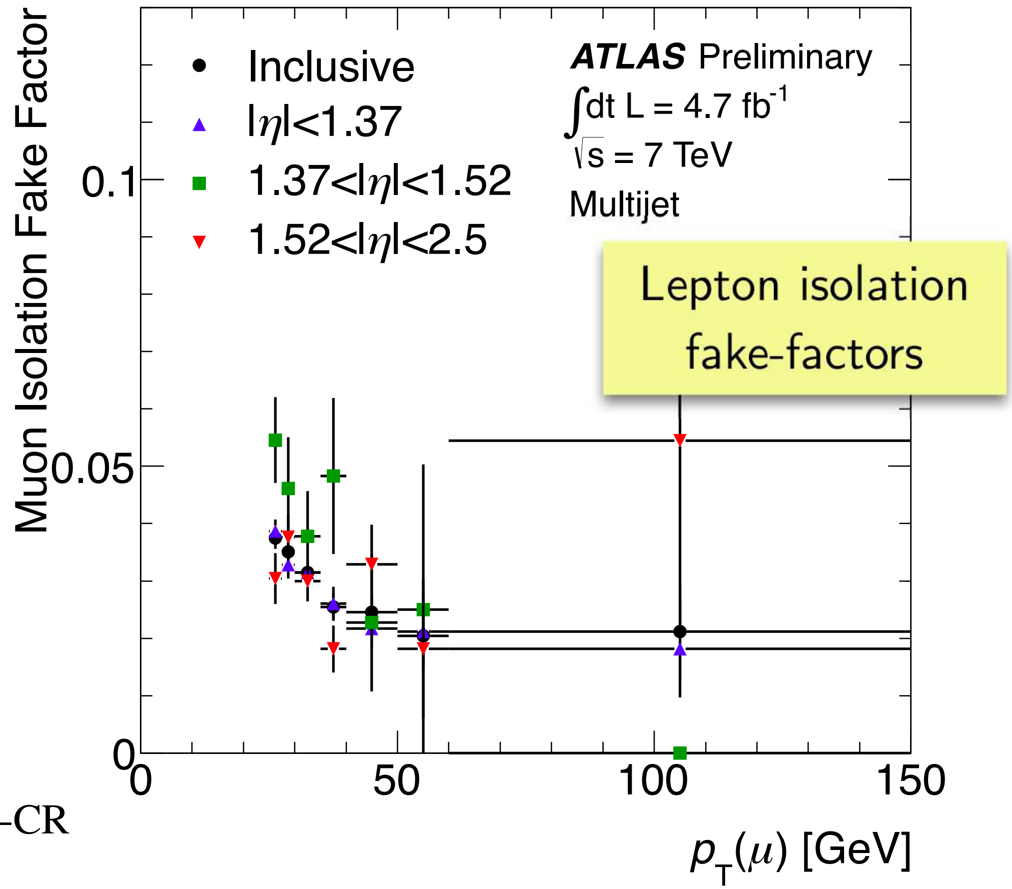
Multijet control region

- no isolation
- $E_{\mathrm{T}}^{\mathrm{miss}} < 30$ GeV
- $m_{\mathrm{T}}(\mu, E_{\mathrm{T}}^{\mathrm{miss}}) < 30$ GeV

- In the control region, divide leptons into pass and fail isolation.

- Define fake factor:

$$f_{\mu\text{–iso}}(p_{\mathrm{T}}, \eta) \equiv \left. \frac{N^{\text{pass } \mu\text{–iso}}(p_{\mathrm{T}}, \eta)}{N^{\text{fail } \mu\text{–iso}}(p_{\mathrm{T}}, \eta)} \right|_{\text{multijet–CR}}$$



- Predict the number of multijet events:

