Searching for new physics in high-mass ditau events at ATLAS

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Outline

1. Introduction
   Questions about the Standard Model, Z', ATLAS
2. Tau lepton physics
   reconstruction, identification, use at ATLAS
3. Search for new physics: Z'$\rightarrow\tau\tau$
   searches with 2011 and 2012 datasets
4. Conclusion

Introduction

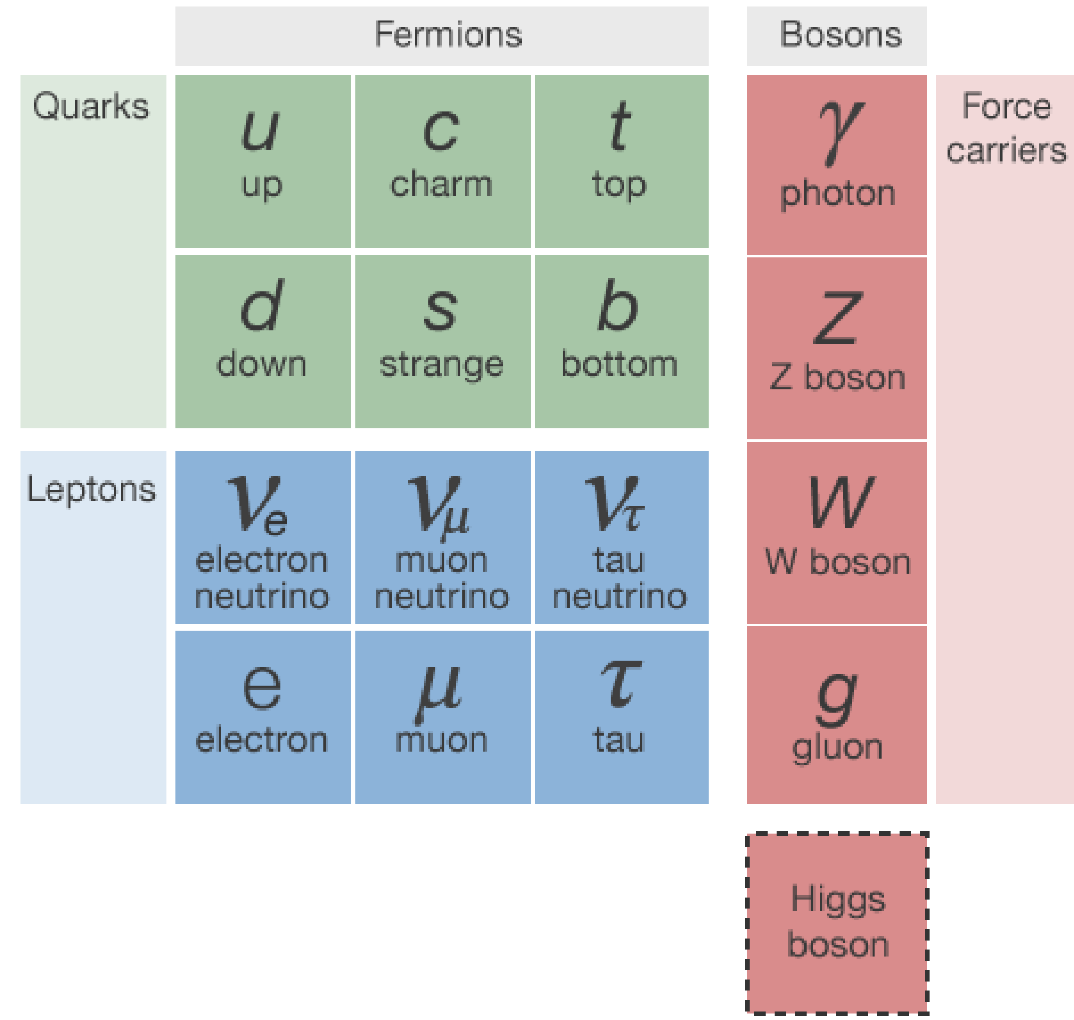
Standard Model

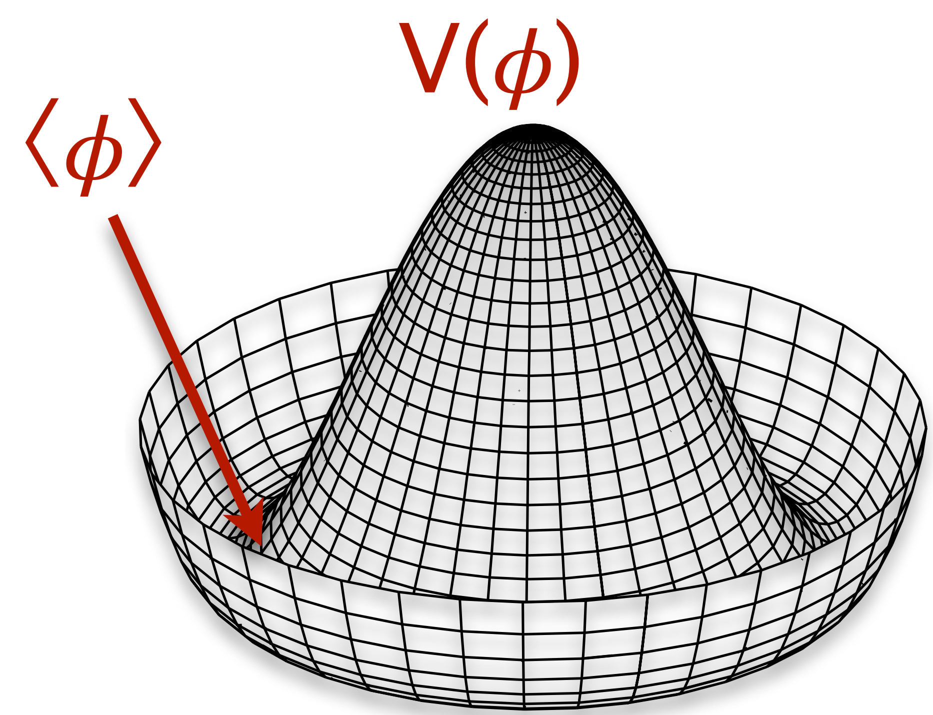
- In QFT, ***fields*** are actually what is fundamental, and particles are localized excitations in the fields.
- ***Gauge symmetries*** determine the character of the forces between fermion fields through gauge bosons.
- The SM gauge group is
$SU(3)_C \times SU(2)_L \times U(1)_Y$

⇓ **Strong force**

⇓ **Higgs mechanism**

EM + weak forces





July 4, 2012
CERN announces the discovery of a new particle by ATLAS and CMS, consistent with the Higgs boson

The New York Times

Late Edition

NEW YORK, THURSDAY, JULY 5, 2012

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With Conservative Voices Within His Party

Physicists Find Elusive Particle Seen as Key to Universe

July 5 cover of the New York Times:
Physicists Find Elusive Particle Seen as Key to the Universe

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**? $Q_{EM} = T_{3L} + Y/2$

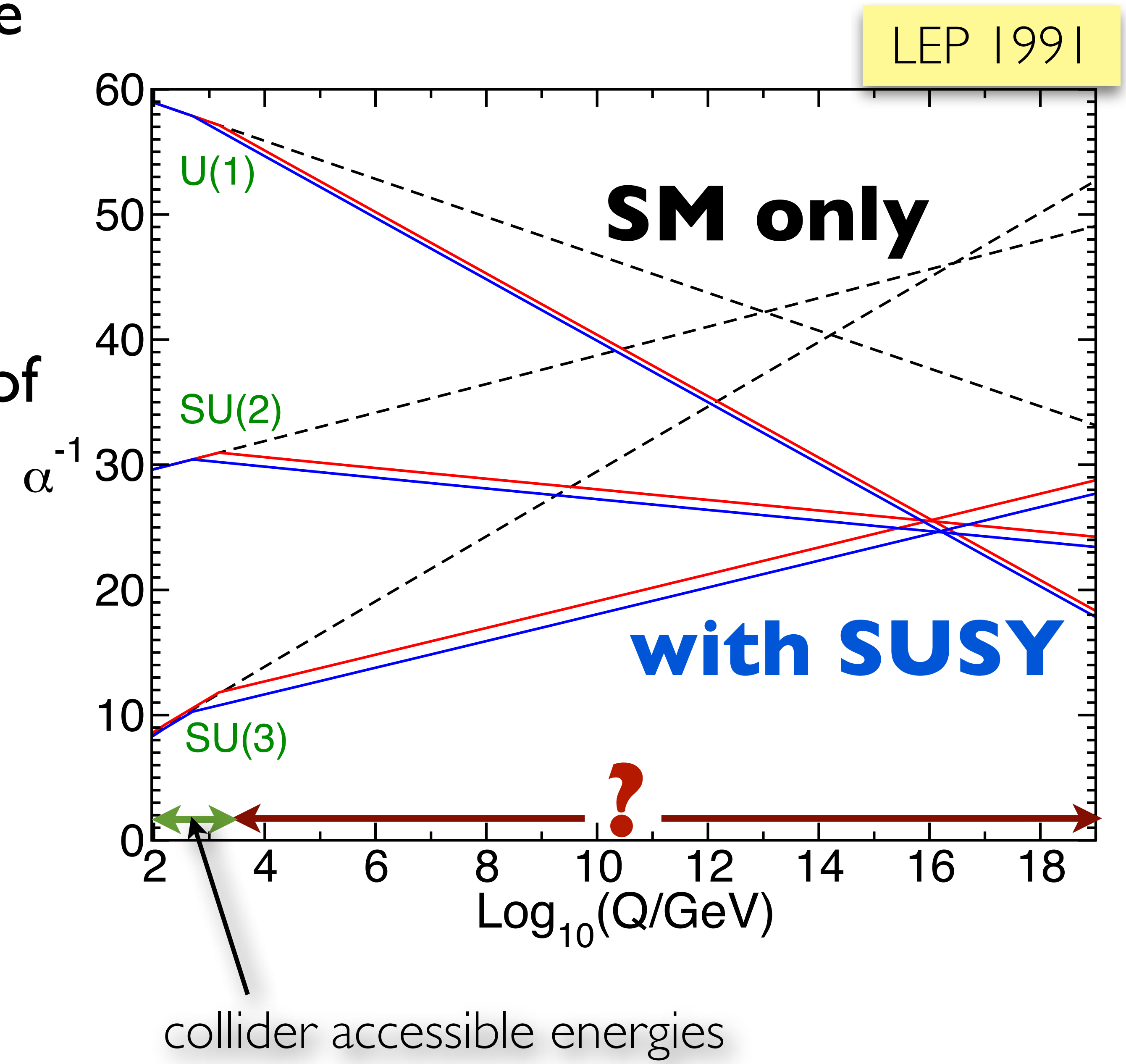
Is it because...

- **the gauge group of Nature is actually bigger?**
- **and the SM is the product of a larger symmetry breaking process than just electroweak symmetry breaking?**
- $SO(10) \rightarrow SU(5) \times U(1)$ Georgi–Glashow
  $SO(10) \rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R$ Pati–Salam
  1974
- e.g. Pati–Salam SO(10): $Q_{EM} = T_{3L} + T_{3R} + 1/2(B - L)$

GUT motivations and Z'

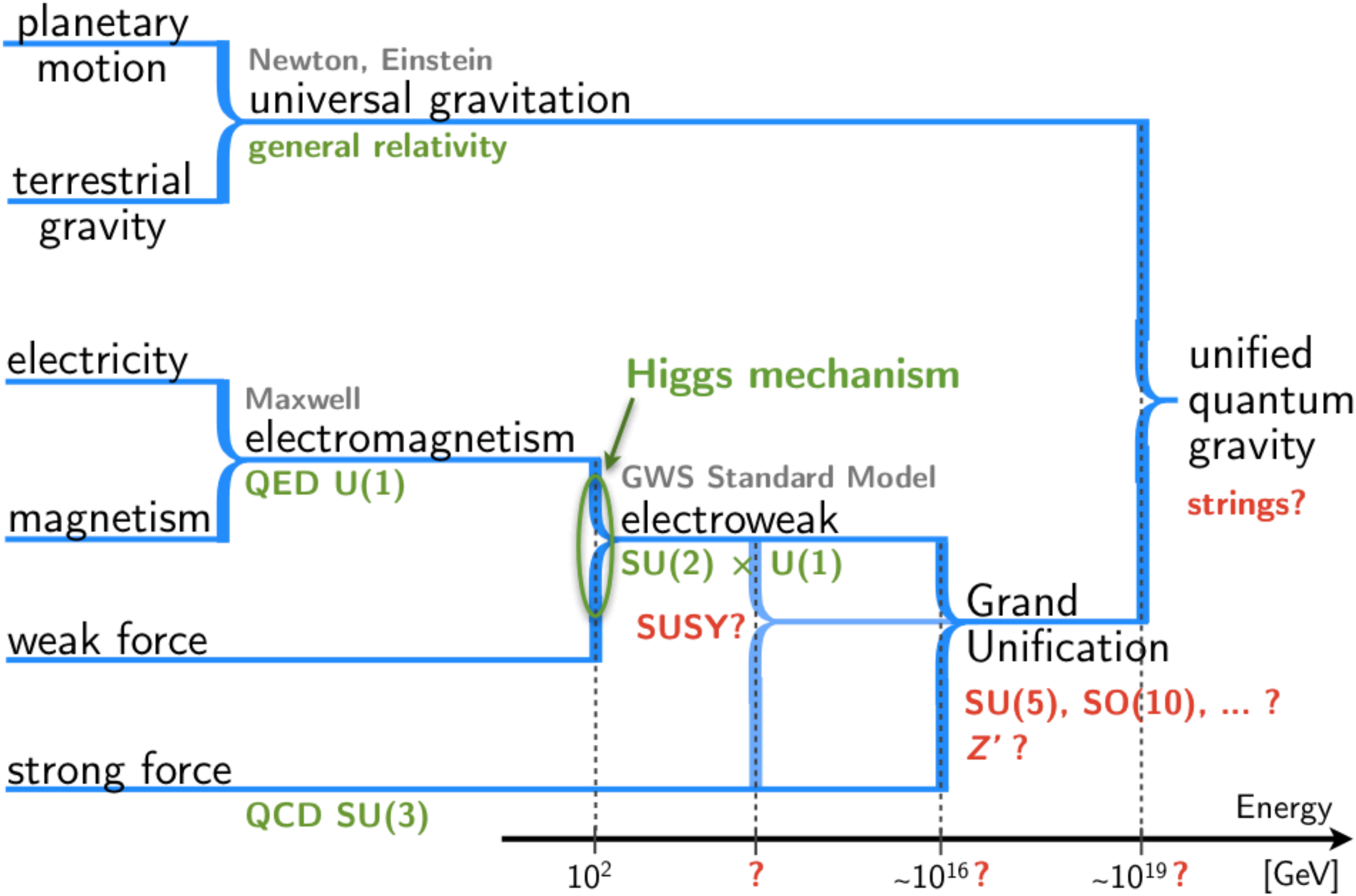
- After precision measurements of the SM couplings at LEP, one could run the couplings according to the RGEs to higher energies.
- The SM ***couplings apparently converge***, motivating the possibility of grand unification (GUTs).
- But the extrapolation is over 10^{14} orders, and ***we need more experimental clues***.
- New high-mass Z' bosons occur in theories with additional U(1) gauge symmetries.

U. Amaldi, W. de Boer, and H. Furstenau, PLB 260 (1991) 447–455
S. P. Martin, A Supersymmetry Primer [arxiv:9709356]



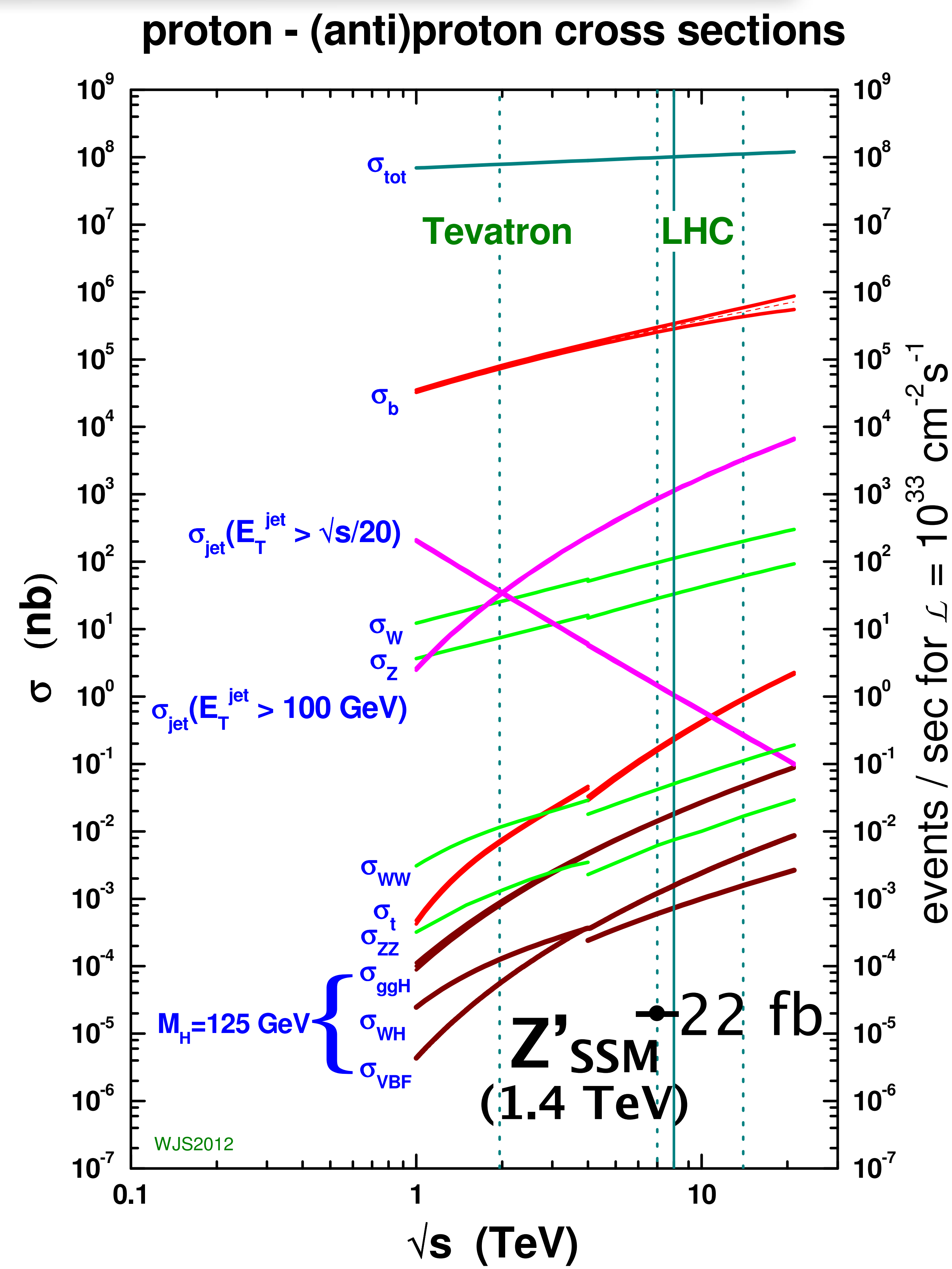
- Z' couplings can be non-universal ⇒important to search for $Z' \to \tau\tau$.

Unification?



We need high energies

- To probe physics at the TeV scale and beyond we need a high-energy collider.
- The cross section ⇒ production rate grows significantly with the collision energy, $\sqrt{s}$.
- W, Z, top, Higgs, Z', ...

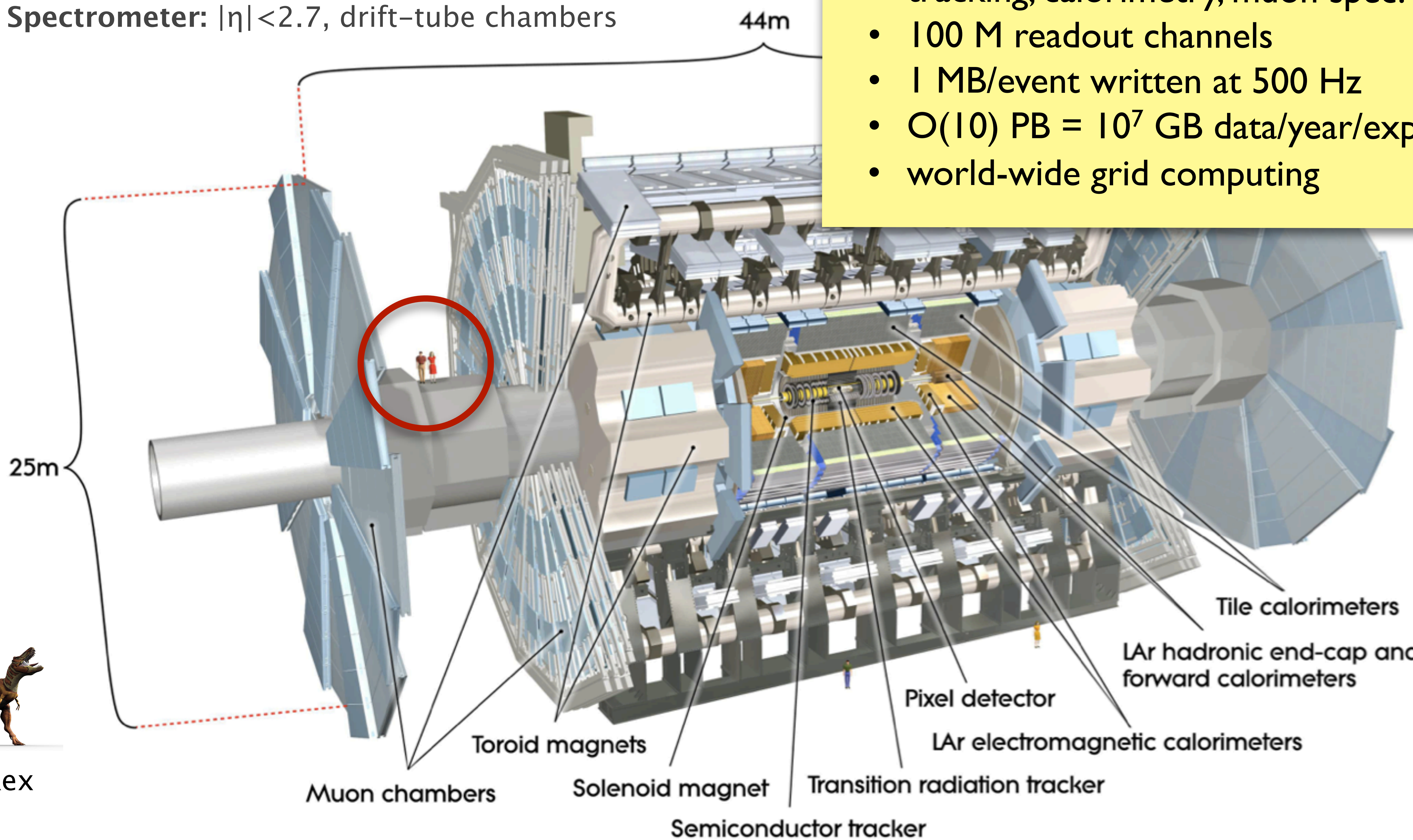


ATLAS Detector

Magnets: 2T solenoid, 4T toroid barrel and end-caps
Muon Spectrometer: |η|<2.7, drift-tube chambers

Both ATLAS and CMS have:

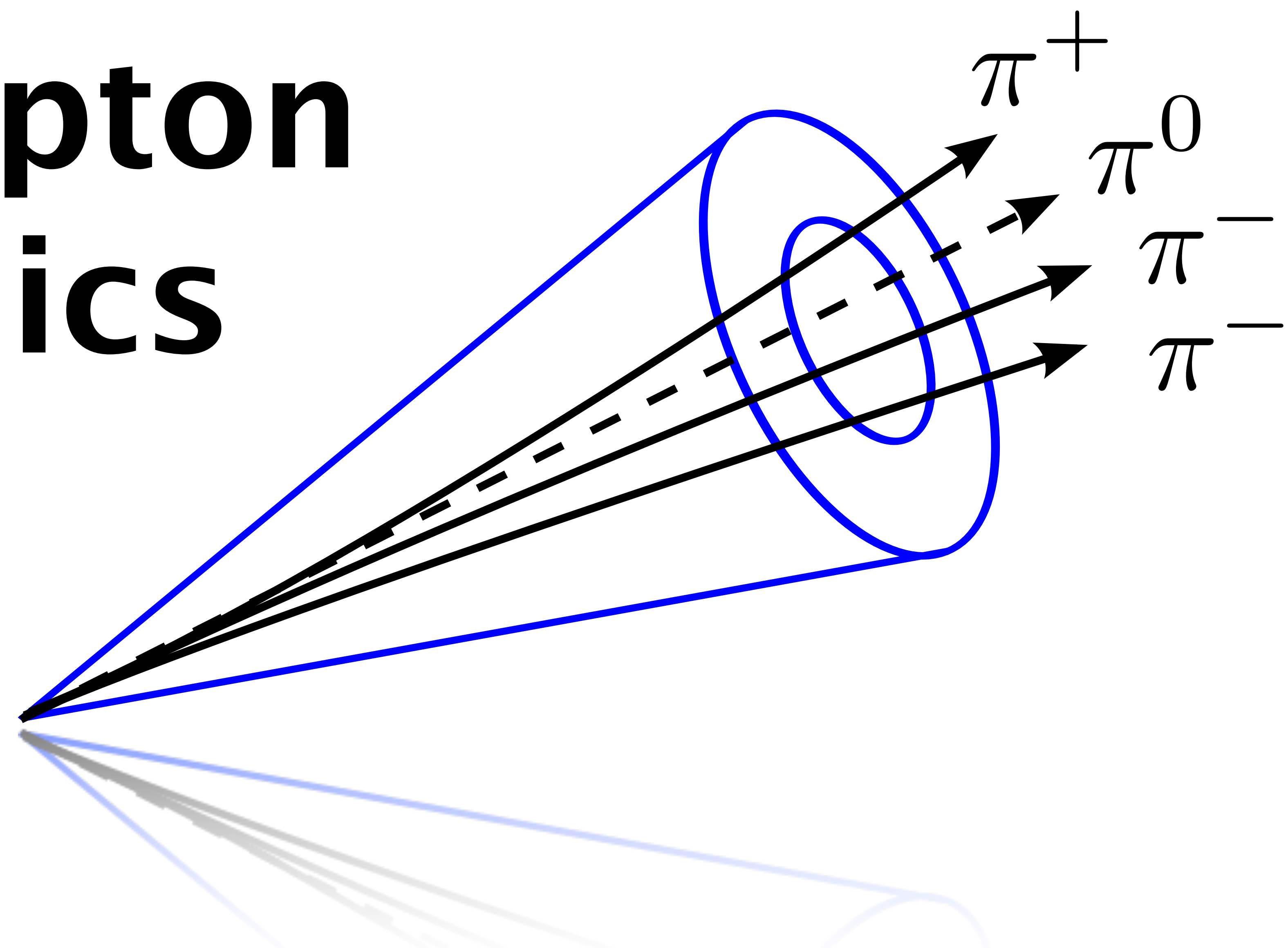
- 3000 scientists, 170+ institutions
- tracking, calorimetry, muon spec.
- 100 M readout channels
- 1 MB/event written at 500 Hz
- O(10) PB = 10^7 GB data/year/exp.
- world-wide grid computing



T.Rex

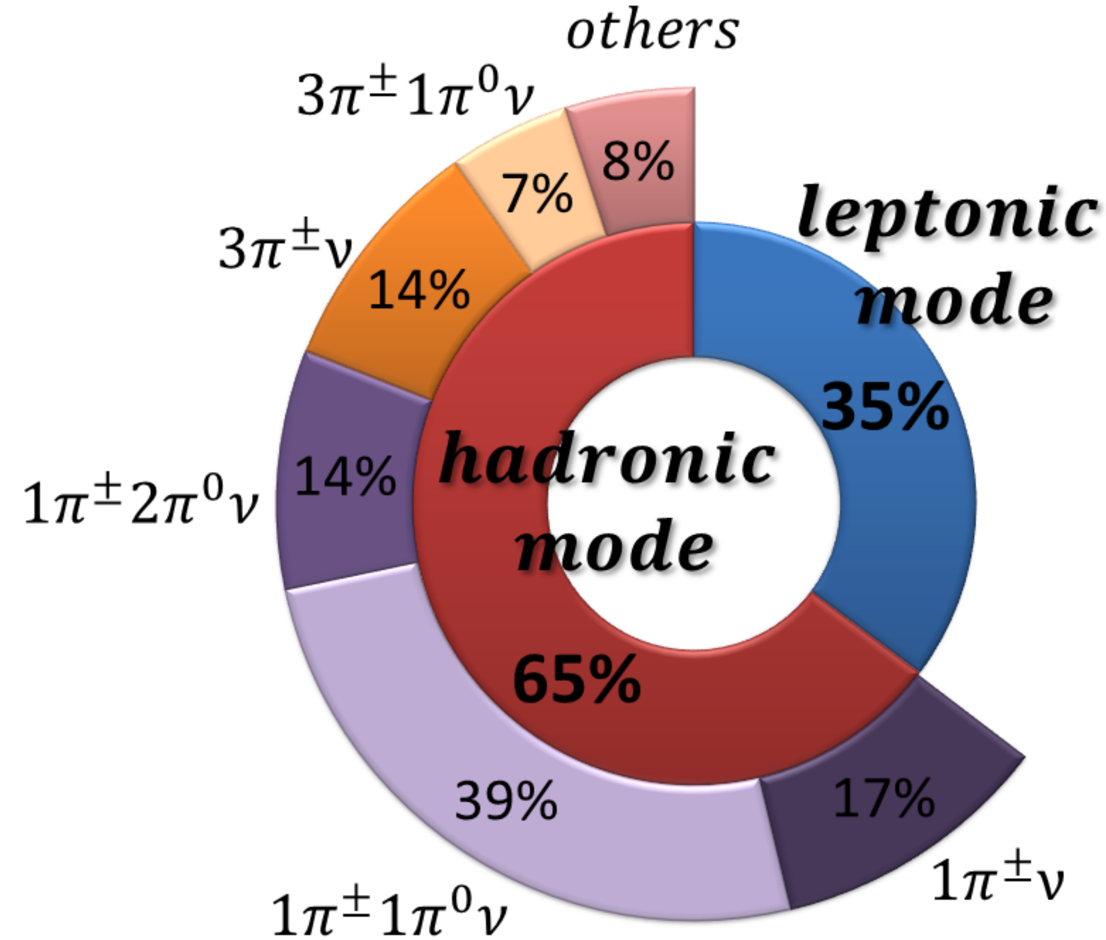
Tracking: |η|<2.5, B=2T, precise tracking and vertexing, Si pixels, strips, and TRT straws, TR electron ID
Electromagnetic Calorimeter: |η|<3.2, 3+1 layers corrugated layers of lead and LAr
Hadronic Calorimeter: |η|<5, Central: iron/scintillator tiles, Forward: copper/tungsten-LAr

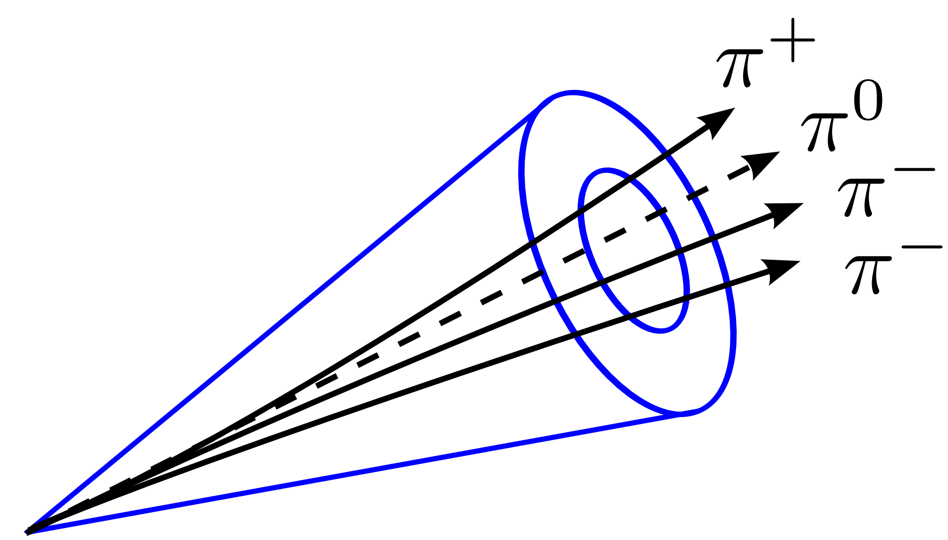
Tau lepton physics

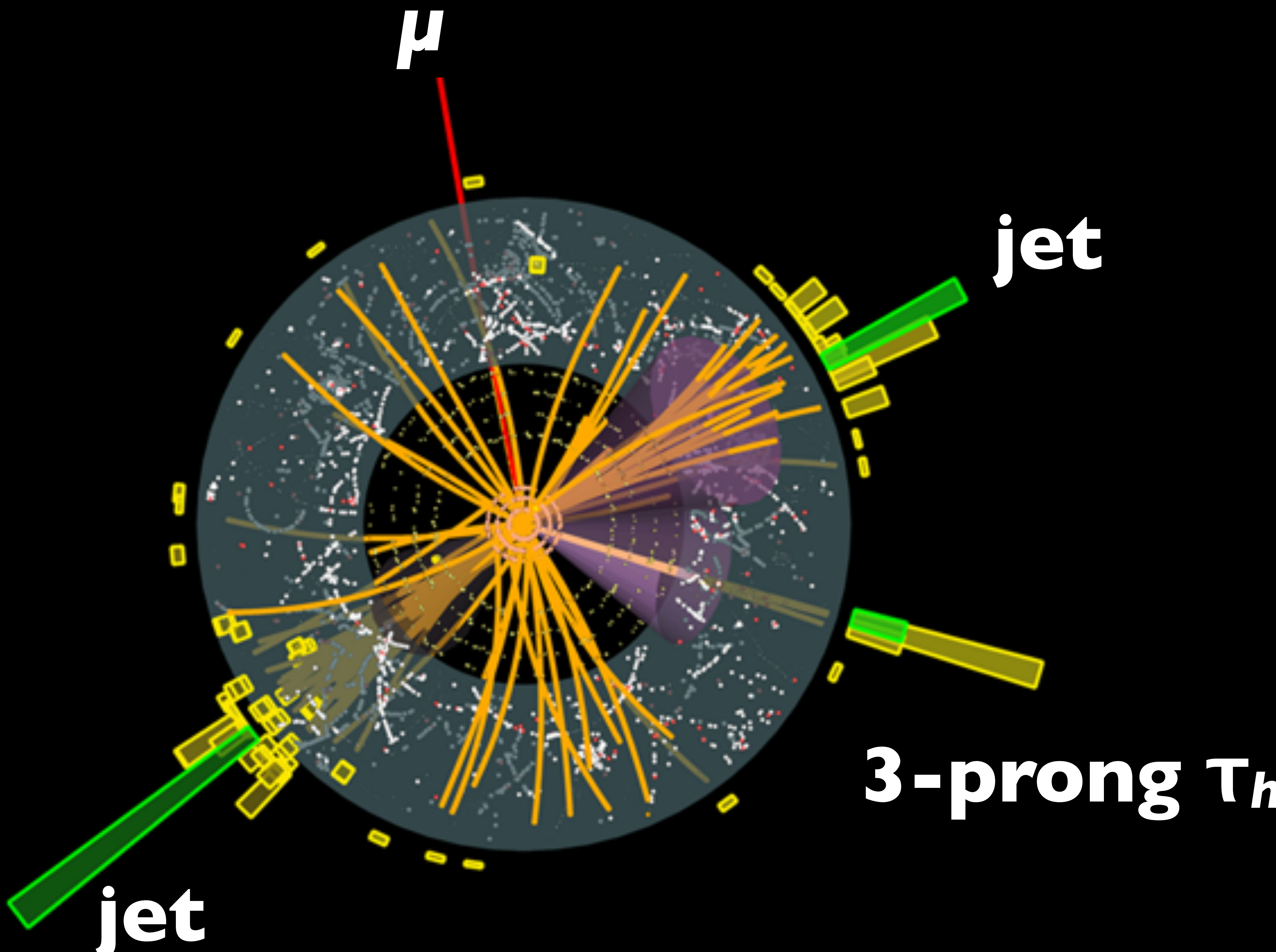


What's a tau?

- 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.
- **Challenge:** large multijet background at hadron colliders.
- **Importance:** can have preferred couplings to new physics:
  SM $H\rightarrow\tau\tau$, $H^+\rightarrow\tau^+\nu$, $Z'\rightarrow\tau\tau$,
  high-tanβ SUSY,...

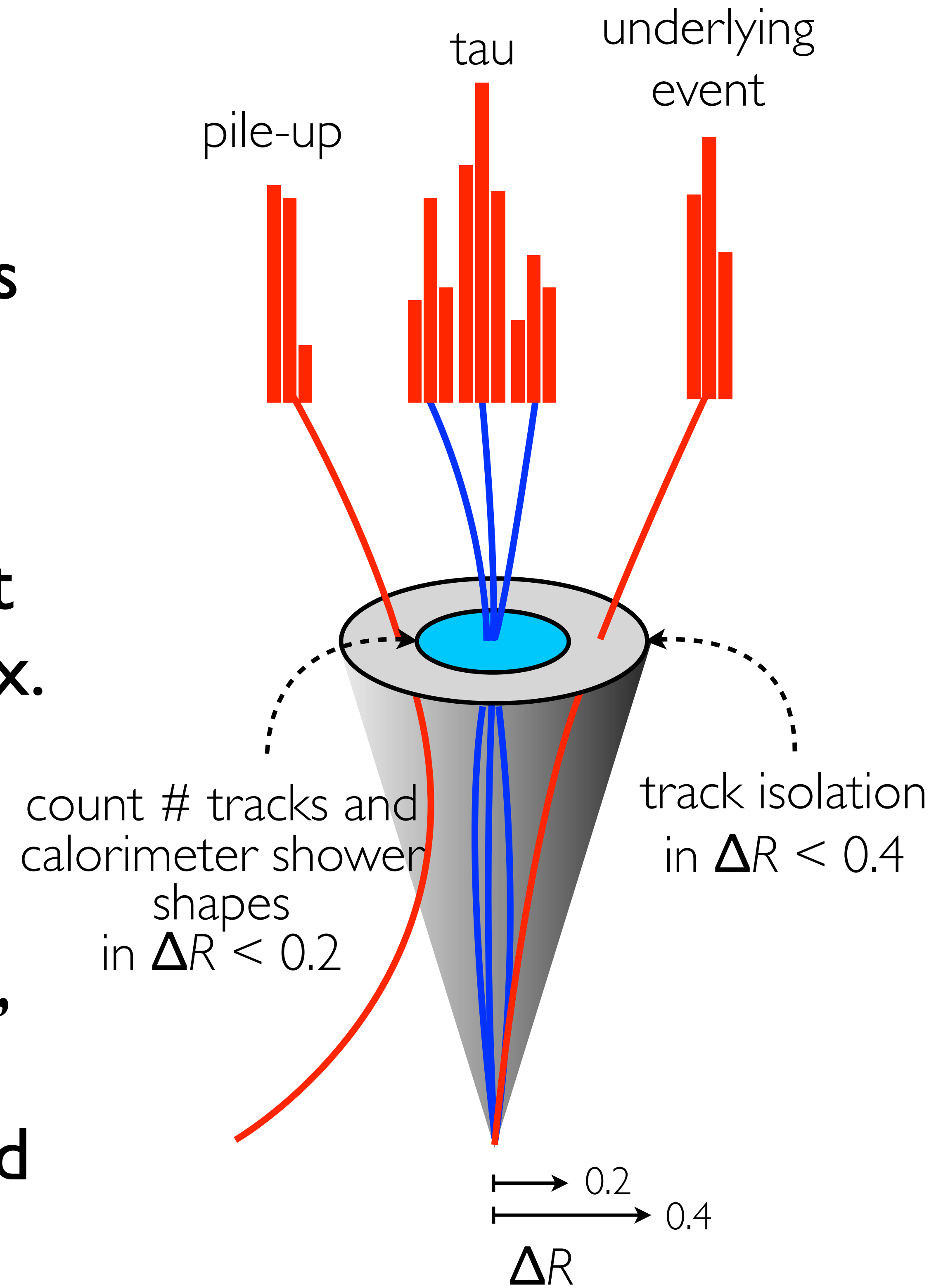





μ
jet
3-prong τ_h
jet

Tau reconstruction

1. **Seeded** by anti-k_t jets (R=0.4) of 3-D topological calorimeter clusters.
2. **Define the four-momentum** as the jet-axis with a tau-specific calibration.
3. **Associate tracks** with the jet that are consistent with the chosen vertex.
4. **Calculate discriminating variables** from the combined calorimeter and tracking information, later used to identify hadronic tau decays with BDT and likelihood based discriminants.



Tau identification

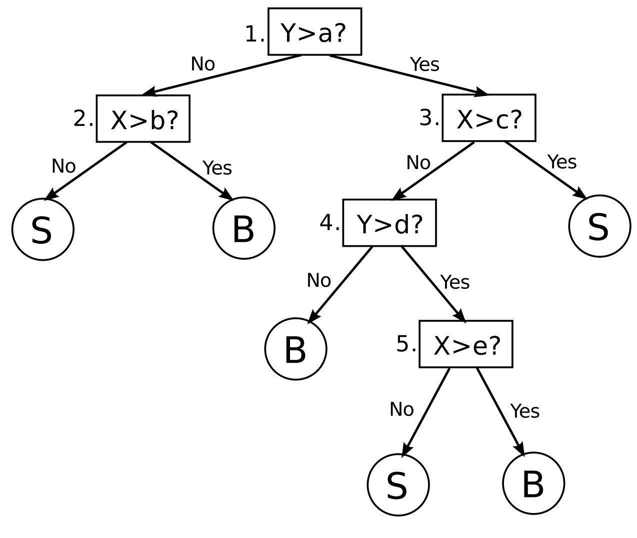
Example ID variable: core energy fraction

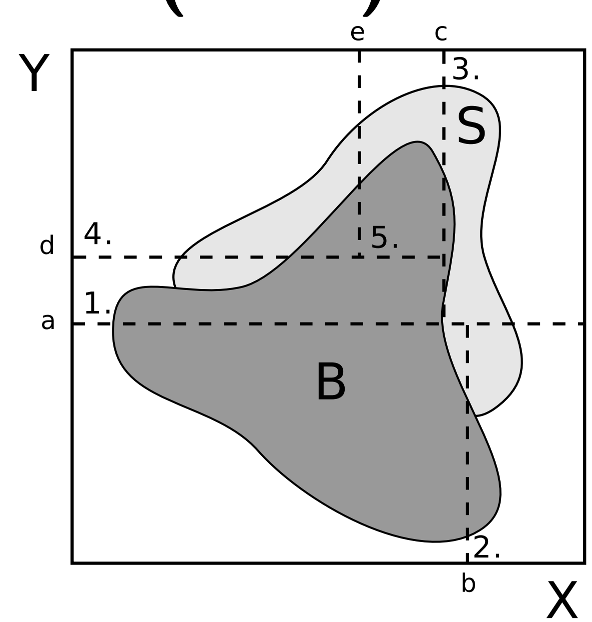
Multivariate techniques:

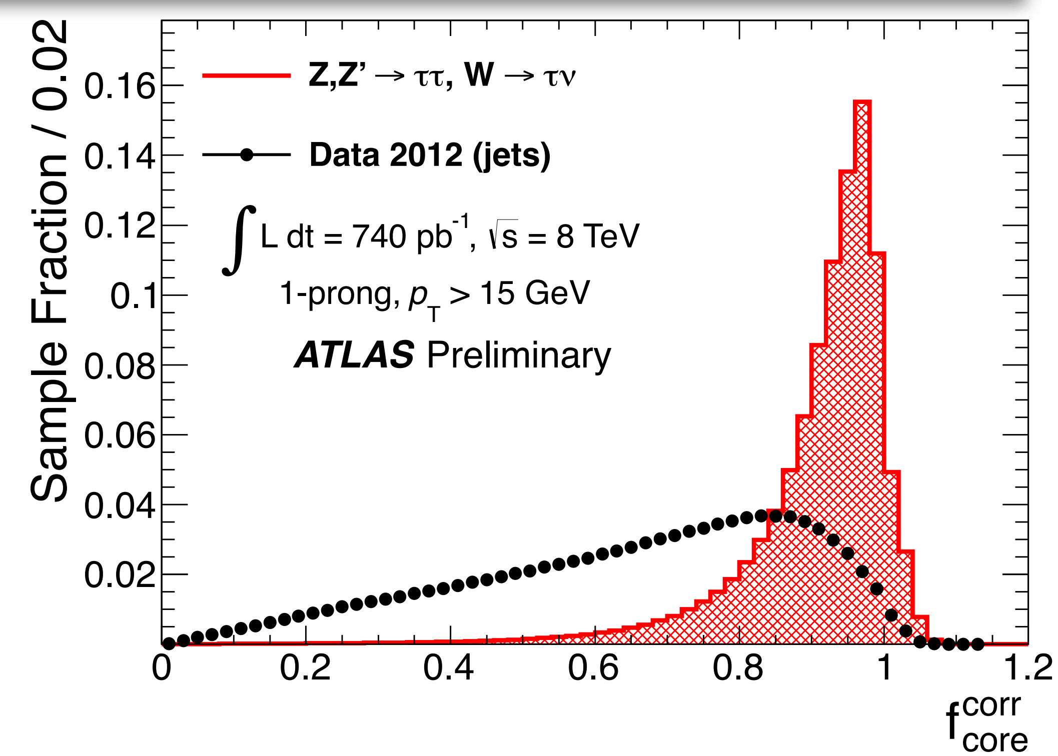
- **Projective likelihood**

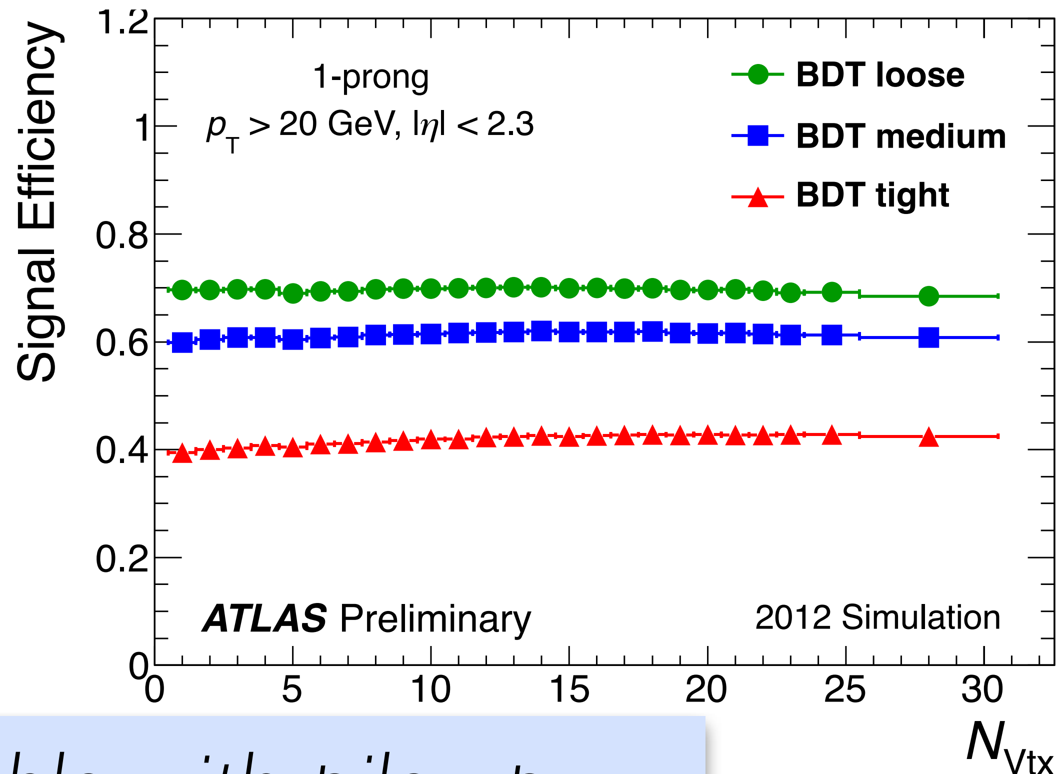
$$d = \ln\left(\frac{L_S}{L_B}\right) = \sum_{i=1}^{N} \ln\left(\frac{p_i^S(x_i)}{p_i^B(x_i)}\right)$$

- **Boosted decision trees (BDT)**



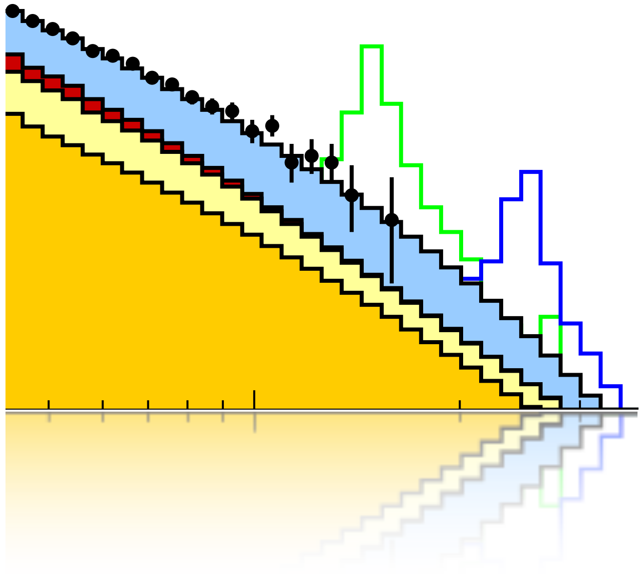






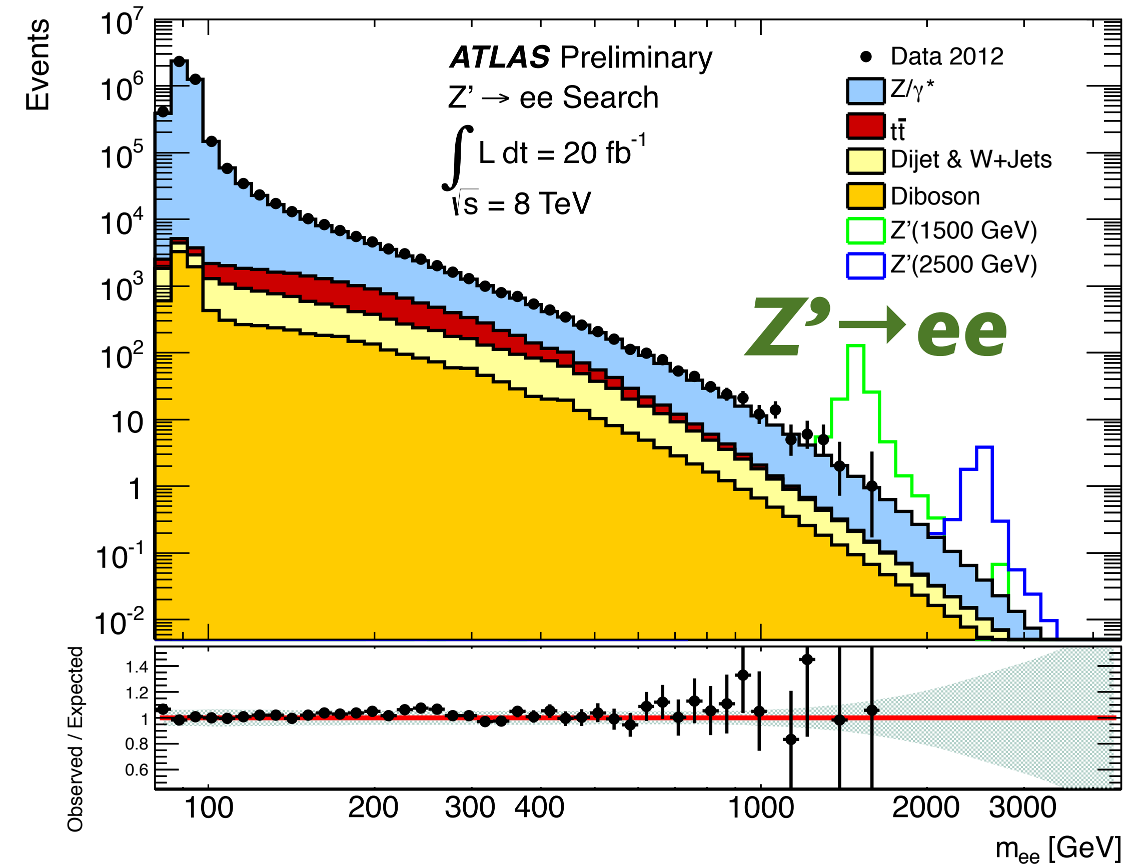
Efficiency stable with pile-up

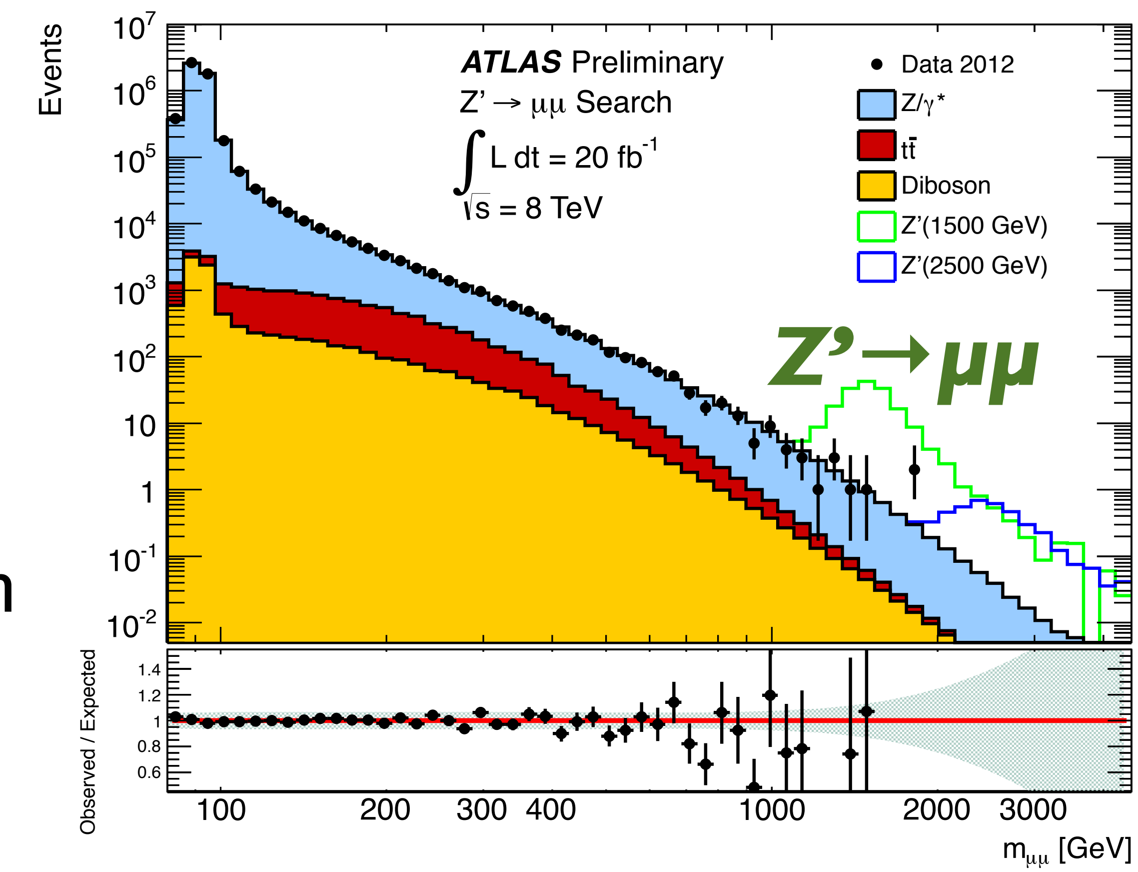
Search for new physics: $Z' \to \tau\tau$



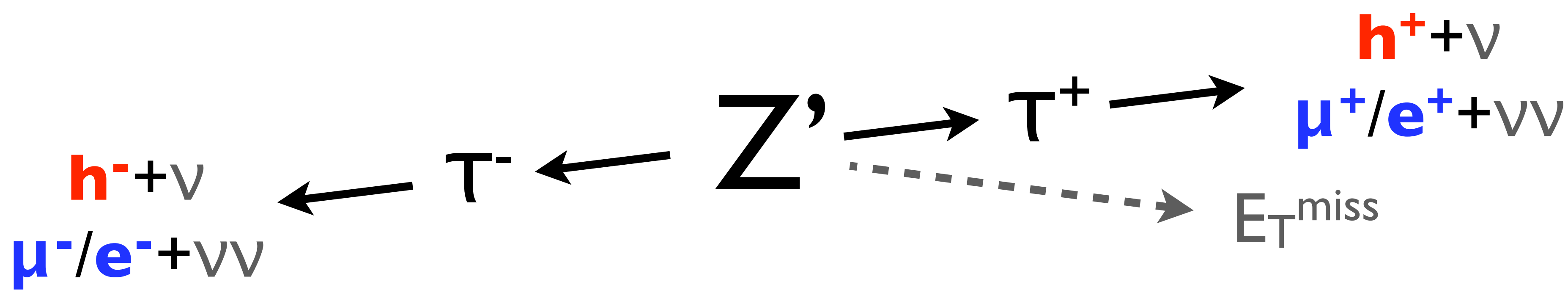
Searching for Z’

- New high-mass Z’ bosons occur in theories with additional U(1) gauge symmetries.
- Sequential Standard Model (SSM) is a benchmark model for a heavy neutral resonance with the same chiral couplings as the SM Z but with a larger mass.
- Best limits on **Z’→ee/μμ**
    - **$m_{Z'}$ > 2.86 TeV** ATLAS [ATLAS-CONF-2013-017]
    - **$m_{Z'}$ > 2.96 TeV** CMS [CMS-PAS-EXO-12-061]
- Important to test the couplings to all lepton flavors (incl. Z’→ττ).
- Some GUT models that predict Z’ bosons **preferentially couple to third-generation** fermions offer an explanation for the high mass of the top quark. [arXiv:hep-ph/0007286]





Searching for Z'→ττ



- **Signature**
  - two tau decays
  - back-to-back in the transverse plane
  - opposite-sign charges
- **"Cut and count"** events above total transverse mass, $m_T^{tot}(\tau 1, \tau 2, E_T^{miss})$, thresholds optimized to exclude a Z'_{SSM} a benchmark high-mass resonance.
- **ATLAS searches for Z'→ττ**
  - 2011 data: 4.6/fb at $\sqrt{s}$ = 7 TeV
    published in PLB [arxiv:1210.6604]
    combined $\tau_h\tau_h$(BR=42%), $e\tau_h$(23%), $\mu\tau_h$(23%), and $e\mu$(6%).
  - 2012 data: 19.5/fb at $\sqrt{s}$ = 8 TeV
    [ATLAS-CONF-2013-066] only $\tau_h\tau_h$ channel so far.

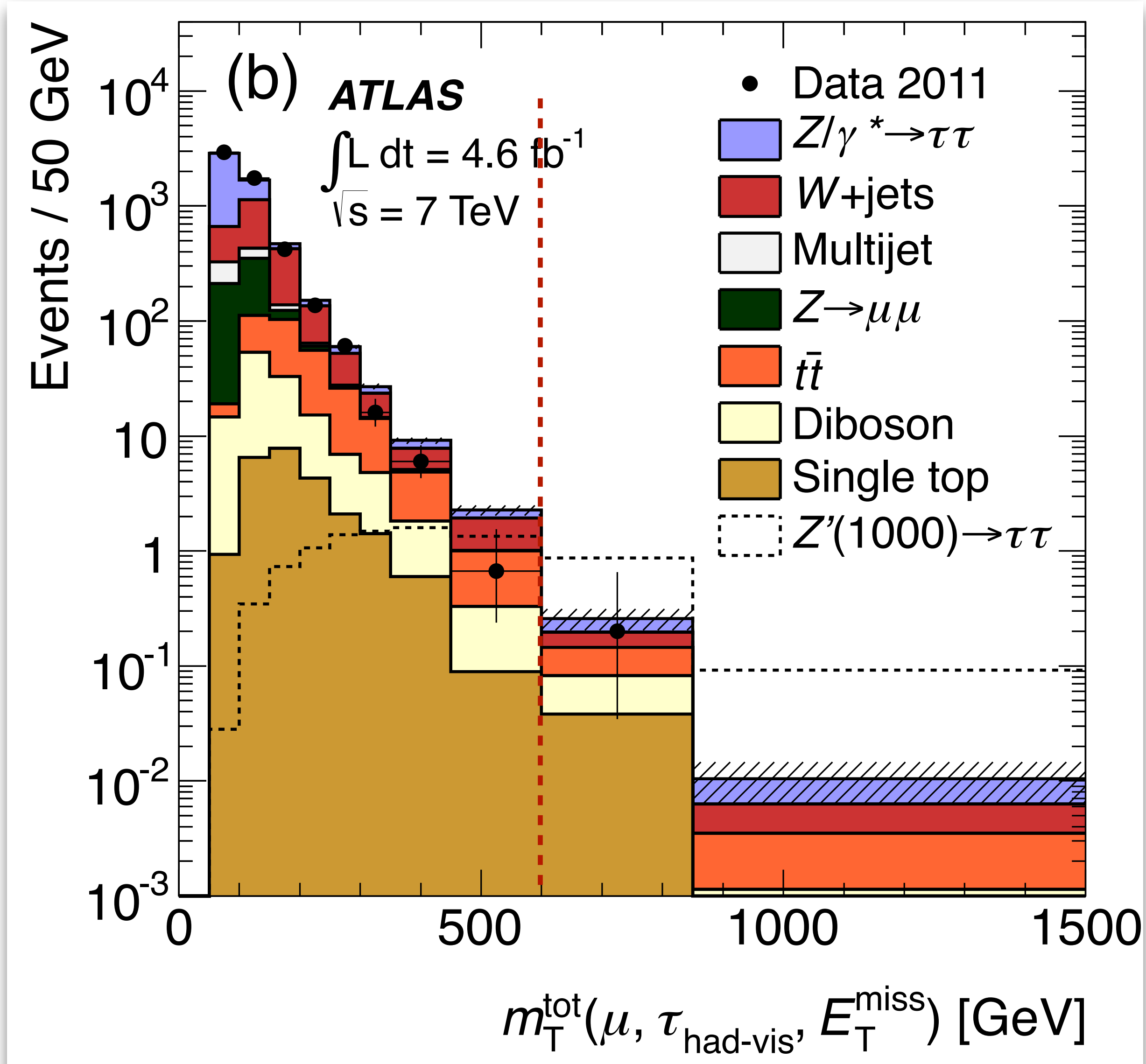
$Z' \rightarrow \tau\tau \rightarrow \mu\tau_h$

2011 dataset

- Select OS back-to-back tau decays.
- Count high-mass events.

Event selection

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



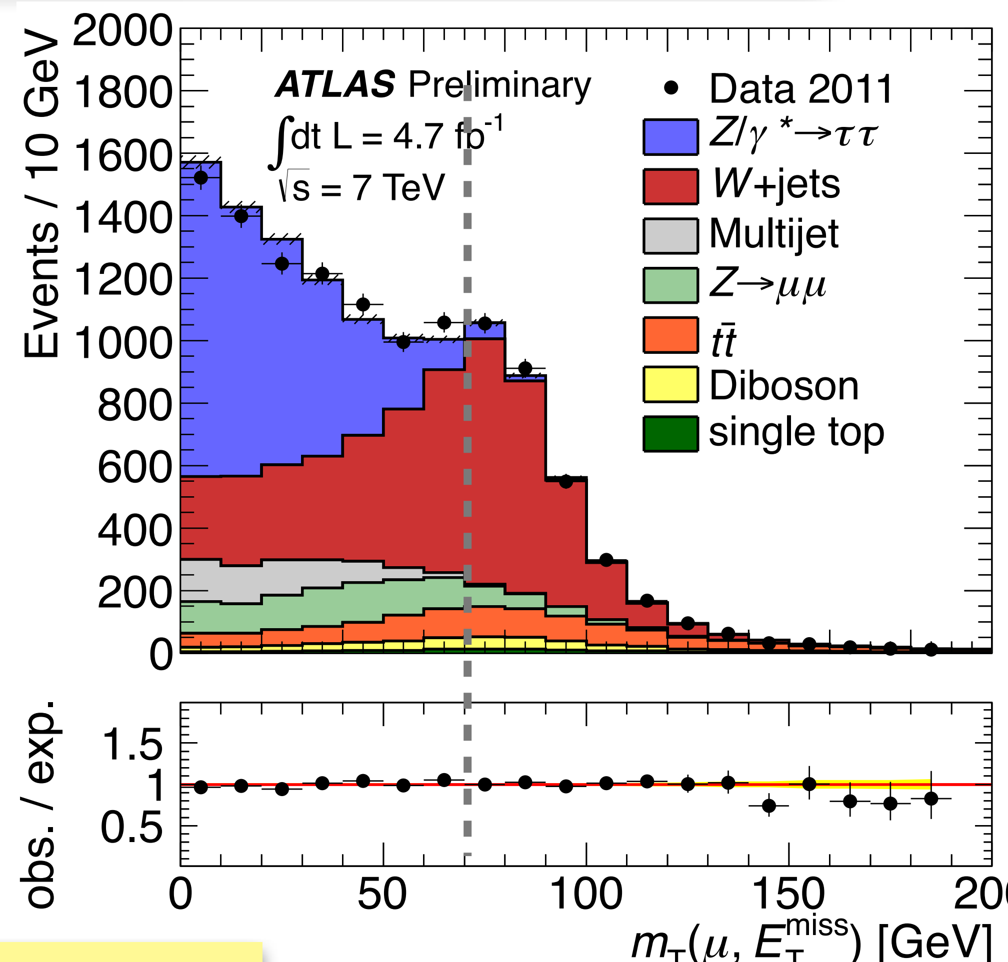
- Fake factor methods used to model multijet and W+jet backgrounds
- Need to be modeled in data-driven ways for two reasons:
  1. jet→ τ_h fake rate is mis-modeled in Monte Carlo.
  2. populate the model in the high-mass tail.

total SM = 1.4 ± 0.4 events
Z'(1000) = 5.5 ± 0.7
observed 1 event

W+jet background estimation

W+jet control region

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



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

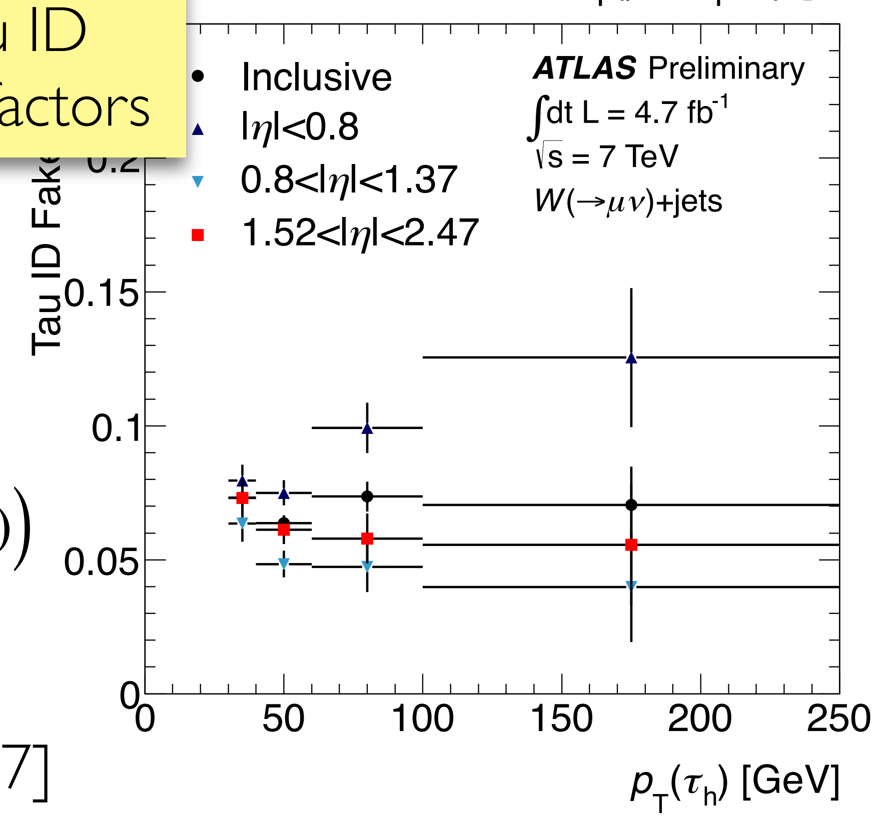
$$f_\tau(p_T, \eta) \equiv \left. \frac{N^{\text{pass } \tau-\text{ID}}(p_T, \eta)}{N^{\text{fail } \tau-\text{ID}}(p_T, \eta)} \right|_{\text{W-CR}}$$

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

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

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

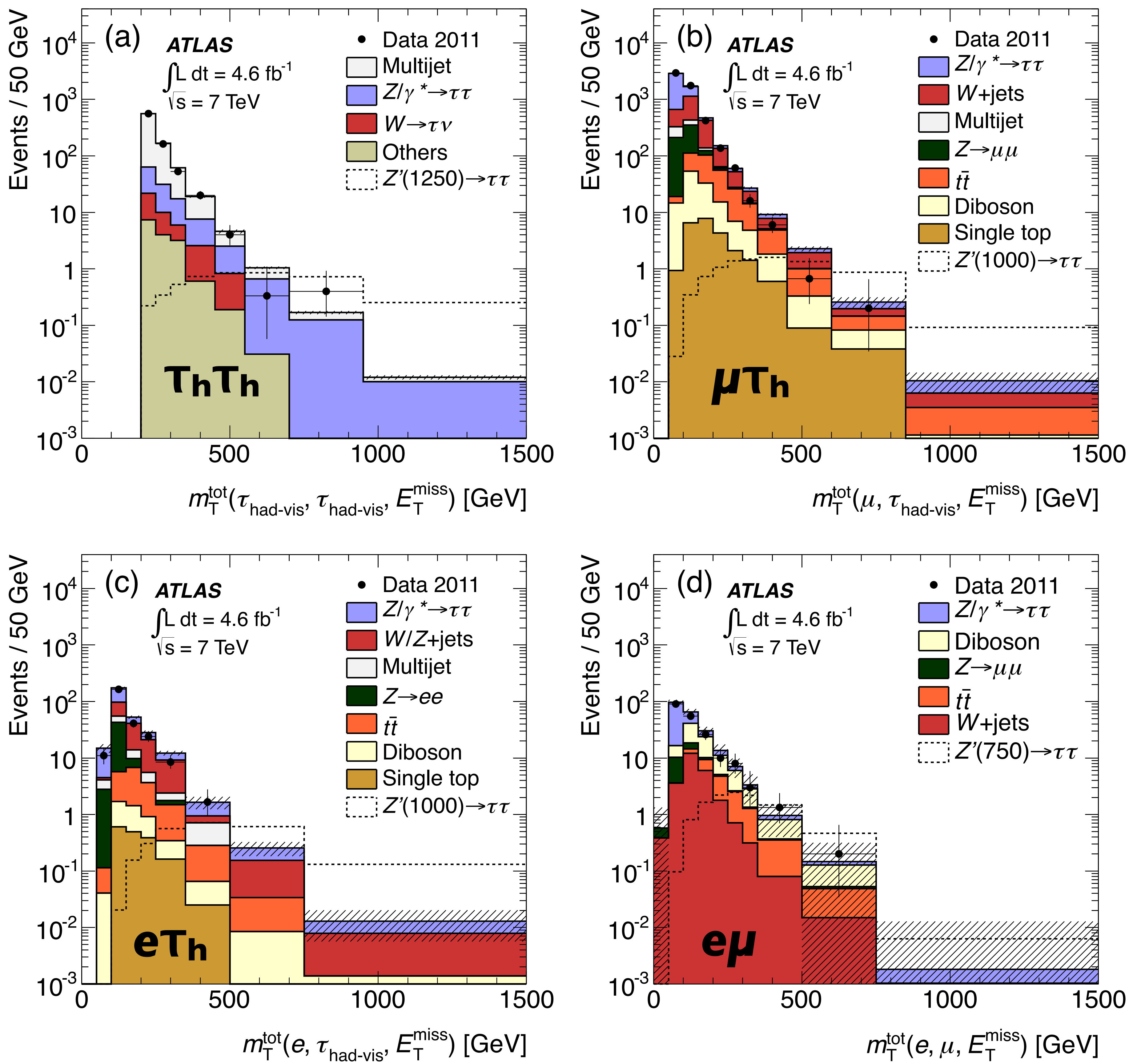
Tau ID fake-factors



[ATLAS-CONF-2012-067]