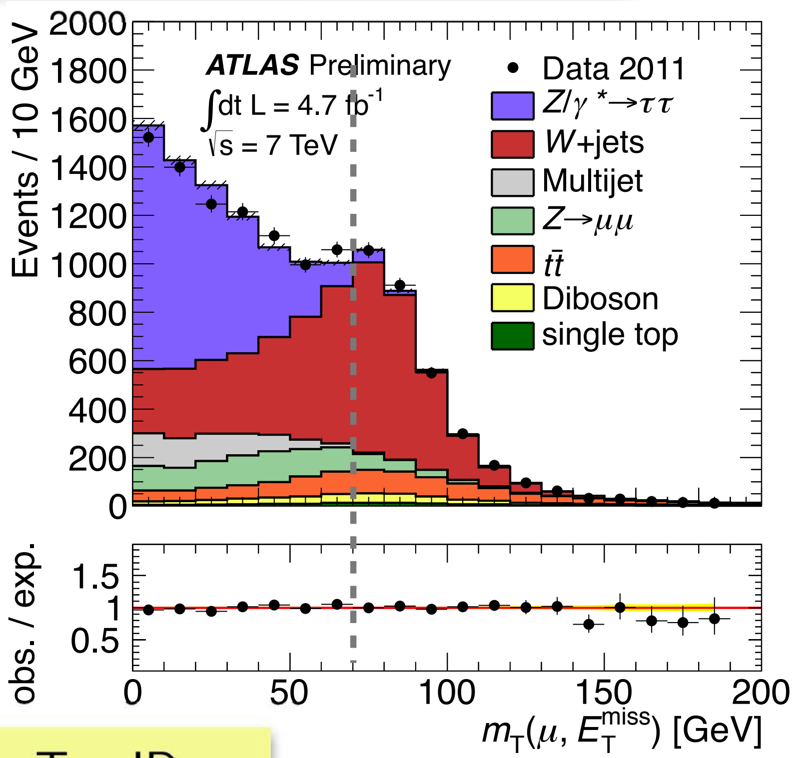
$$N_{\text{multijet}}(p_{\mathrm{T}}, \eta, x) = f_{\mu\text{–iso}}(p_{\mathrm{T}}, \eta) \cdot N^{\text{fail } \mu\text{–iso}}_{\text{multijet}}(p_{\mathrm{T}}, \eta, x)$$

$$= f_{\mu\text{–iso}}(p_{\mathrm{T}}, \eta) \cdot \left(N^{\text{fail } \mu\text{–iso}}_{\text{data}}(p_{\mathrm{T}}, \eta, x) - N^{\text{fail } \mu\text{–iso}}_{\text{MC}}(p_{\mathrm{T}}, \eta, x) \right)$$

W+jet background estimation

W+jet control region

- $m_T(\mu, E_T^{miss}) = 70\text{-}200$ GeV
- isolated lepton

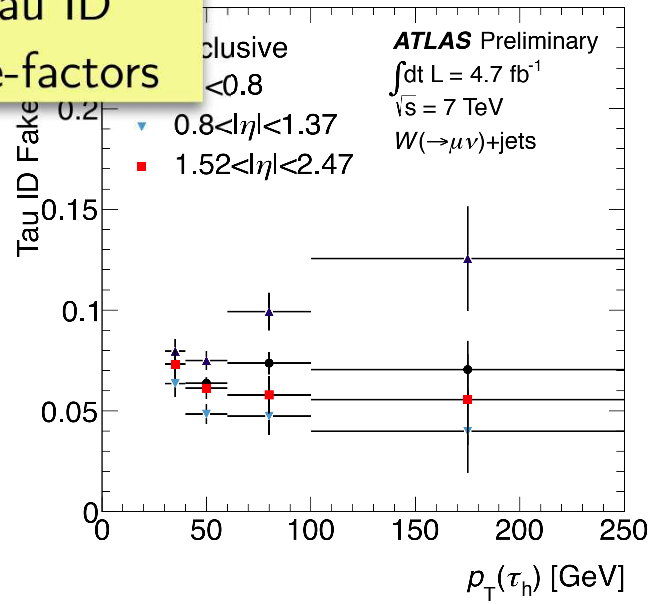


- In a W+jet control region, divide tau candidates into pass and fail identification.