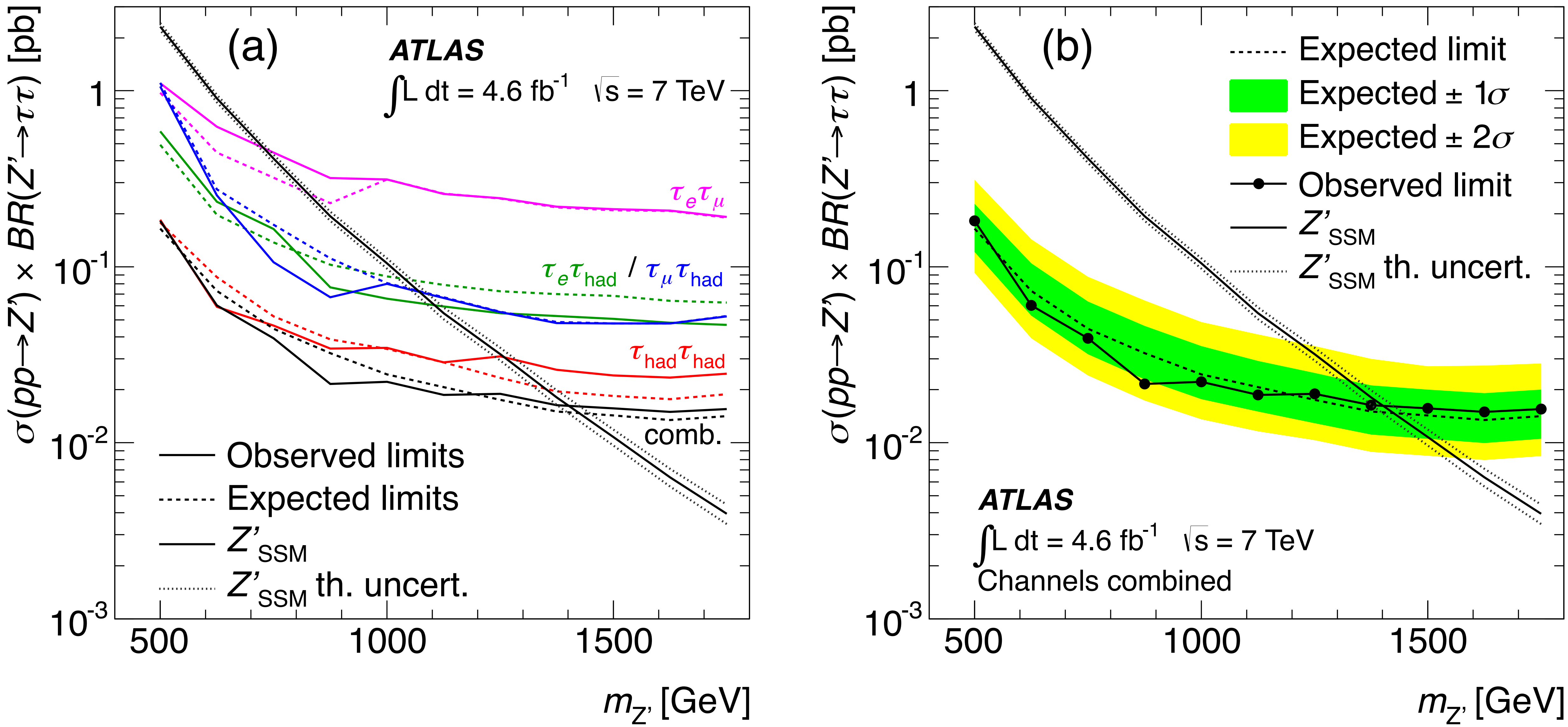
m_T^{tot} distributions

2011 dataset



[arxiv:1210.6604]

Combined limit



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

- $\tau_h\tau_h$: 1.26 (1.35) TeV
- $\mu\tau_h$: 1.07 (1.06) TeV
- $e\tau_h$: 1.10 (1.03) TeV
- eμ: 0.72 (0.82) TeV

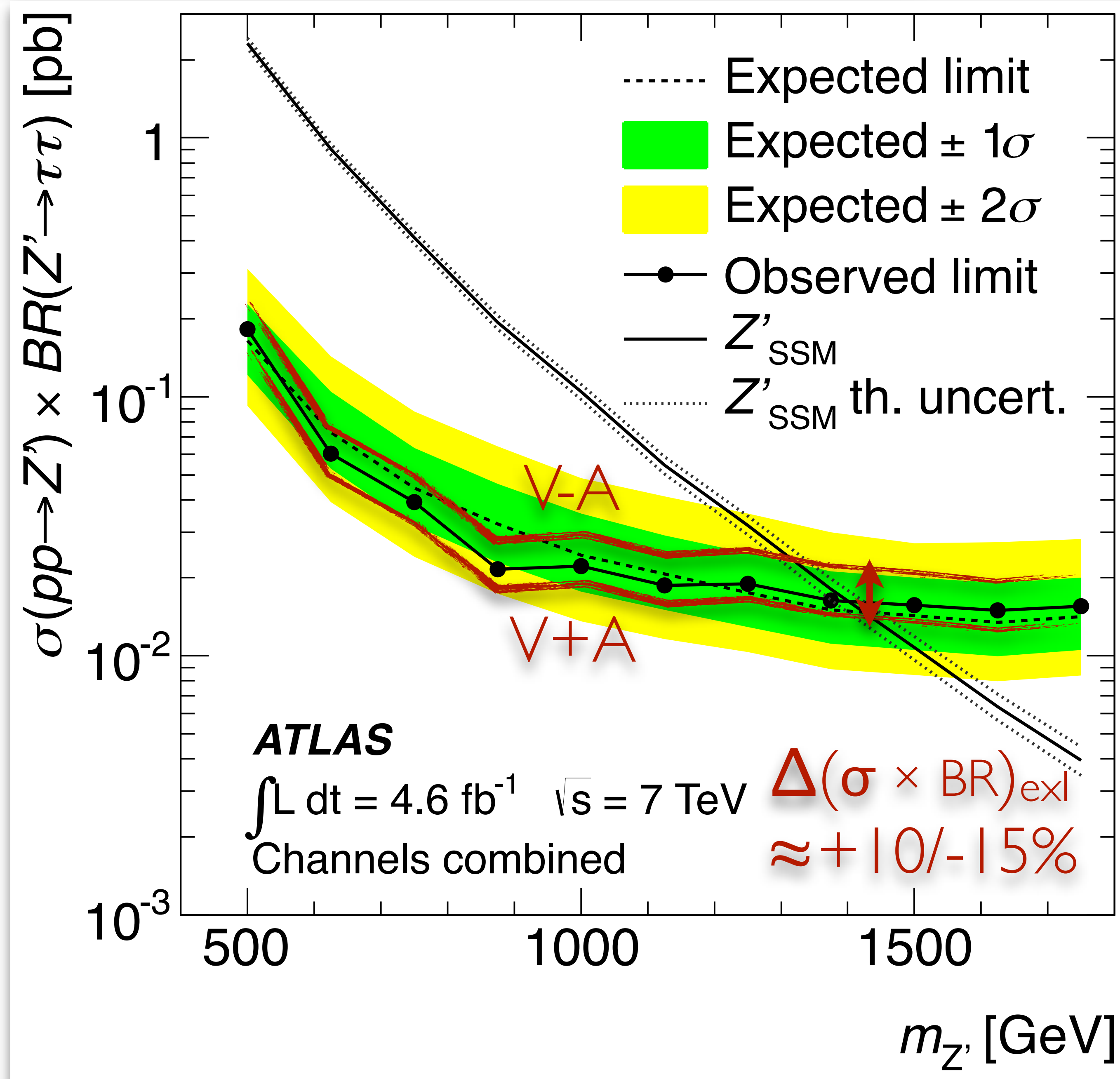
combined: 1.40 (1.42) TeV

Published in PLB [arxiv:1210.6604]

CMS search also excludes 1.4 TeV [arxiv:1206.1725]

Model dependence

- Z'_{SSM} has the same chiral couplings as the Z of the SM, but with a higher mass.
- The visible momentum fraction in hadronic tau decays can depend on the handedness of the couplings because it decays left-handed through a W.
- We studied the dependence of the limit by testing two extreme cases:
  1. V-A pure left
  2. V+A pure right

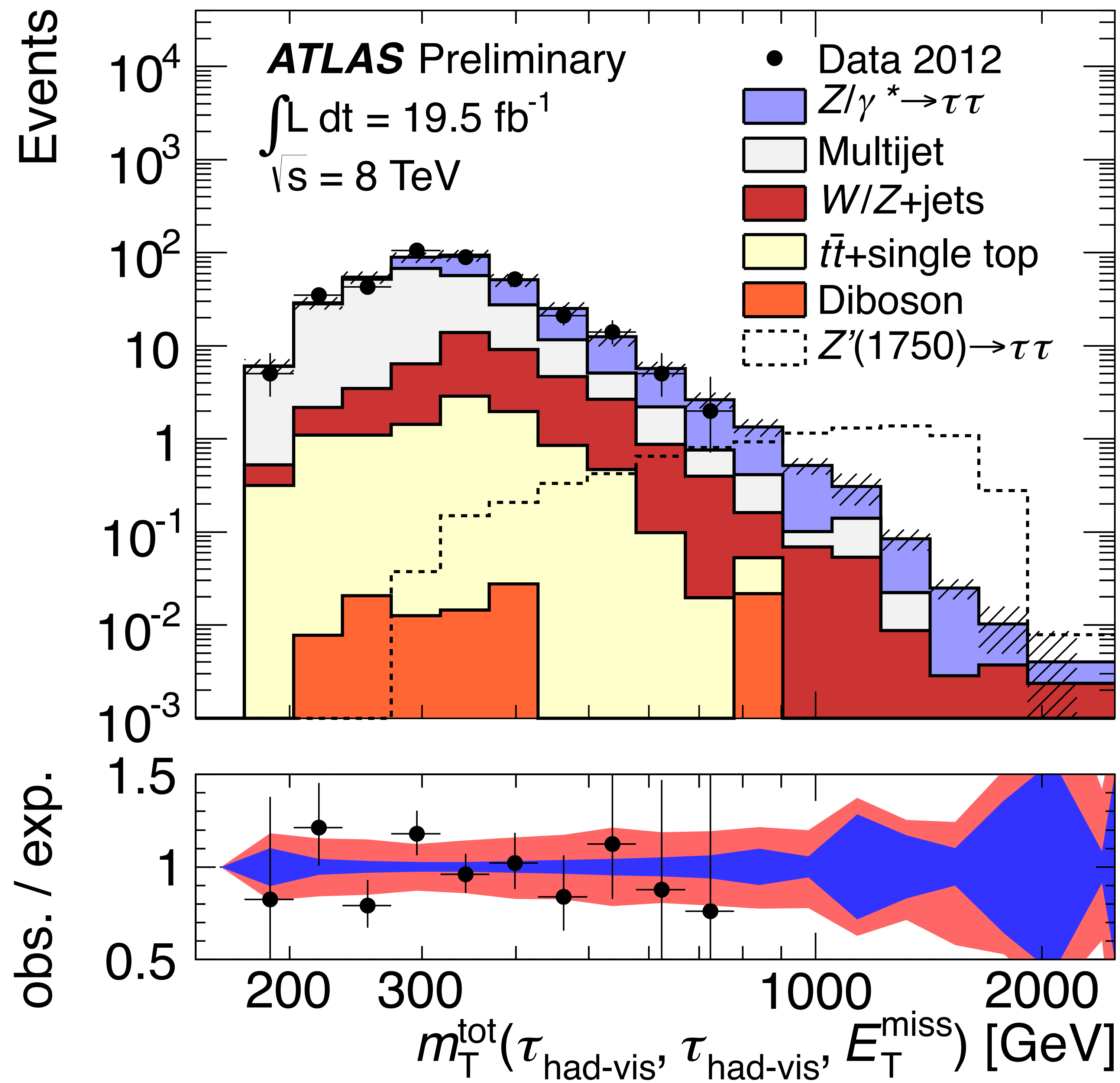


- The change in acceptance results in a change in the excluded σ × BR of 10-15% at high mass.

2012: Z' → $\tau_h \tau_h$

Event Selection

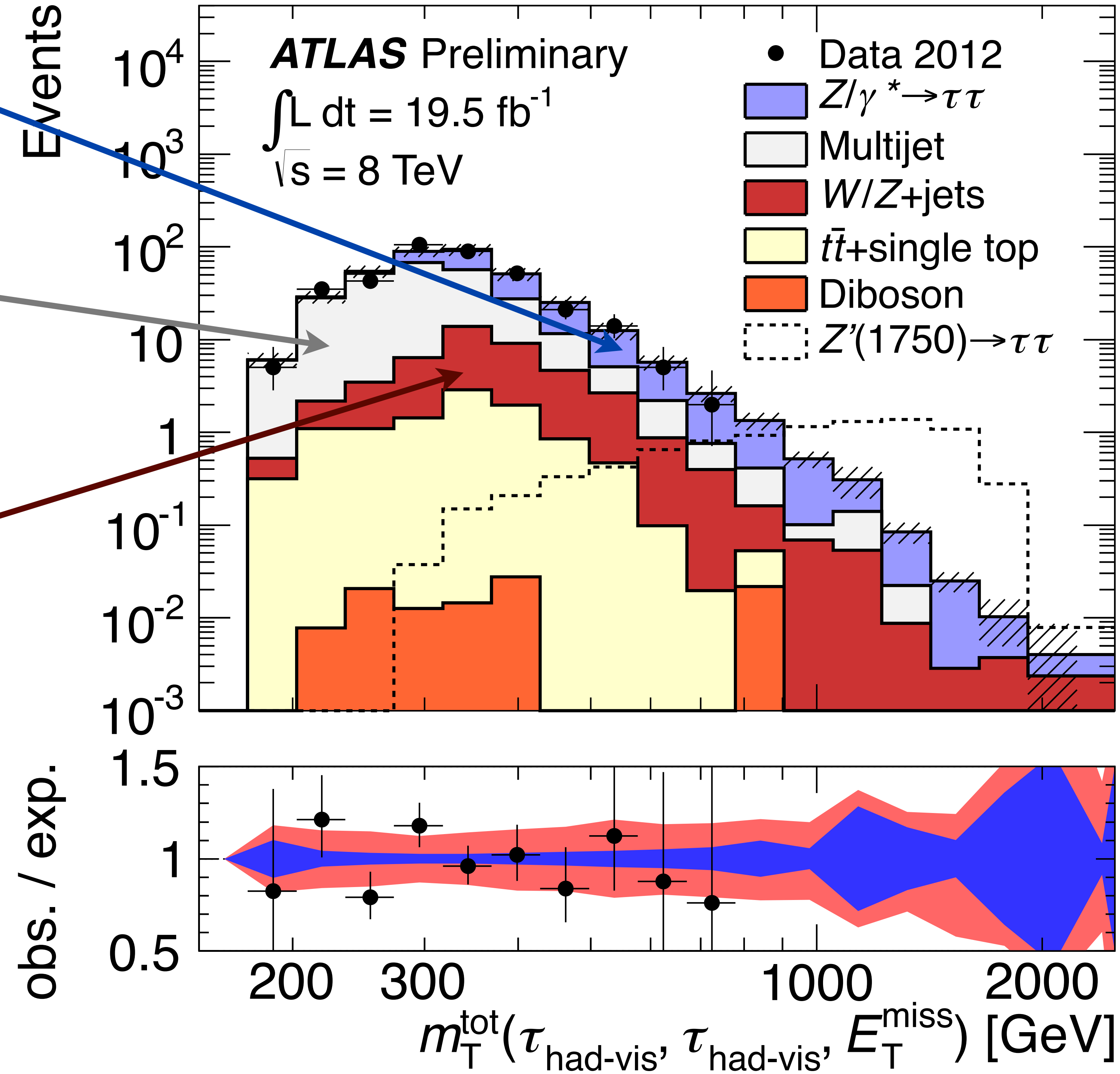
- At least two selected hadronic tau decays:
  - $p_T > 50$ GeV, $|\eta| < 2.47$ (and veto crack)
  - 1 or 3 tracks, |charge|=1
- Lead tau trigger-matched and $p_T > 150$ GeV
- Taus have opposite charges
- $\Delta\varphi(\tau_{h1}, \tau_{h2}) > 2.7$ radians
- m_T^{tot} thresholds optimized to exclude Z'_{SSM} mass.



$\tau_h\tau_h$ background

Dominant backgrounds

- **$Z/\gamma^* \to \tau\tau$** - estimated with high-mass Pythia MC
- **multijet** - data-driven estimate with tau ID fake factors
- **W/Z+jets** - estimated with MC Sherpa samples corrected with scale factors for the jet-to-tau fake rate.



for m_T^{tot} > 850 GeV
total SM = 1.4 ± 0.3 events
$Z'_{SSM}(1750)$ = 5.6 ± 1.0
observed 0 events

Systematics

	$Z/\gamma^* \to \tau\tau$	Multijet	W/Z+jets	Diboson	SM total	$Z'_{\rm SSM}(1750)$
Expected Events	0.99 ± 0.02	0.17 ± 0.09	0.18 ± 0.03	0.02 ± 0.02	1.36 ± 0.10	5.58 ± 0.14
Theory Cross Section [%]	$^{+9}_{-6}$	–	±28	±13	$^{+7}_{-6}$	–
Luminosity [%]	±2.8	–	±2.8	±2.8	±2.5	±2.8
Tau trigger [%]	±10	–	< 1	–	±7	±10
Tau ID [%]	±13	–	±5	±5	±10	±13
Tau 3-prong [%]	±4	–	< 1	–	±3	±4
Jet-to-tau fake-rate [%]	< 1	–	±61	±60	±9	< 1
Tau energy scale [%]	±12	–	±5	–	±9	±2
Jet energy scale [%]	< 1	–	$^{+1}_{-5}$	–	< 1	< 1
$E_{\rm T}^{\rm miss}$ [%]	< 1	–	$^{-3}_{+0.2}$	–	< 1	< 1
Multijet fake-factor [%]	–	±58	–	–	±7	–

[ATLAS-CONF-2013-066]

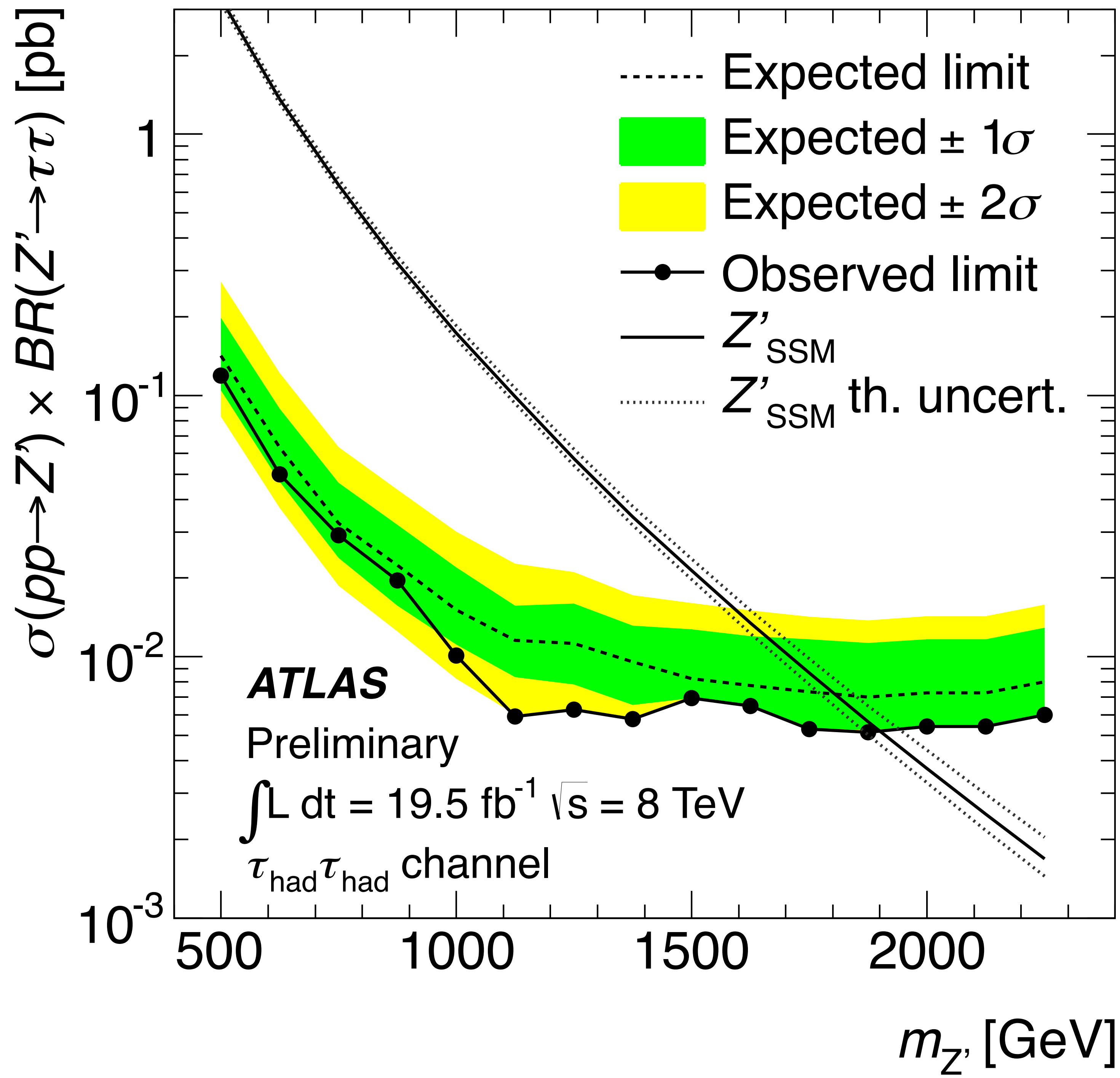
- Tau identification efficiency (≈2-10%/τ_h)
- Tau energy scale (≈2-3%/τ_h)
- Tau fake rate (≈60%/τ_h)

} data-driven with $Z \to \tau\tau$ with conservative extrapolations to higher p_T

→ conservative uncertainty covering sample dependence in OS/SS fake factors

2012: Z' → $\tau_h\tau_h$ limit

- Calculated Bayesian limits from the counts in the high-mass signal regions using a flat prior on signal strength.
- **$m_{Z'SSM}$ < 1.9 (1.8) TeV** @ 95% CL obs (exp)
- will be combined with the $\tau_l\tau_h$ channels.



[ATLAS-CONF-2013-066]

Conclusions

- The performance of the LHC, and the ATLAS and CMS experiments have **extended many exclusions** for new physics.
- No sign of **Z’** yet, GUTs, or SUSY.
- Expect some improvements as the $Z' \to \tau\tau$ as the $\tau_l \tau_h$ channels are updated with the 2012 data.
- Many searches **will be improved with the 2015** dataset and further their reach with increases in luminosity and energy after the shutdown.

Back up

$Z'\rightarrow\tau\tau$ References

ATLAS

- **arxiv:1210.6604** - ***Z'→ττ*** search with 2011 data
  - 4.6/fb at $\sqrt{s}$ = 7 TeV
  - lower limit on ***Z'*$_{SSM}$ mass > 1.4 TeV** at 95% CL
- **ATLAS-CONF-2013-066** - *Z'*→ττ search with 2012 data
  - 19.5/fb at $\sqrt{s}$ = 8 TeV
  - lower limit on ***Z'*$_{SSM}$ mass > 1.9 TeV** at 95% CL

CMS

- **arxiv:1206.1725** - ***Z'→ττ*** search with 2011 data
  - 4.9/fb, $\sqrt{s}$ = 7 TeV
  - lower limit on *Z'*$_{SSM}$ **mass > 1.4 TeV** at 95% CL

$H \to \tau\tau$ References

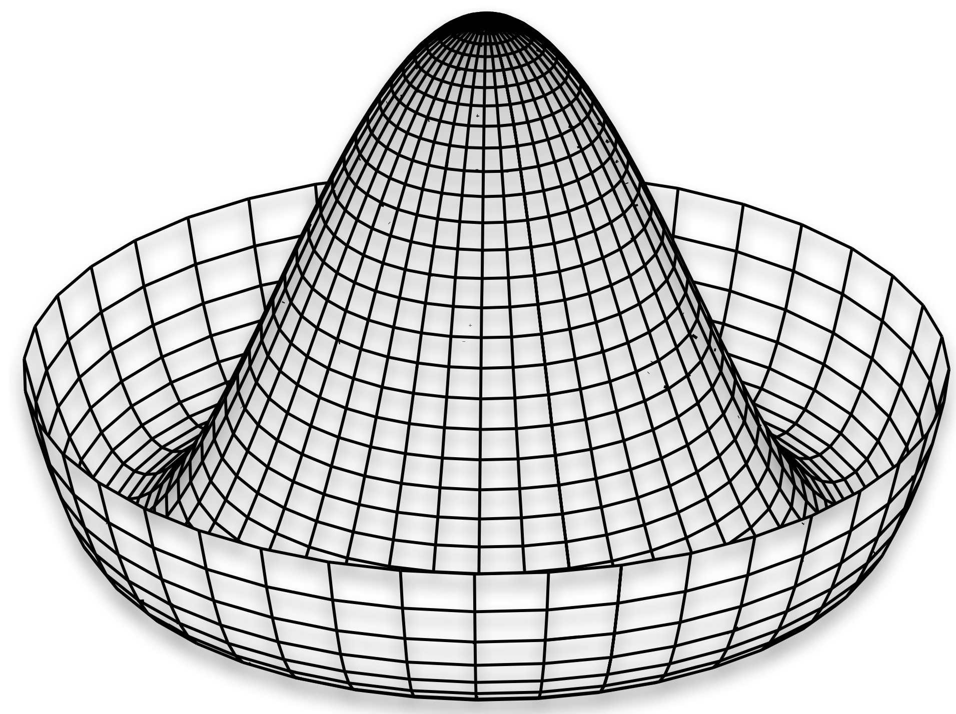
ATLAS

- **arxiv:1206.5971** - $H \to \tau\tau$ search with 2011 data
  - 4.7/fb at $\sqrt{s}$ = 7 TeV
  - **upper limit on $\mu = \sigma/\sigma_{SM} < 3\text{-}4$** for $m_H \approx 125$ GeV
- **ATLAS-CONF-2012-160** - $H \to \tau\tau$ search with 2011+2012 data
  - 4.6/fb at $\sqrt{s}$ = 7 TeV and 13.0/fb at $\sqrt{s}$ = 8 TeV
  - **upper limit on $\mu < 1.9$** for $m_H \approx 125$ GeV

CMS

- **CMS-PAS-HIG-13-004** - $H \to \tau\tau$ search with 2011+2012 data
  - 4.9/fb, $\sqrt{s}$ = 7 TeV and 19.4/fb at $\sqrt{s}$ = 8 TeV
  - best fit **$\mu = 1.1 \pm 0.4$** consistent with the SM
  - **2.85σ significance** over background only for $m_H \approx 125$ GeV

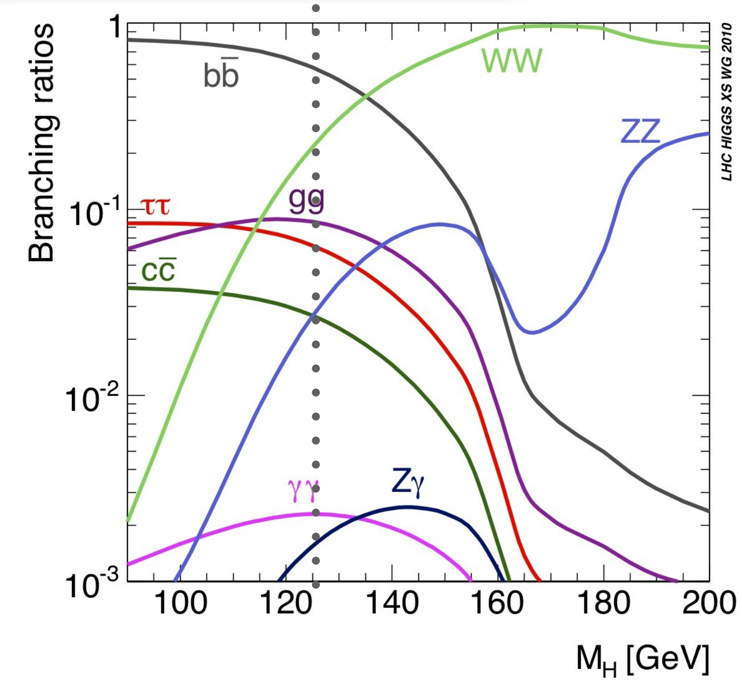
Review of Higgs search results



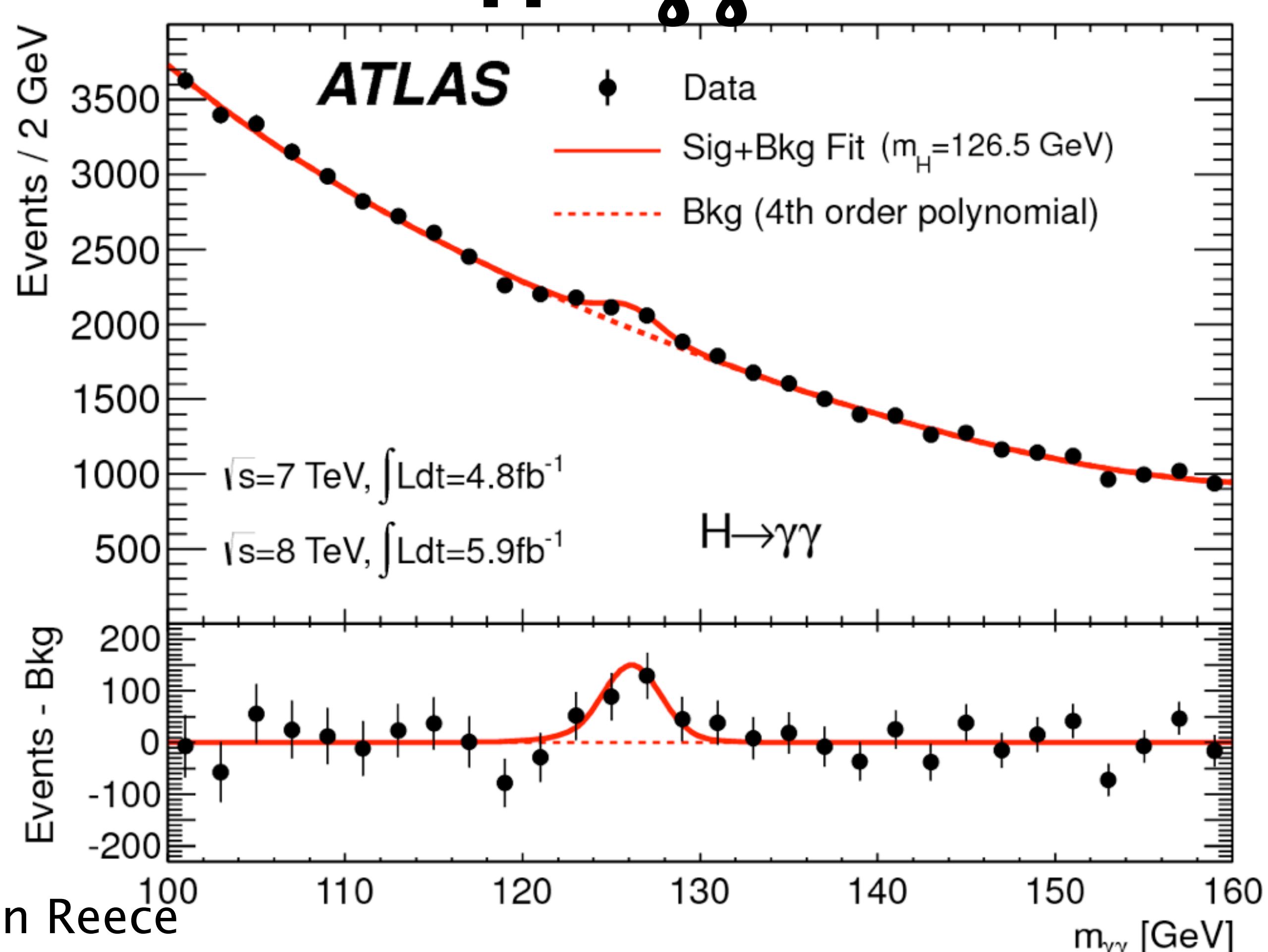
Current Higgs results

- Two channels with precise mass measurements: **H→γγ** and **H→ZZ→4l** .
- **H→WW** observes a broad but clear excess.

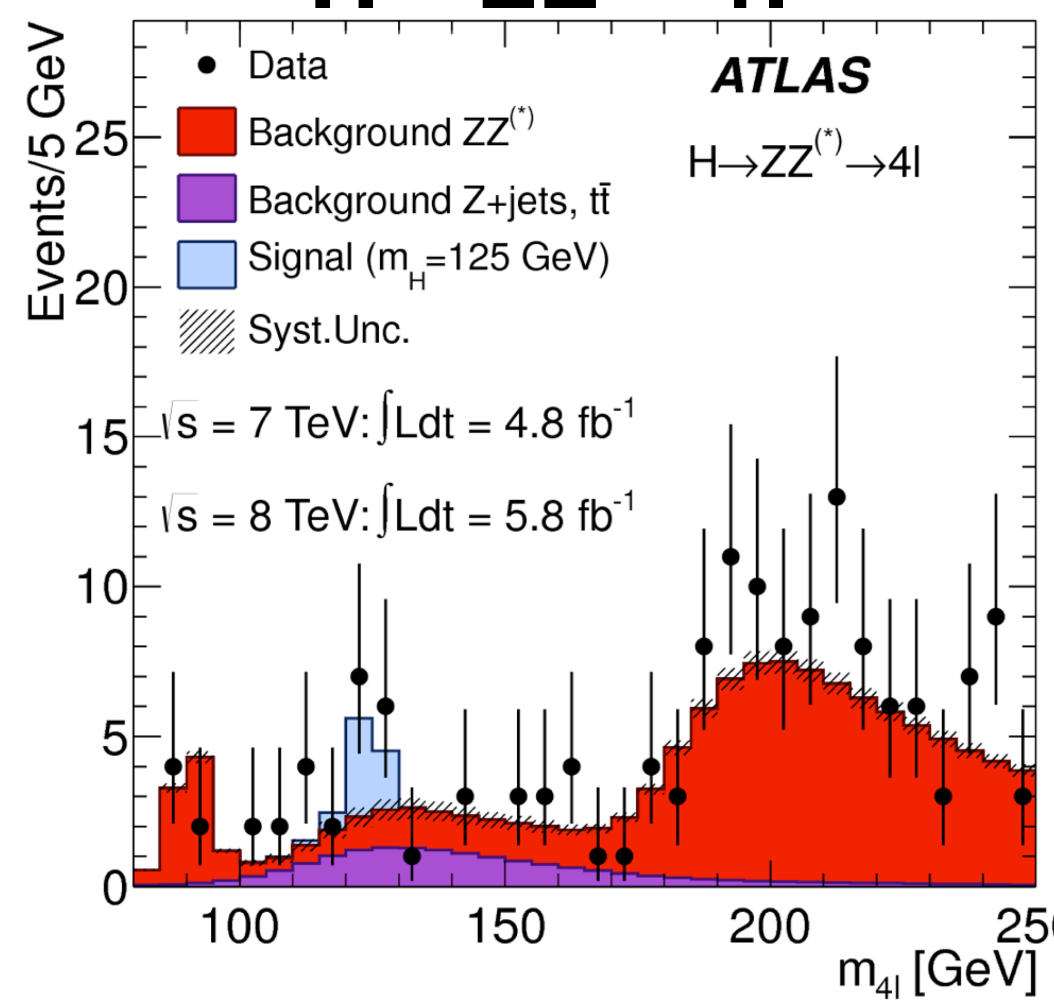
channel	bb	ττ	WW	ZZ	γγ
BR	58%	6%	22%	3%	0.2%



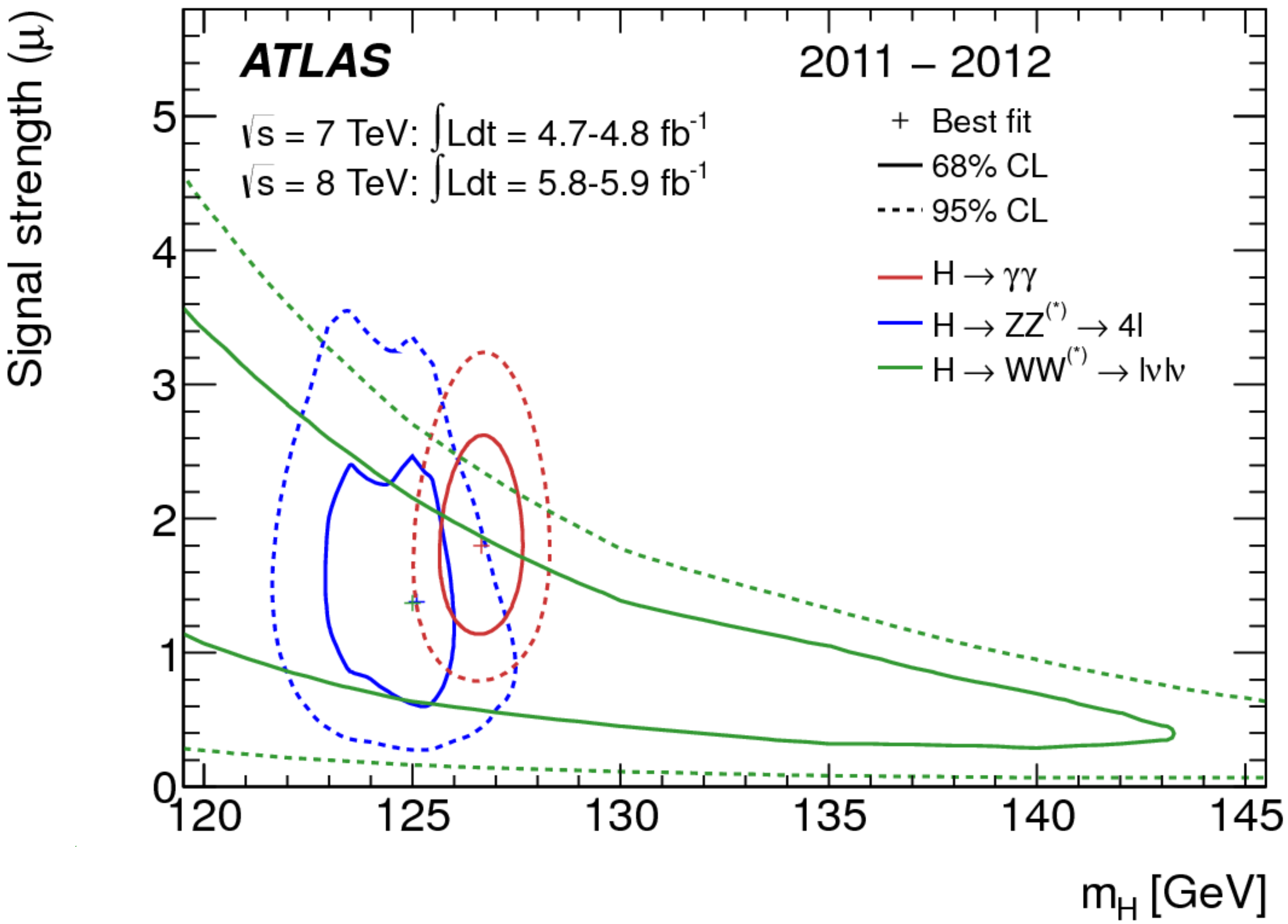
H→γγ

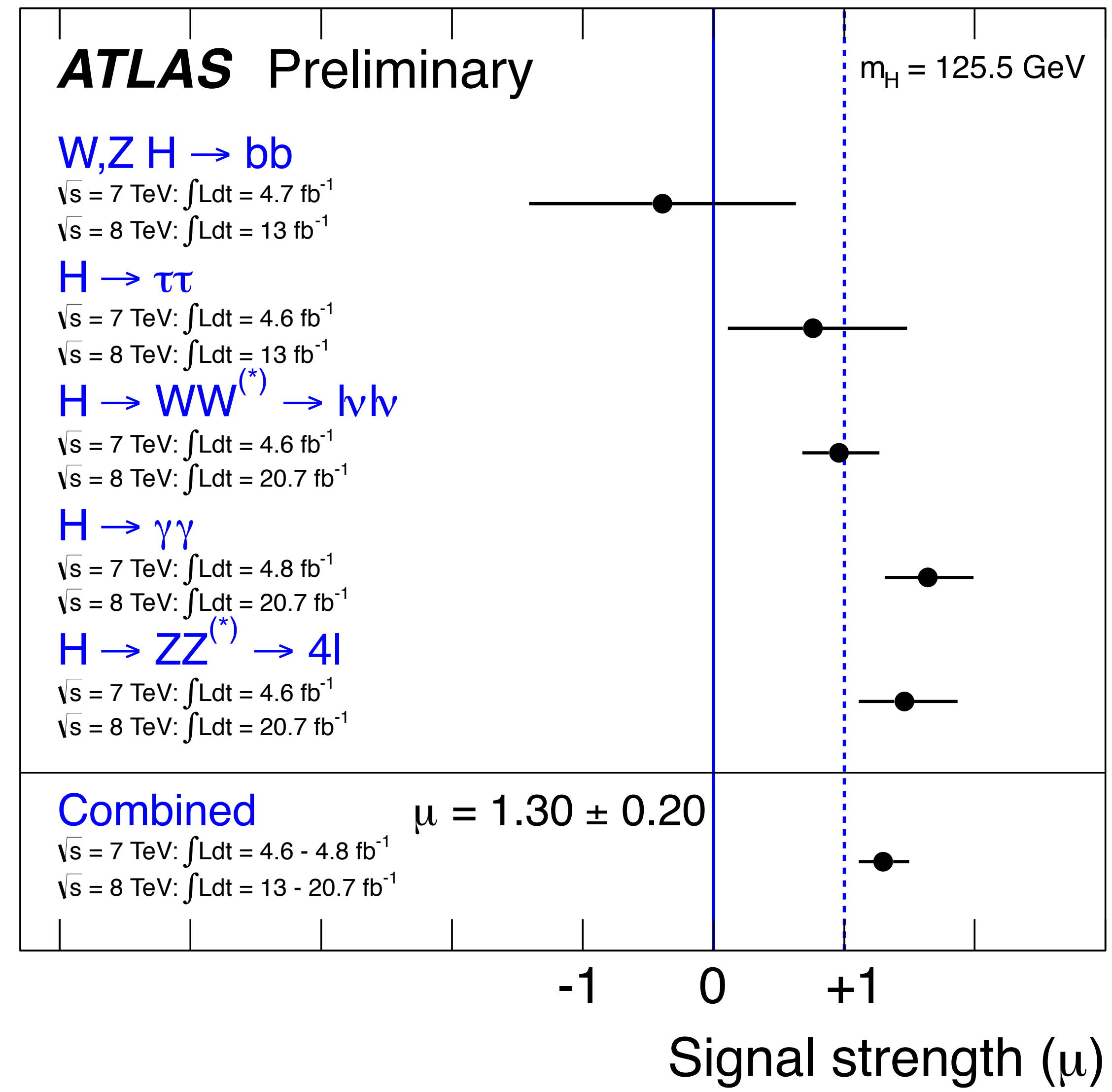


H→ZZ→4l



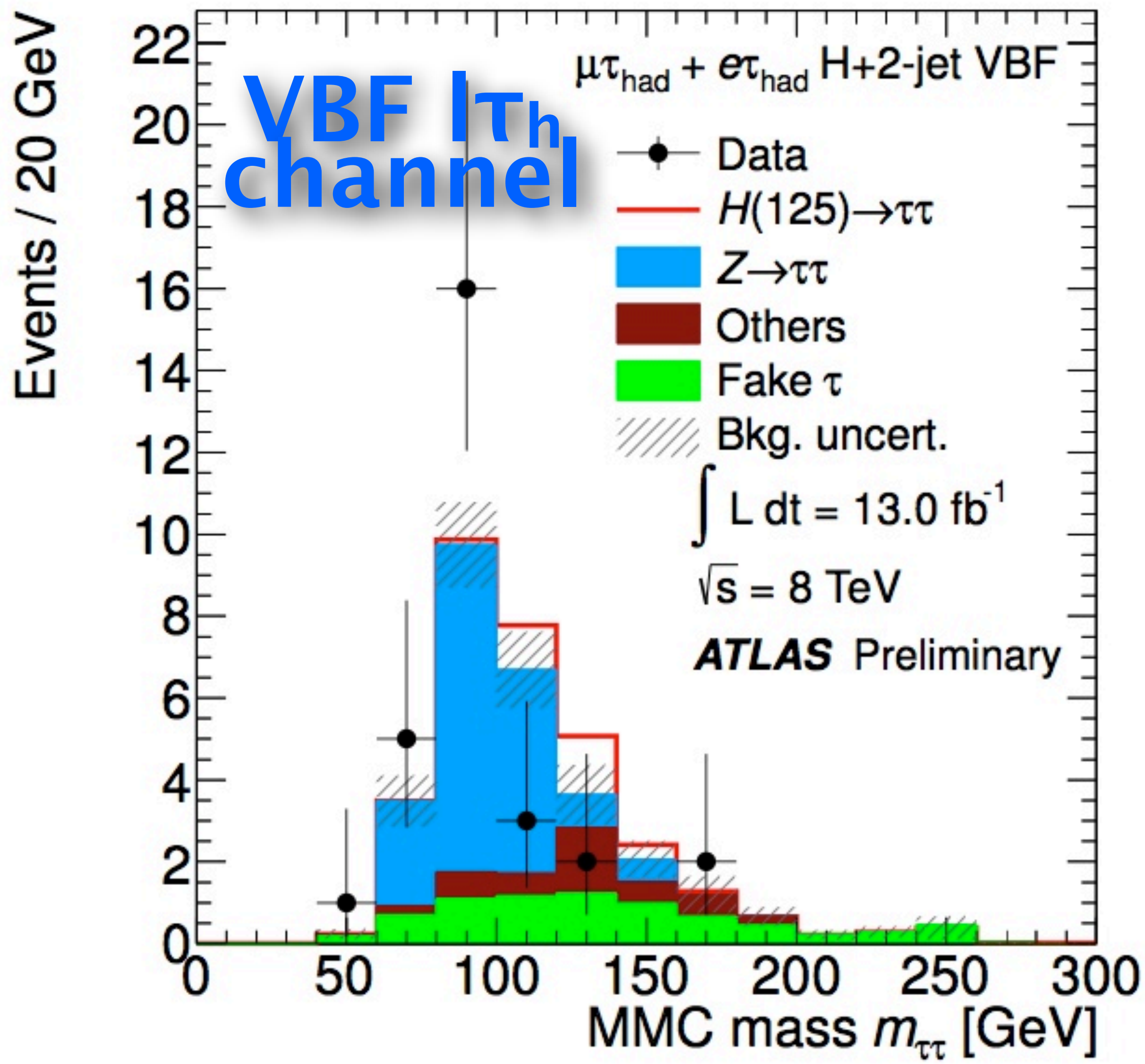
Current Higgs results

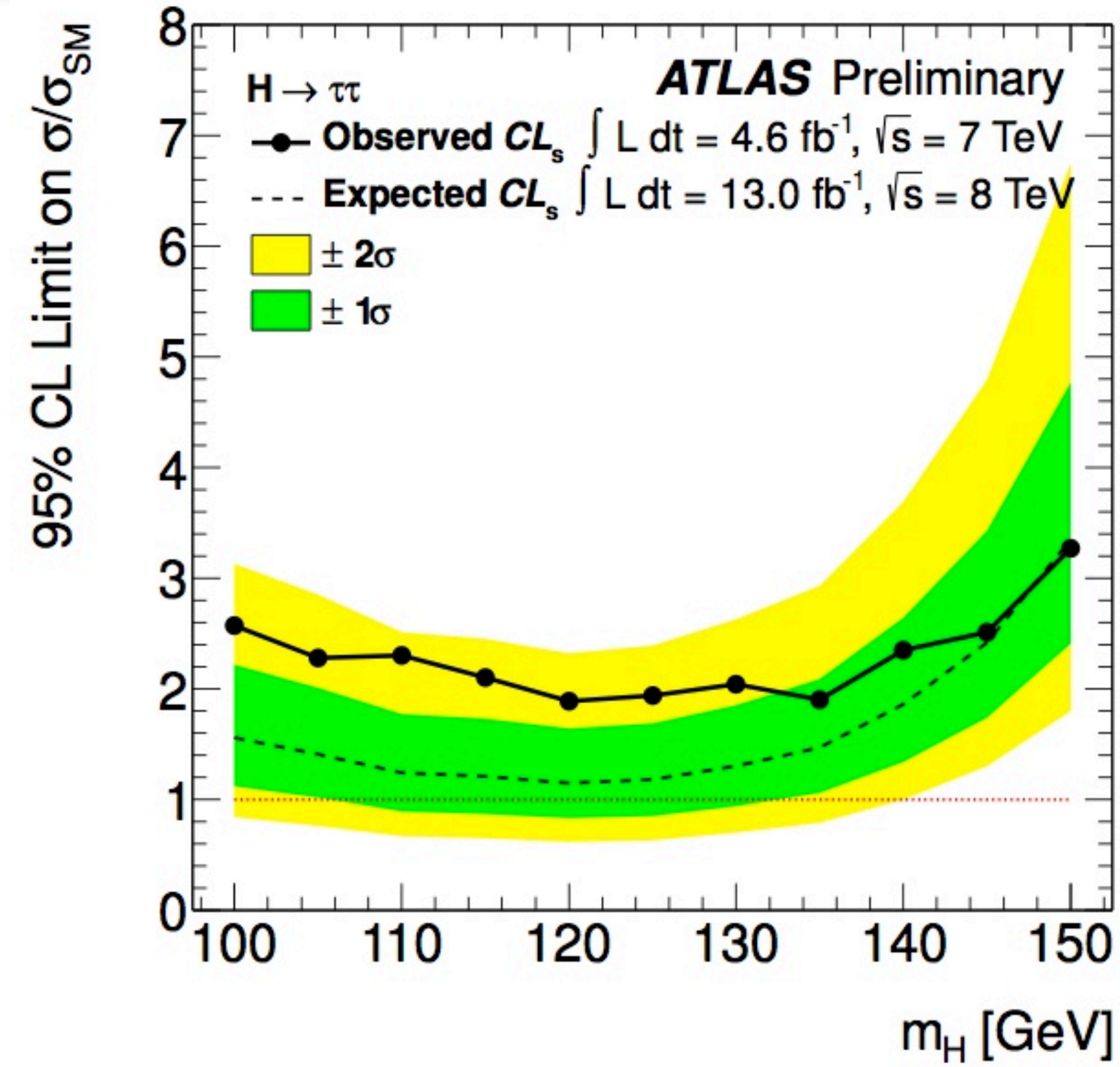




- The measurements in the γγ/ZZ/WW channels are consistent with a new neutral boson with m≈126 GeV.
- Interestingly, both ATLAS and CMS observe the signal strength in the γγ channel to be higher than the SM over 1σ, but still consistent with the SM.
- H→ττ and H→bb are approaching sensitivity.