- Define fake factor:

$$f_\tau(p_T, \eta) \equiv \left. \frac{N^{\text{pass } \tau\text{–ID}}(p_T, \eta)}{N^{\text{fail } \tau\text{–ID}}(p_T, \eta)} \right|_{\text{W–CR}}$$

Tau ID fake-factors

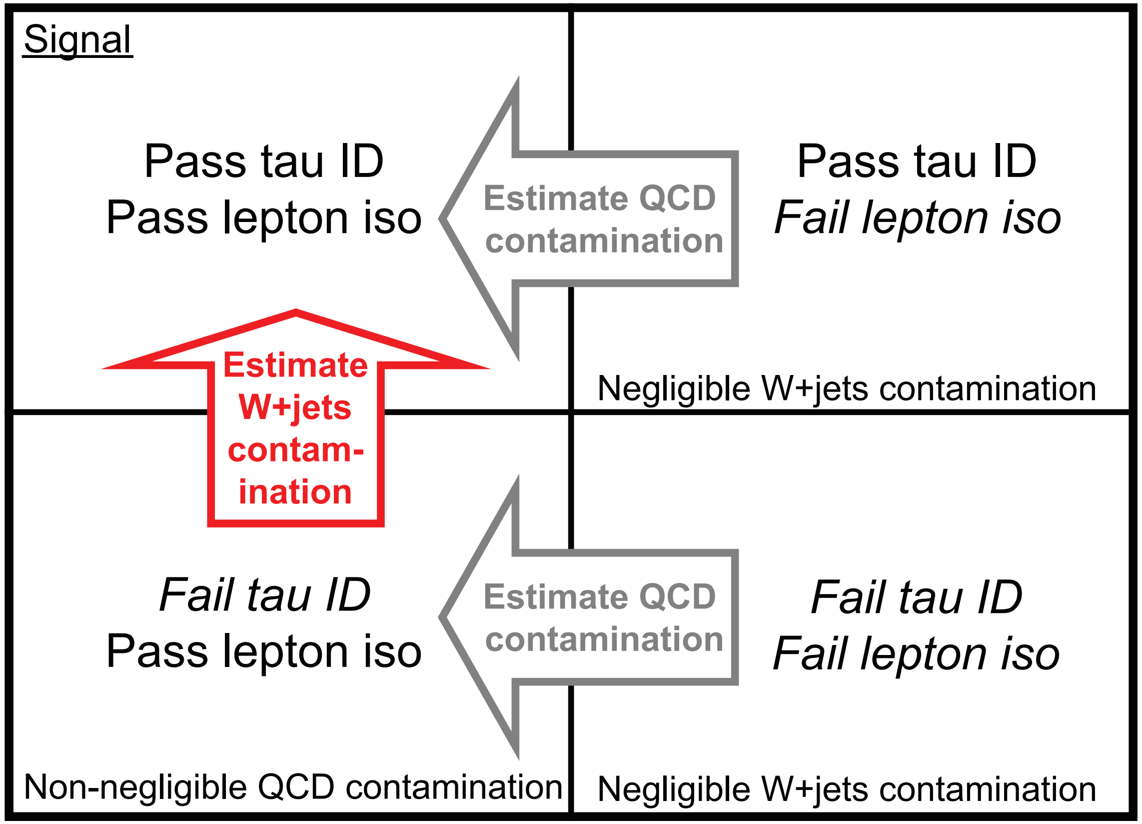


- Predict the number of W/Z+jet events:

$$N_{W/Z\text{+jet}}(p_T, \eta, x) = f_\tau(p_T, \eta) \cdot N^{\text{fail } \tau\text{–ID}}_{W/Z\text{+jet}}(p_T, \eta, x)$$

$$= f_\tau(p_T, \eta) \cdot \left(N^{\text{fail } \tau\text{–ID}}_{\text{data}}(p_T, \eta, x) - N^{\text{fail } \tau\text{–ID}}_{\text{multijet}}(p_T, \eta, x) - N^{\text{fail } \tau\text{–ID}}_{\text{MC}}(p_T, \eta, x) \right)$$

Double fake factor procedure



- The multijet contamination is estimated from the rate of non-isolated leptons, in both the signal region that passes tau ID, and the sample that fails.
- Then, the corrected number of tau candidates failing ID are weighted to predicted the W+jet background.
- This way, *the corrections are small at each step*.

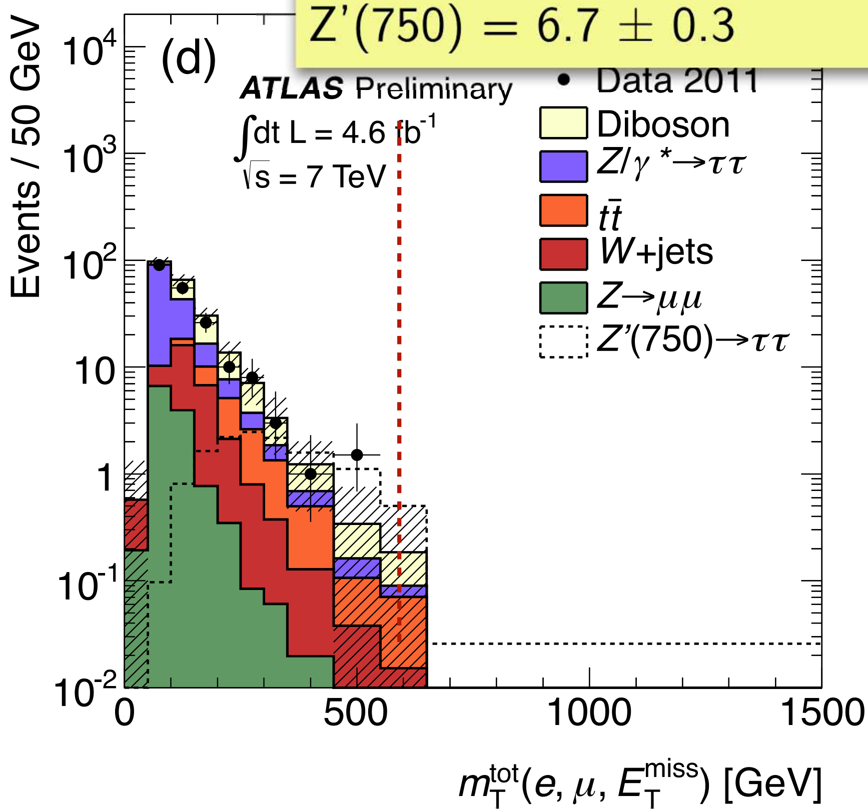
$Z' \to \tau\tau \to e\mu$ overview

Event selection

- isolated e and μ *with* $p_T(\mu) > 25$, $p_T(\tau_h) > 35$ GeV
- oppositesign μ and τ_h
- N(jets) < 2
- $p_\zeta^{vis} < 10$ GeV
- $|\Delta\phi(lead\ lep,\ E_T^{miss})| > 2.6$
- $m_T(e,\ \mu,\ E_T^{miss}) > 350$ GeV