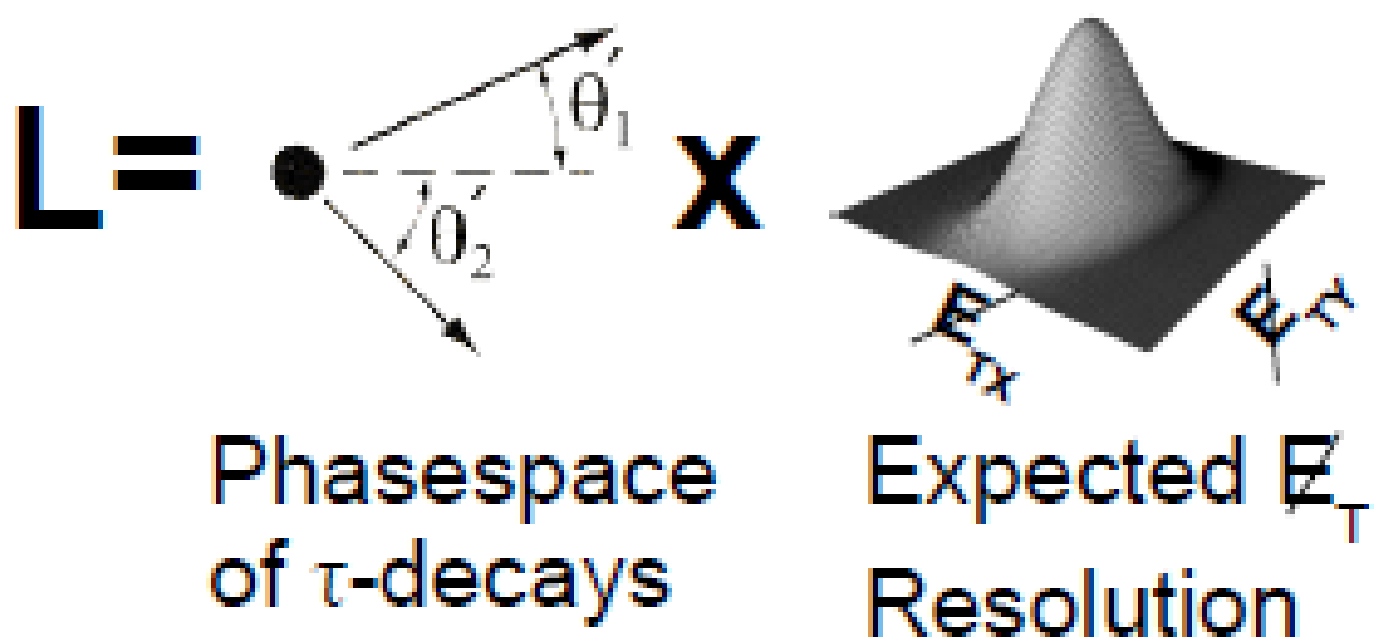
Current H→ττ result





- A lot of shared experience between Z/Z'/H→ττ analyses.
- Uses similar $\sum\Delta\phi$ cut for suppressing W+jet.
- Uses fake factor method for predicting fake backgrounds.
- Eagerly approaching sensitivity to 1×SM H→ττ.
- 21.7 fb^{-1} collected this year.

MMC mass

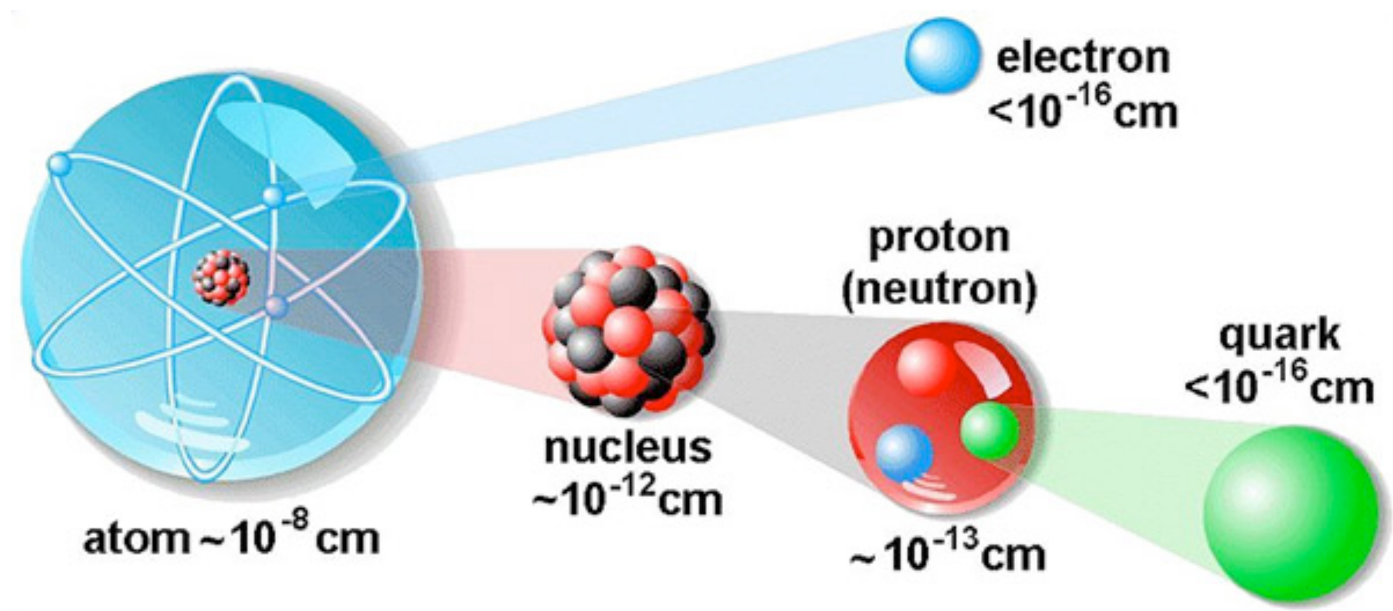


The LHC, ATLAS, and CMS

Particle Physics

Fundamental questions of particle physics:

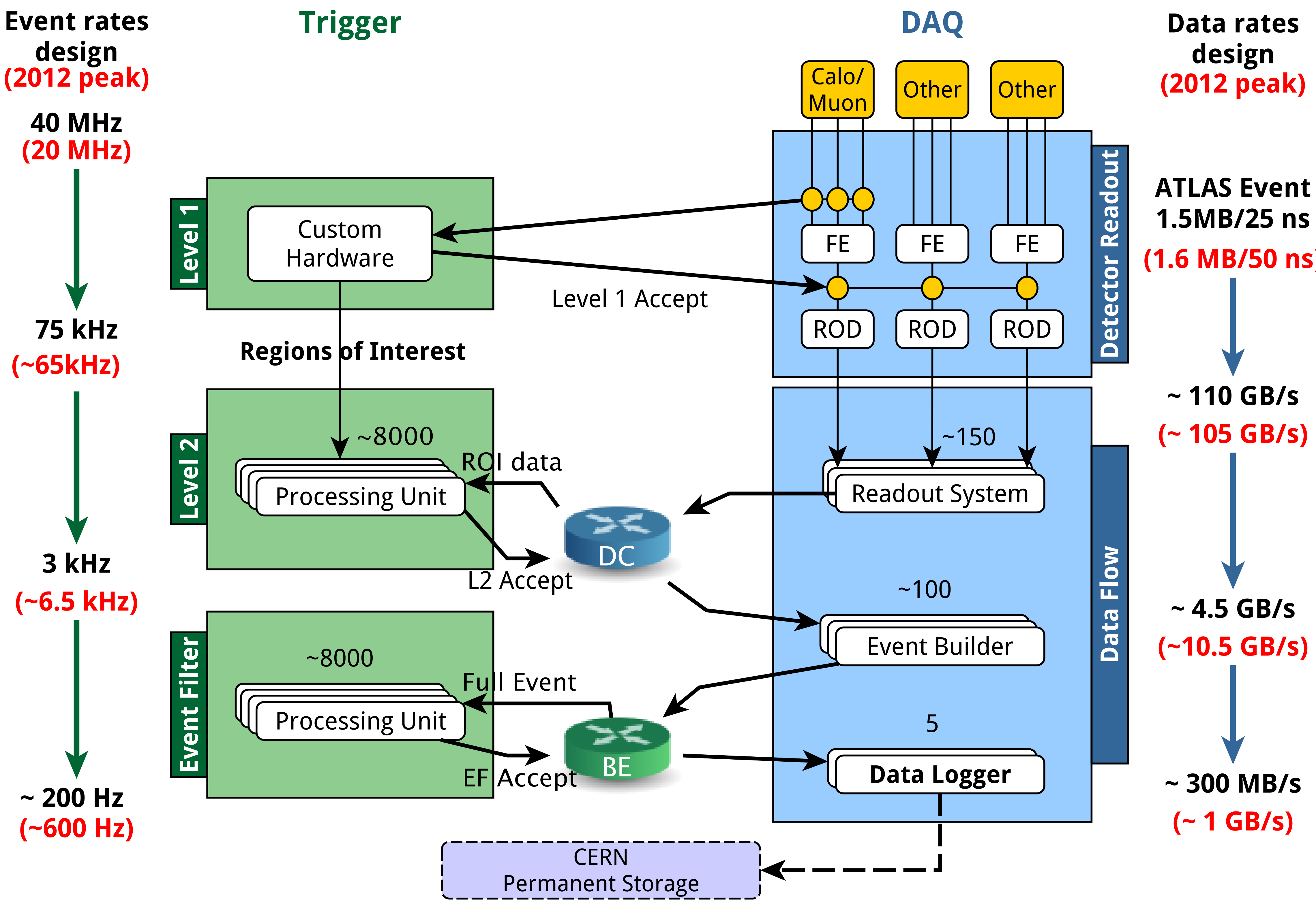
1. **What is matter?**
2. **How does it interact?**



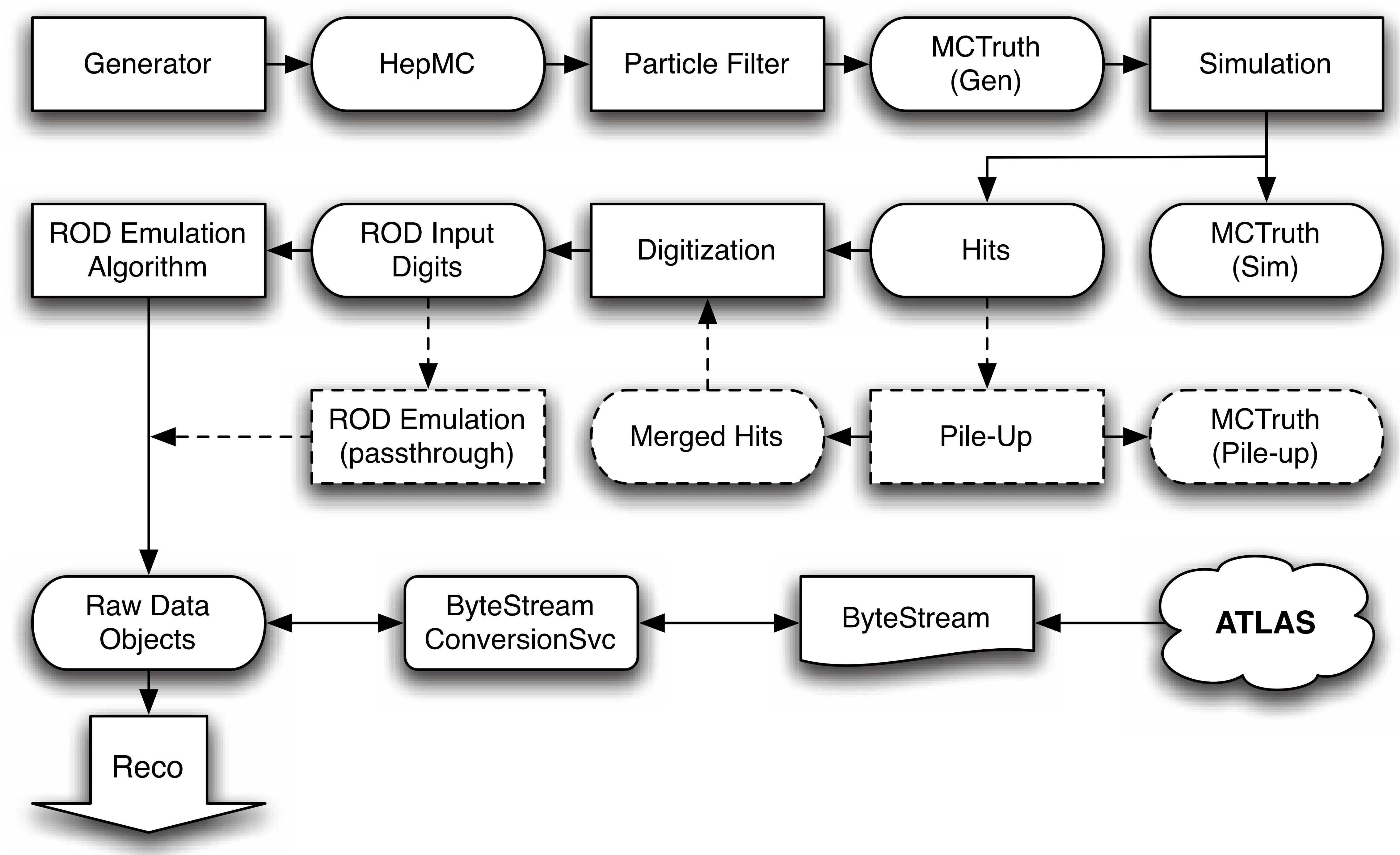
Four fundamental forces at low energies:

1. Gravity – very weak, no complete quantum theory
2. Electromagnetism – binds atoms, chemistry
3. Strong force – nuclear range, binds nuclei
4. Weak force – nuclear range, radioactivity, solar fusion

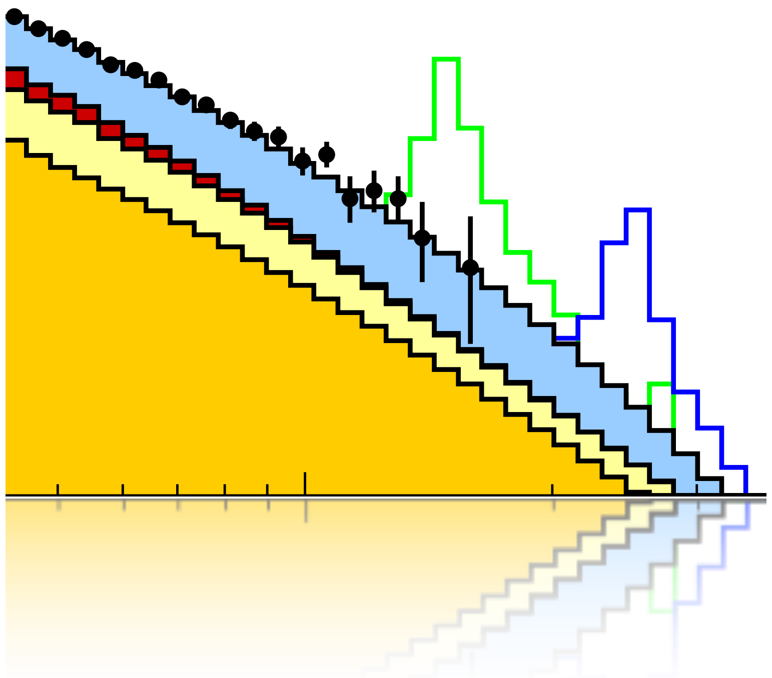
Trigger and DAQ



MC simulation chain



Z’→ττ



Z'→ττ 2011 event

	$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\mu}\tau_{\rm had}$	$\tau_{e}\tau_{\rm had}$	$\tau_{e}\tau_{\mu}$
$m_{Z'}$ [GeV]	1250	1000	1000	750
$m_{\rm T}^{\rm tot}$ threshold [GeV]	700	600	500	350
$Z/\gamma^* \to \tau\tau$	0.73±0.23	0.36±0.06	0.57±0.11	0.55±0.07
W+jets	< 0.03	0.28±0.22	0.8 ±0.4	0.33±0.10
$Z(\to \ell\ell)$+jets	< 0.01	< 0.1	< 0.01	0.06±0.02
$t\bar{t}$	< 0.02	0.33±0.15	0.13±0.09	0.97±0.22
Diboson	< 0.01	0.23±0.07	0.06±0.03	1.69±0.24
Single top	< 0.01	0.19±0.18	< 0.1	< 0.1
Multijet	0.24±0.15	< 0.01	< 0.1	< 0.01
Total expected background	0.97±0.27	1.4 ±0.4	1.6 ±0.5	3.6 ±0.4
Events observed	2	1	0	5
Expected signal events	6.3 ±1.1	5.5 ±0.7	5.0 ±0.5	6.72±0.26
Signal efficiency (%)	4.3	1.1	1.0	0.4

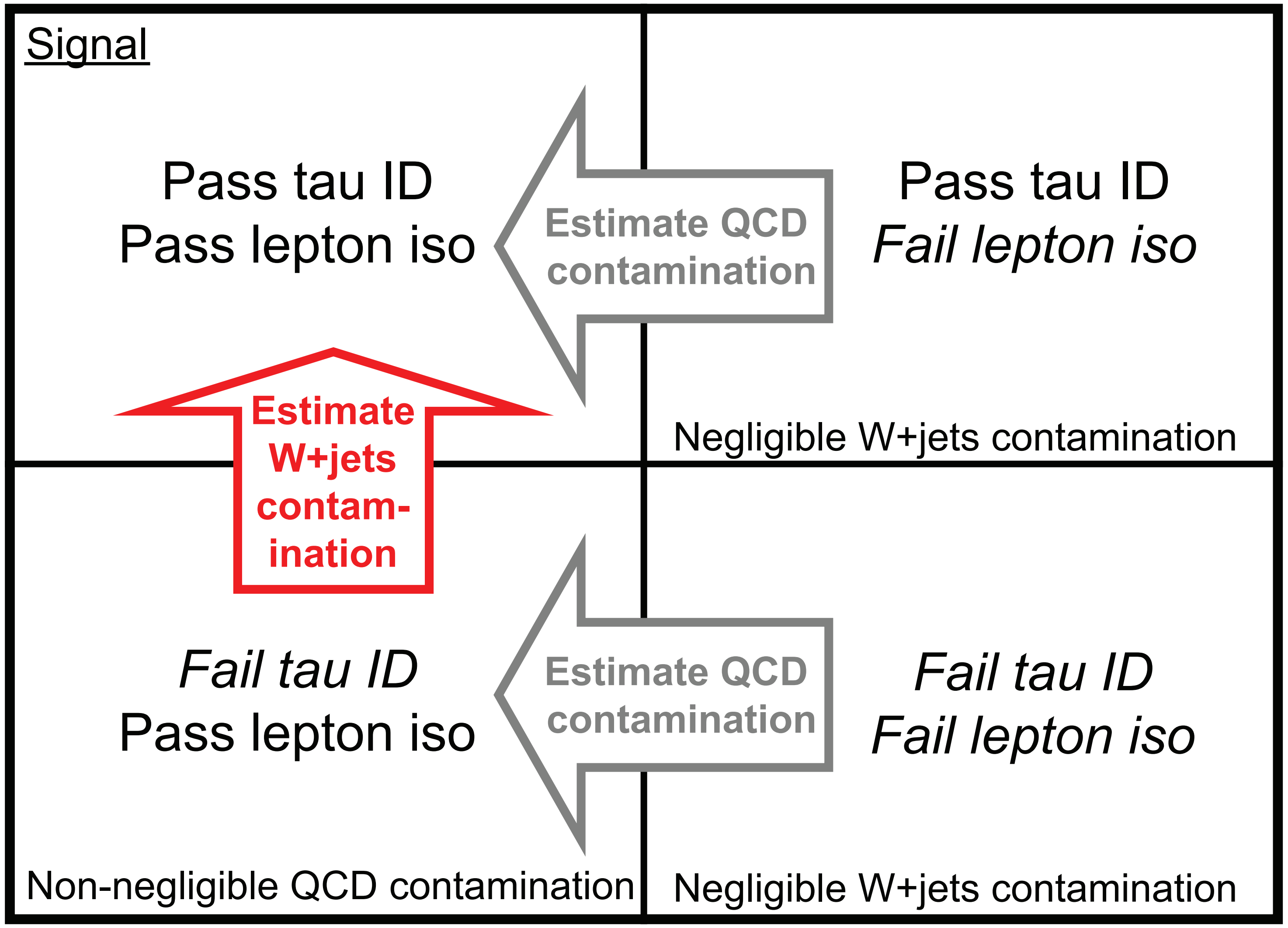
2011 Systematics

Uncertainty [%]	Signal				Background			
	hh	μh	eh	$e\mu$	hh	μh	eh	$e\mu$
Stat. uncertainty	1	2	2	3	5	20	23	7
Eff. and fake rate	16	10	8	1	12	16	4	3
Energy scale and res.	5	7	6	2	$^{+22}_{-11}$	3	8	5
Theory cross section	8	6	6	5	9	4	4	5
Luminosity	4	4	4	4	2	2	2	4
Data-driven methods	–	–	–	–	$^{+21}_{-11}$	6	16	–

Table 2: Uncertainties on the estimated signal and total background contributions in percent for each channel. The following signal masses, chosen to be close to the region where the limits are set, are used: 1250 GeV for $\tau_{\text{had}}\tau_{\text{had}}$ (hh); 1000 GeV for $\tau_\mu\tau_{\text{had}}$ (μh) and $\tau_e\tau_{\text{had}}$ (eh); and 750 GeV for $\tau_e\tau_\mu$ ($e\mu$). A dash denotes that the uncertainty is not applicable. The statistical uncertainty corresponds to the uncertainty due to limited sample size in the MC and control regions.