total SM $= 3.6 \pm 0.4$ events

Z'(750) $= 6.7 \pm 0.3$



Dominant systematics

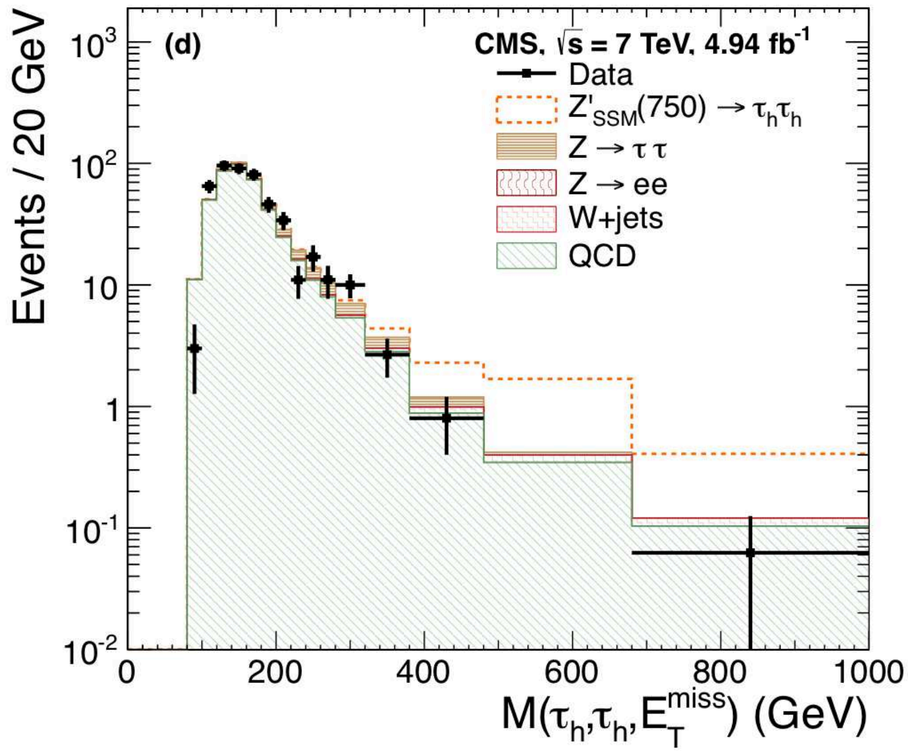
- all object-level systematics are few perecent
- *Statistical* uncert. from limited Monte Carlo $\approx$ 7% background, 3% signal

Back up: CMS Exotics

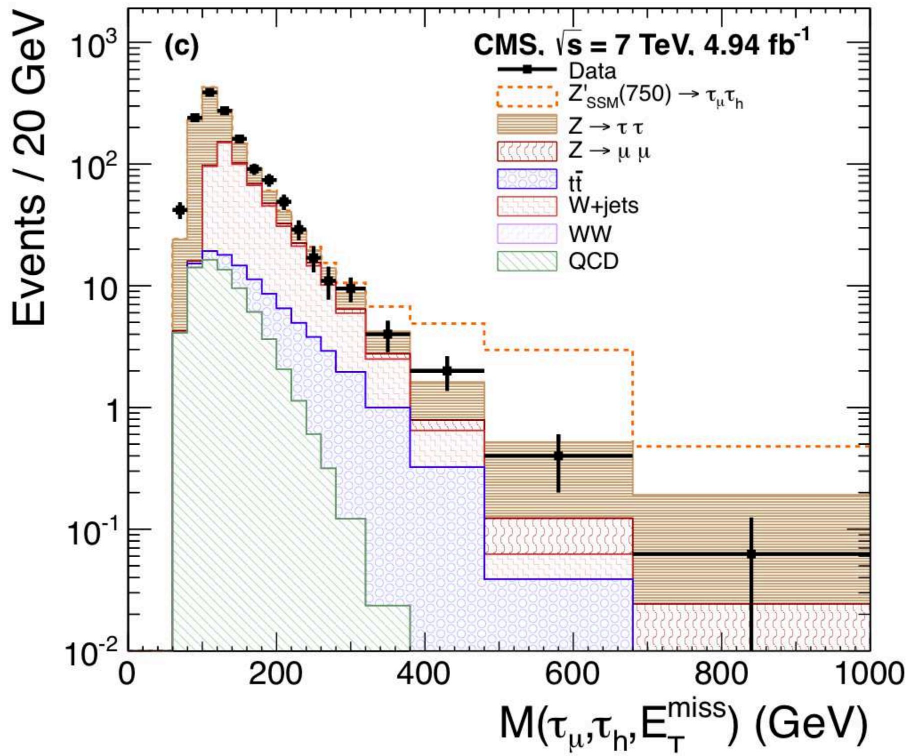
$Z' \rightarrow \tau\tau$

CMS

$Z' \rightarrow \tau\tau \rightarrow \tau_h\tau_h$



$Z' \rightarrow \tau\tau \rightarrow \mu\tau_h$



[arvix:1206.1725]