Double fake factor procedure

'11-'12



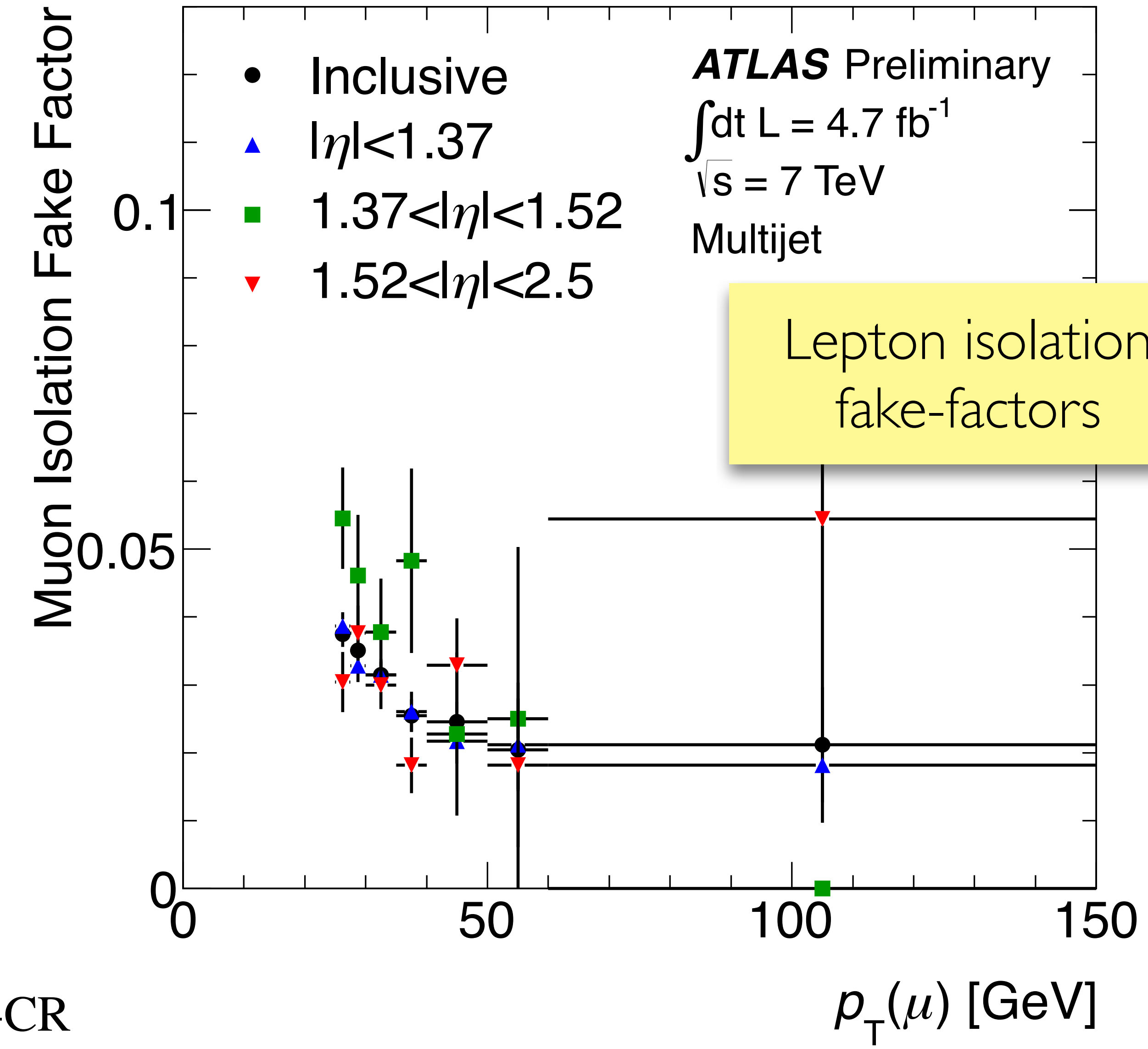
- The multijet contamination is estimated from the rate of non-isolated leptons, in both the signal region that passes tau ID, and the sample that fails.
- Then, the corrected number of tau candidates failing ID are weighted to predicted the W+jet background.
- This way, *the corrections are small at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

Z'→τ$_l$τ$_h$ Multijet background estimation

'11-'12

Multijet control

- no isolation
- $E_T^{miss} < 30$ GeV
- $m_T(\mu, E_T^{miss}) < 30$ GeV



Lepton isolation fake-factors

- In the control region, divide leptons into pass and fail isolation.
- Define fake factor:

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

- Predict the number of multijet events:

$$N_{\text{multijet}}(p_T, \eta, x) = f_{\mu\text{–iso}}(p_T, \eta) \cdot N_{\text{multijet}}^{\text{fail }\mu\text{–iso}}(p_T, \eta, x)$$

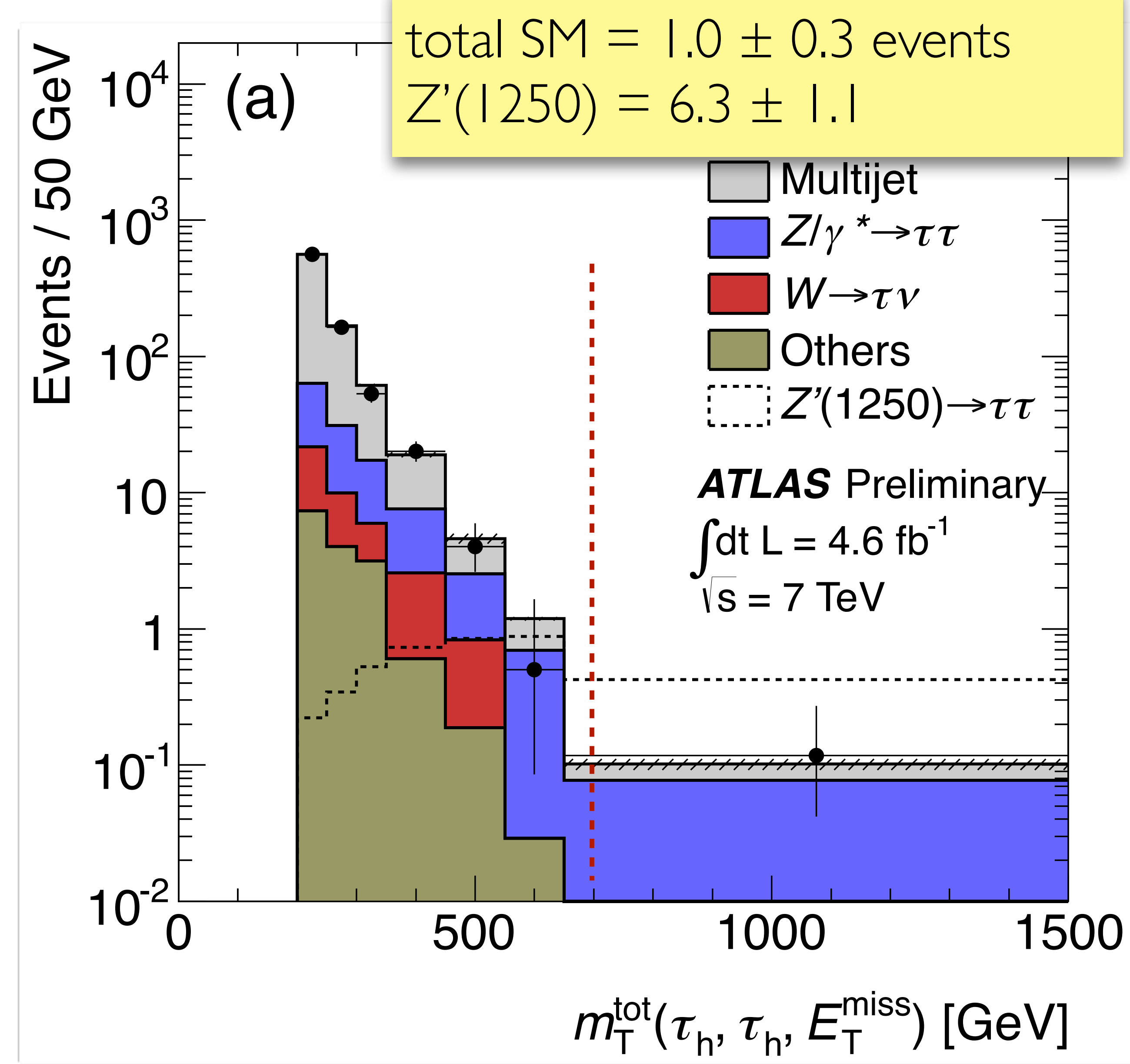
$$= f_{\mu\text{–iso}}(p_T, \eta) \cdot \left(N_{\text{data}}^{\text{fail }\mu\text{–iso}}(p_T, \eta, x) - N_{\text{MC}}^{\text{fail }\mu\text{–iso}}(p_T, \eta, x)\right)$$

2011 Z' → ττ → τhτh

- 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



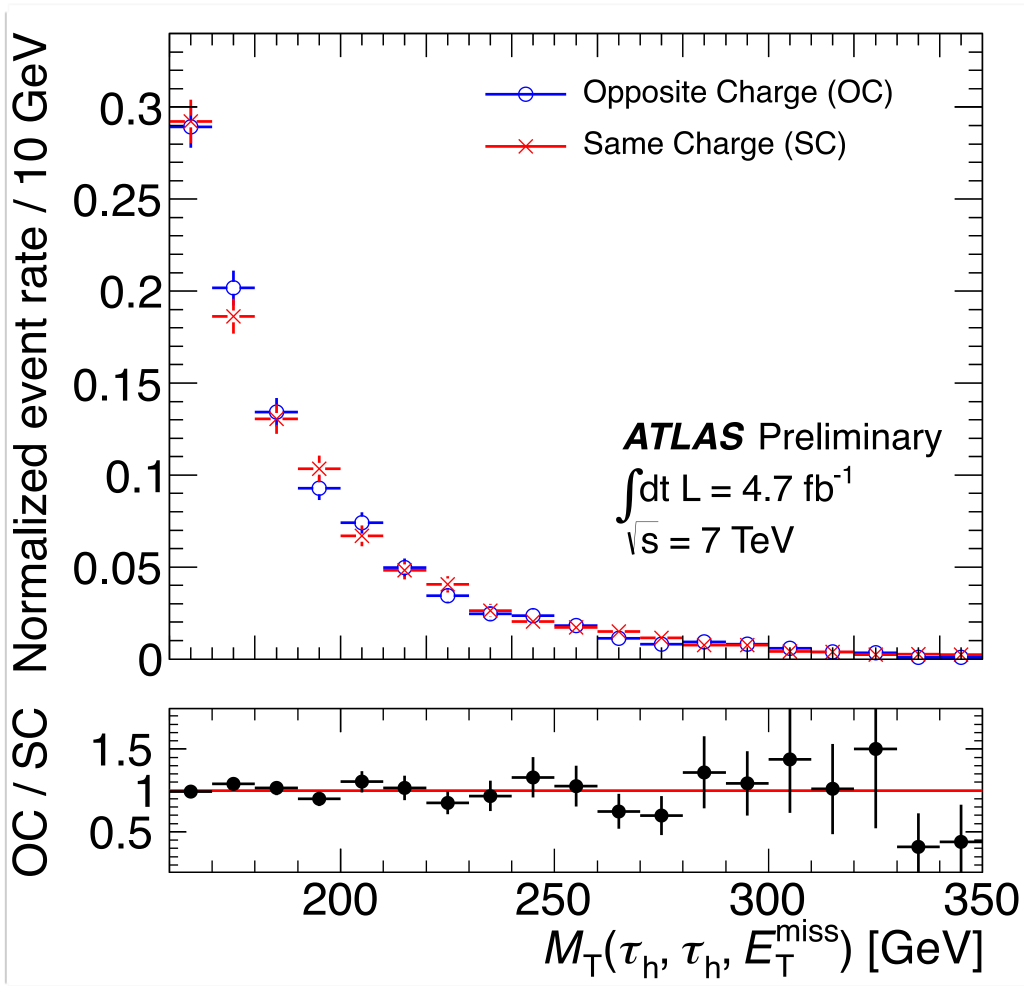
- Tau ID efficiency uncert. ≈ 11% on the signal. (4% from $Z \to \tau\tau$ tag-and-probe)
- Jet/tau energy scale uncert. ≈ +22/-11%
- Multijet modeled by fitting the shape of the SS data. uncert. ≈ +21/-11%

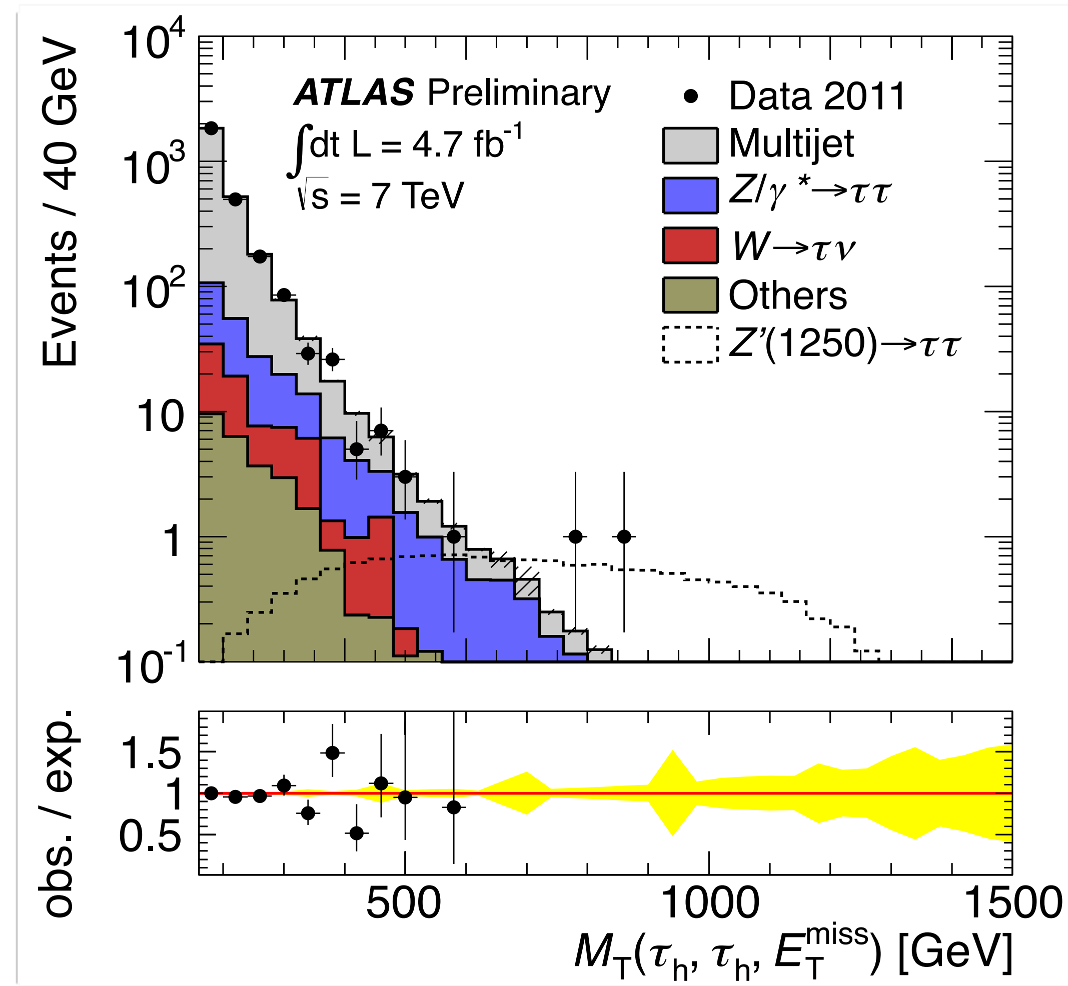
[ATLAS-CONF-2012-067]

Z'→$\tau_h\tau_h$ multijet background

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]

Z'→τhτh 2012 cut flow

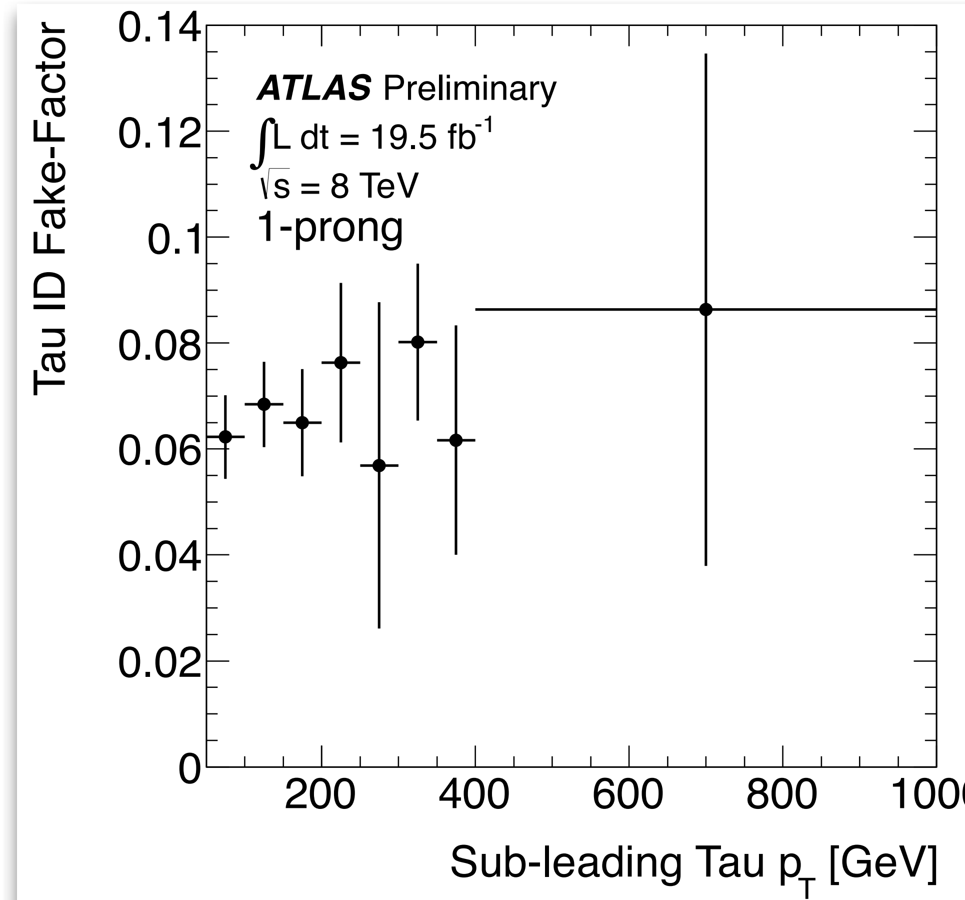
	$Z/\gamma^* \to \tau\tau$	Multijet	W/Z+jets	Top	Diboson	SM total	Data	$Z'_{\mathrm{SSM}}(1750)$
Preselection	270 ± 50	630 ± 100	80 ± 50	27 ± 15	1.1 ± 0.6	1000 ± 140	1016	9.4 ± 1.5
$\Delta\phi(\tau_1, \tau_2)$	120 ± 20	420 ± 70	48 ± 30	13 ± 6	0.1 ± 0.1	600 ± 80	577	9.2 ± 1.5
OS	113 ± 18	210 ± 40	34 ± 22	10 ± 4	0.1 ± 0.1	370 ± 50	372	8.7 ± 1.4
$m_{\mathrm{T}}^{\mathrm{tot}} > 300$ GeV	102 ± 17	96 ± 17	28 ± 19	7 ± 3	0.1 ± 0.1	230 ± 40	235	8.7 ± 1.4
$m_{\mathrm{T}}^{\mathrm{tot}} > 350$ GeV	63 ± 11	40 ± 9	18 ± 12	5.0 ± 1.9	0.1 ± 0.0	126 ± 21	123	8.6 ± 1.4
$m_{\mathrm{T}}^{\mathrm{tot}} > 400$ GeV	37 ± 7	18 ± 4	10 ± 7	2.0 ± 1.1	< 0.1	66 ± 12	59	8.4 ± 1.4
$m_{\mathrm{T}}^{\mathrm{tot}} > 450$ GeV	22 ± 4	9 ± 3	6 ± 4	1.2 ± 0.6		38 ± 7	31	8.3 ± 1.4
$m_{\mathrm{T}}^{\mathrm{tot}} > 500$ GeV	14 ± 3	4.4 ± 1.6	4 ± 3	0.6 ± 0.3		23 ± 5	20	8.0 ± 1.3
$m_{\mathrm{T}}^{\mathrm{tot}} > 550$ GeV	8.9 ± 1.8	2.7 ± 1.1	1.8 ± 1.3	0.4 ± 0.3		14 ± 3	12	7.7 ± 1.3
$m_{\mathrm{T}}^{\mathrm{tot}} > 600$ GeV	5.9 ± 1.2	1.8 ± 0.8	1.1 ± 0.8	0.1 ± 0.1		9.0 ± 1.8	5	7.4 ± 1.3
$m_{\mathrm{T}}^{\mathrm{tot}} > 650$ GeV	4.1 ± 0.8	1.0 ± 0.5	0.7 ± 0.5	0.1 ± 0.1		5.9 ± 1.2	3	7.1 ± 1.2
$m_{\mathrm{T}}^{\mathrm{tot}} > 700$ GeV	2.8 ± 0.6	0.6 ± 0.3	0.5 ± 0.3	< 0.1		3.9 ± 0.8	0	6.7 ± 1.1
$m_{\mathrm{T}}^{\mathrm{tot}} > 750$ GeV	1.9 ± 0.4	0.5 ± 0.3	0.3 ± 0.2			2.8 ± 0.6	0	6.3 ± 1.1
$m_{\mathrm{T}}^{\mathrm{tot}} > 800$ GeV	1.4 ± 0.3	0.3 ± 0.2	0.2 ± 0.2			2.0 ± 0.4	0	6.0 ± 1.0
$m_{\mathrm{T}}^{\mathrm{tot}} > 850$ GeV	1.0 ± 0.2	0.2 ± 0.1	0.2 ± 0.1			1.4 ± 0.3	0	5.6 ± 1.0
$m_{\mathrm{T}}^{\mathrm{tot}} > 900$ GeV	0.7 ± 0.2	0.1 ± 0.1	0.1 ± 0.1			1.0 ± 0.2	0	5.2 ± 0.9

region with 95% CL exclusion: $m_{\mathrm{T}}^{\mathrm{tot}} > 850$ GeV
total SM = 1.4 ± 0.3 events $Z'_{\mathrm{SSM}}(1750) = 5.6 \pm 1.0$
observed 0 events

Z'→$\tau_h\tau_h$ multijet background

- In a dijet sample, select same-sign (SS) to remove Drell-Yann contamination.
- measure tau ID **fake factors** for the sub-leading tau.

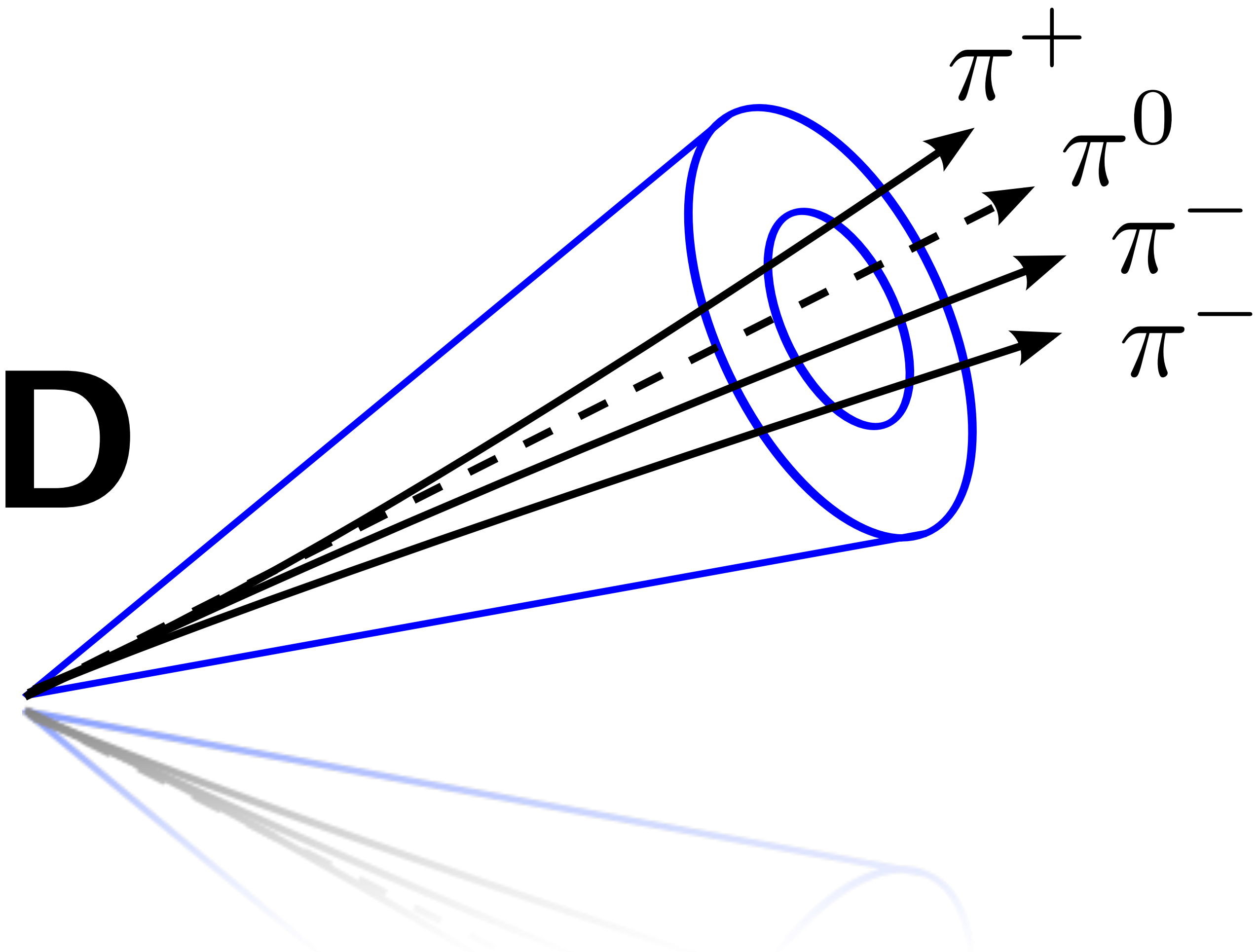
$$f_{\tau-\mathrm{ID}}(p_{\mathrm{T}}, N_{\mathrm{track}}) \equiv \left. \frac{N^{\mathrm{pass}\ \tau-\mathrm{ID}}(p_{\mathrm{T}}, N_{\mathrm{track}})}{N^{\mathrm{fail}\ \tau-\mathrm{ID}}(p_{\mathrm{T}}, N_{\mathrm{track}})} \right|_{\mathrm{dijet}}$$



- Predict the number of multijet events by weighting the events failing tau ID:

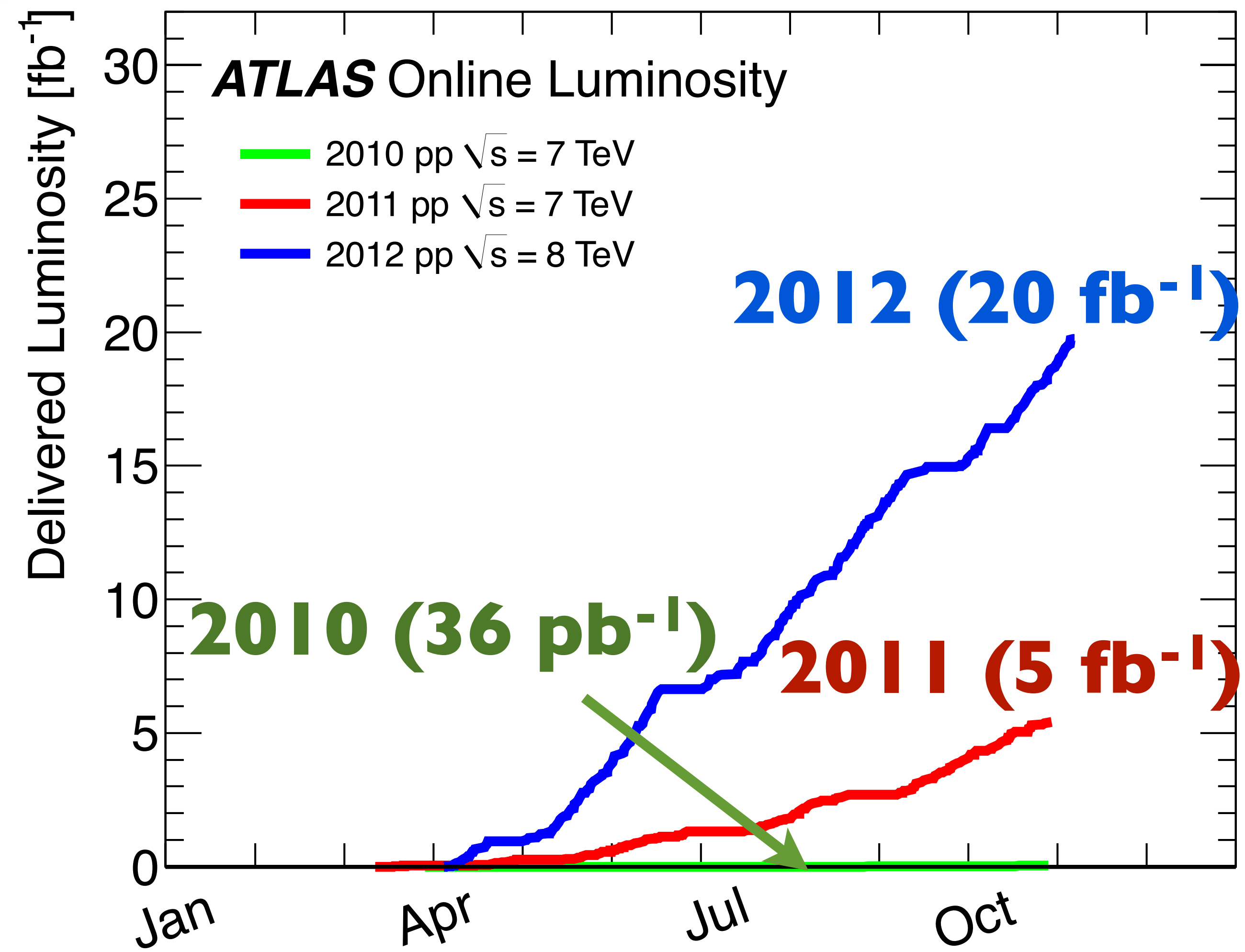
$$N_{\mathrm{multijet}}(p_{\mathrm{T}}, N_{\mathrm{track}}, x) = f_{\tau-\mathrm{ID}}(p_{\mathrm{T}}, N_{\mathrm{track}}) \times N^{\mathrm{fail}\ \tau-\mathrm{ID}}{}_{\mathrm{data}}(p_{\mathrm{T}}, N_{\mathrm{track}}, x)$$

ATLAS Tau ID



Timeline of taus at

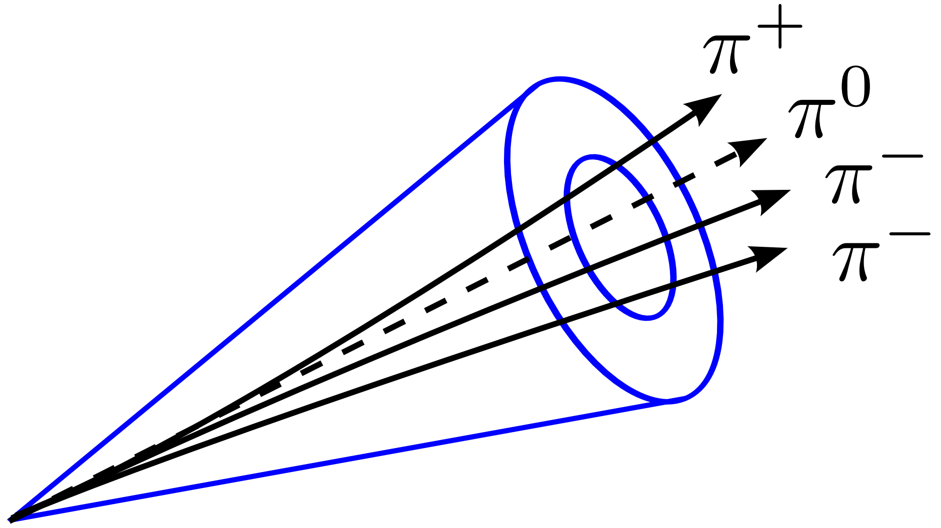
- Nov 2010: Obseravation of **W→τν** ($546\ nb^{-1}$)
- Feb 2011: Observation of **Z→ττ** ($8.5\ pb^{-1}$)
- July 2011: **W→τν** and **Z→ττ** cross section measurements ($36\ pb^{-1}$)
- June 2012: **SM H→ττ** excluded **3-4×SM at m_H≈125 GeV** [arXiv:1206.5971]
- 2012: Several other analyses: MSSM H→ττ, tt with τ, H^+→τν, **Z'→ττ**, SUSY τ +MET, ...



- Nov 2012: **SM H→ττ** excluded **1.9×SM at m_H≈125 GeV** (13/fb) [ATLAS-CONF-2012-160]
- 2013: Expecting further improvements in updated **ττ** analysis results using the entire 2012 data for **H→ττ** and **Z'→ττ** searches.

Phenomenology of tau decays

$\tau^- \rightarrow$	$e^- \, \bar{\nu}_e \, \nu_\tau$	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%	

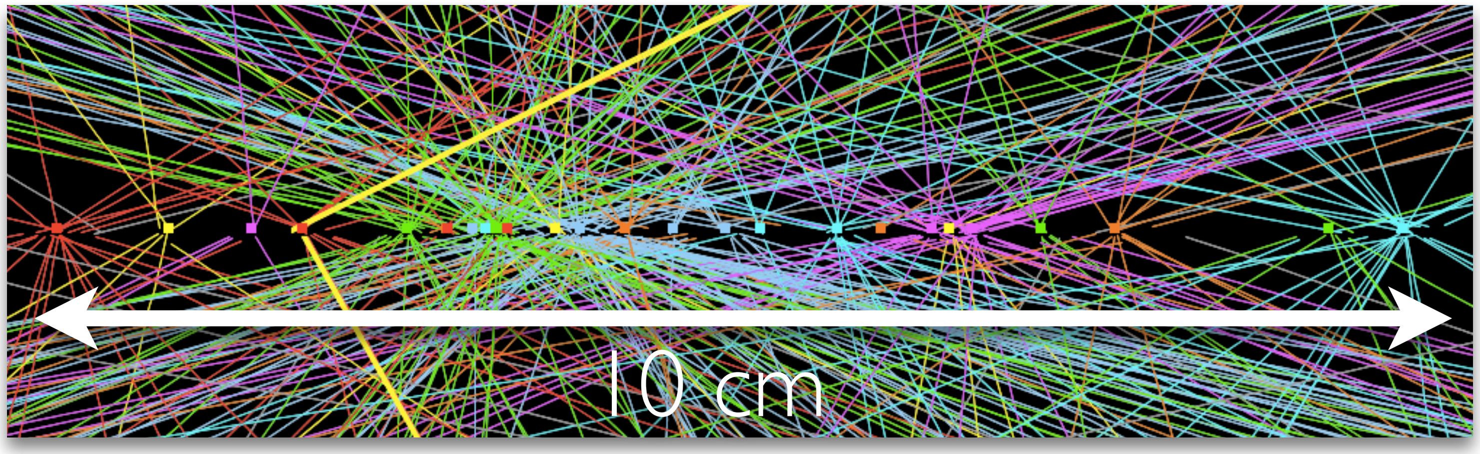


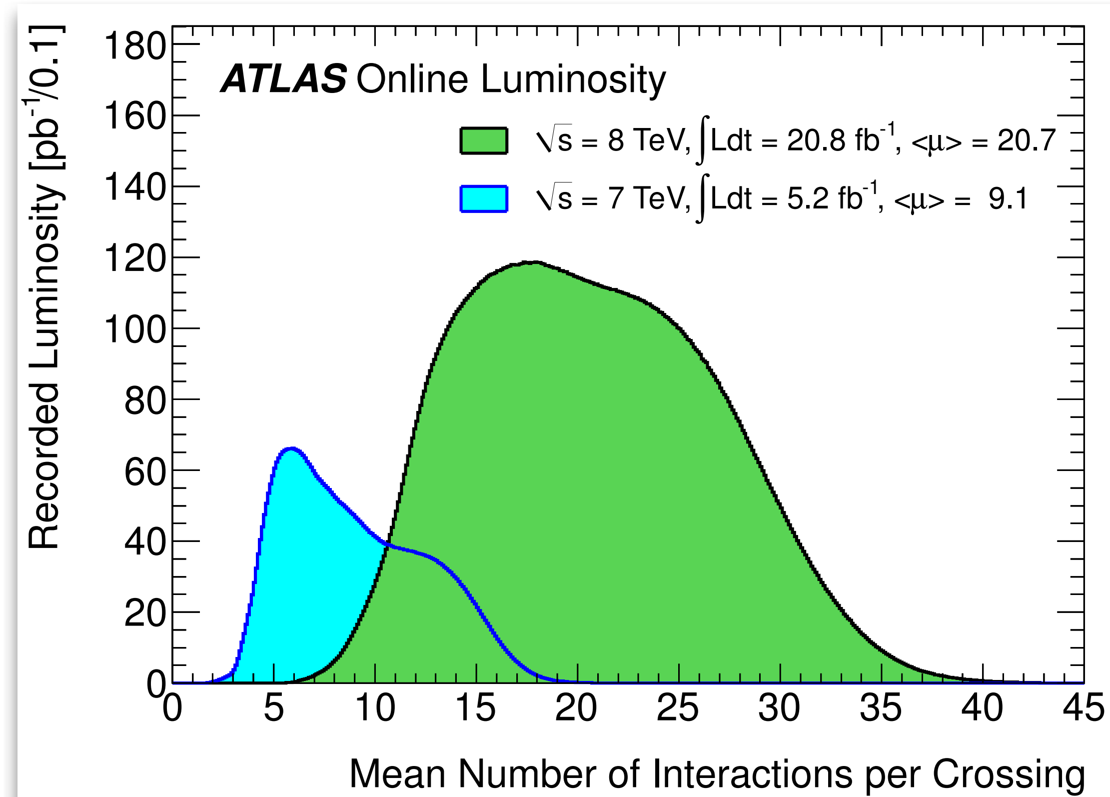
Current tau identification variables

1. Core energy fraction* $$f_{\mathrm{core}} = \frac{\sum_{\{\Delta R<0.1\}} E_{\mathrm{T}}^{\mathrm{EM}}(\mathrm{cell})}{\sum_{\{\Delta R<0.2\}} E_{\mathrm{T}}^{\mathrm{EM}}(\mathrm{cell})}$$
2. Leading track momentum fraction*
3. Track radius $$R_{\mathrm{track}} = \frac{\sum_{\{\Delta R<0.4\}} p_{\mathrm{T}}(\mathrm{track})\, \Delta R(\mathrm{track},\ \mathrm{jet})}{\sum_{\{\Delta R<0.4\}} p_{\mathrm{T}}(\mathrm{track})}$$
4. Number of isolation tracks $N_{\mathrm{trk}}^{0.2<\Delta R<0.4}$
5. Leading track impact parameter significance $$S_{\mathrm{lead\ track}} = \frac{d_0}{\sigma_{d_0}}$$
6. Transverse flight path significance $$S_{\mathrm{T}}^{\mathrm{flight}} = \frac{L_{\mathrm{T}}^{\mathrm{flight}}}{\sigma_{L_{\mathrm{T}}^{\mathrm{flight}}}}$$
7. Mass of track system
8. Maximum ΔR between jet-axis and core tracks

*has pile-up correction term linear in N(vertex)

Pile-up





- 1-40 pile-up interactions / crossing
- The additional tracks and clusters from pile-up are especially challenging
- for tau identification, which discriminates hadronic tau decays from jets with isolation-related track and calorimeter quantities.
- Efforts in 2011-2012 involved re-defining or adding corrections to identification variables to be more robust against the increasing pile-up.

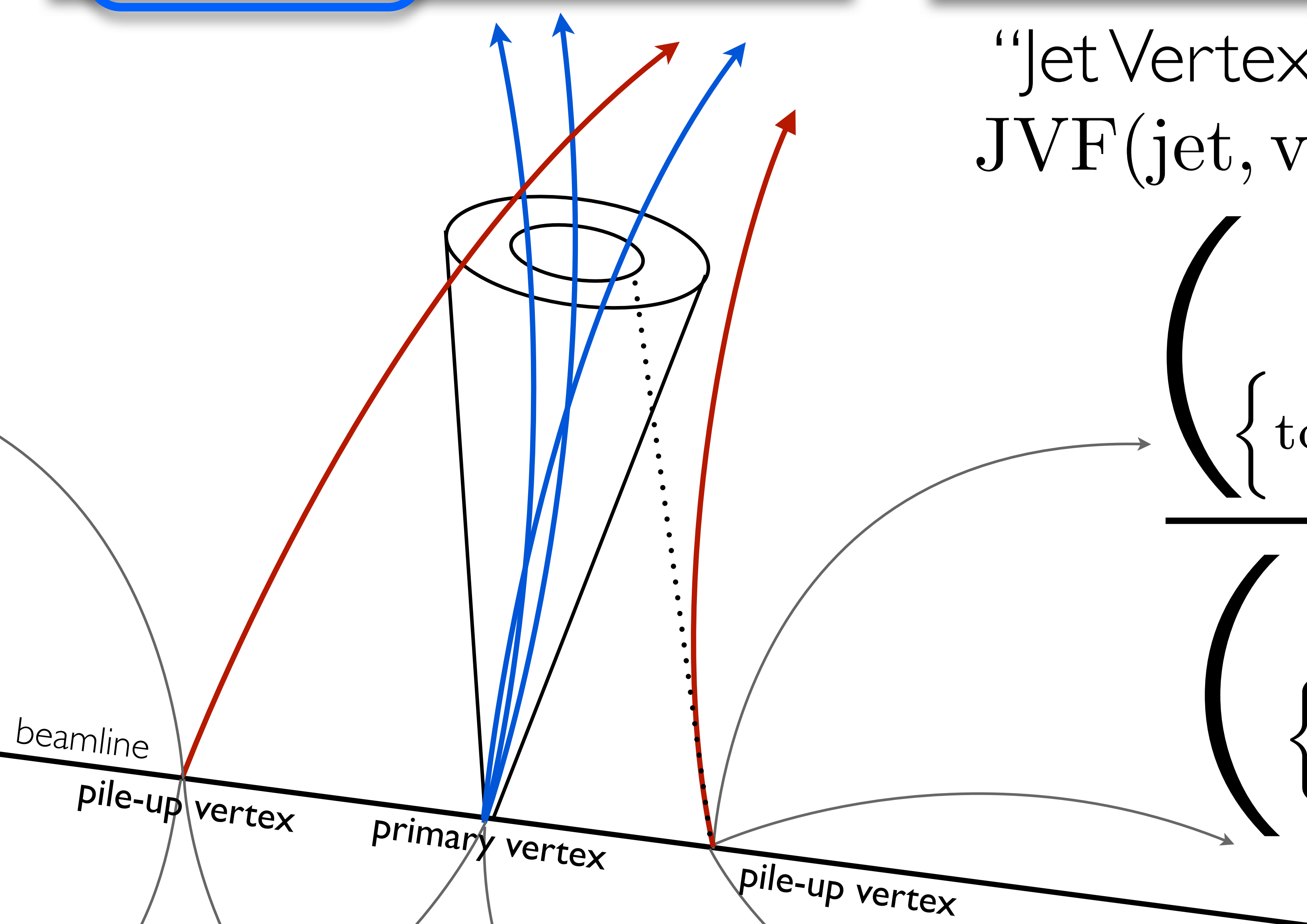
[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults]

Tau vertex association

Tau track selection

- $p_T > 1$ GeV,
- Number of pixel hits ≥ 2,
- Number of pixel hits + number of SCT hits ≥ 7,
- $|d_0| < 1.0$ mm,
- $|z_0 \sin\theta| < 1.5$ mm,

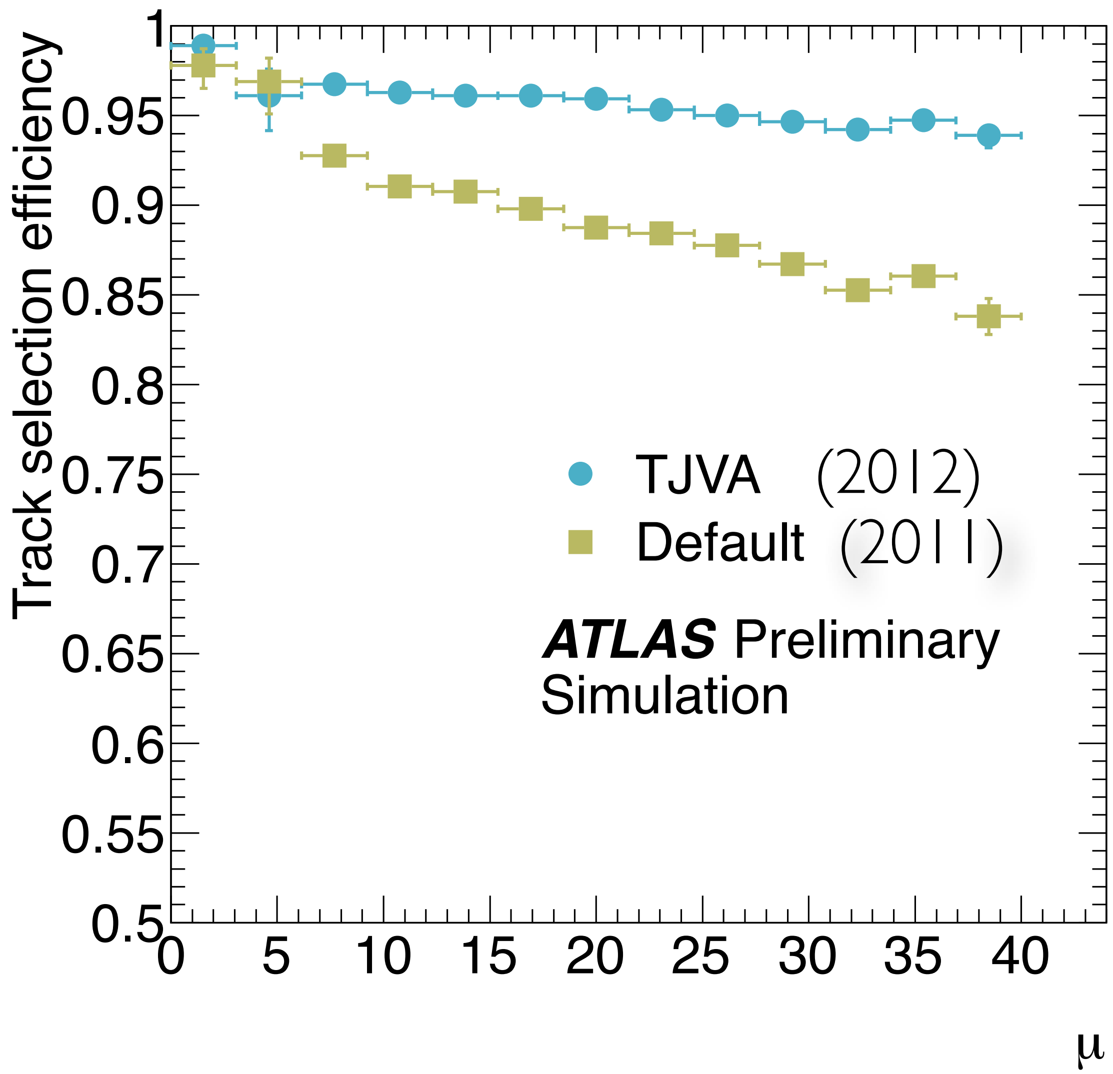
- The d_0 and z_0 requirements depend on the choice of vertex.
- Beginning in 2012, choose the vertex with the highest JVF for that tau candidate.

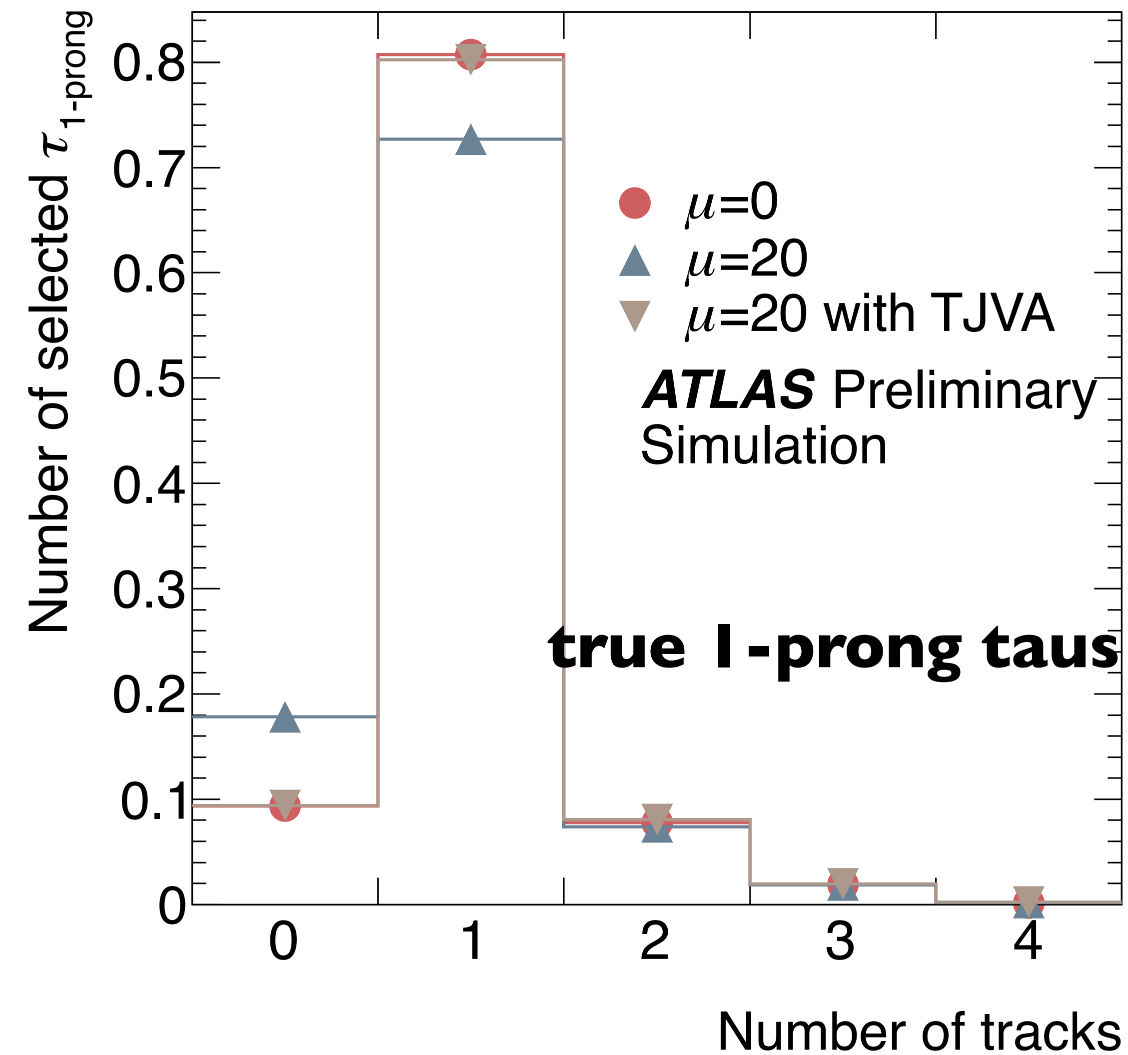


"Jet Vertex Fraction"

$$\mathrm{JVF(jet, vertex)} = \frac{\left(\sum_{\{\text{tracks matched to jet and vertex}\}} p_T(\text{track})\right)}{\left(\sum_{\{\text{tracks matched to jet}\}} p_T(\text{track})\right)}$$

Track selection

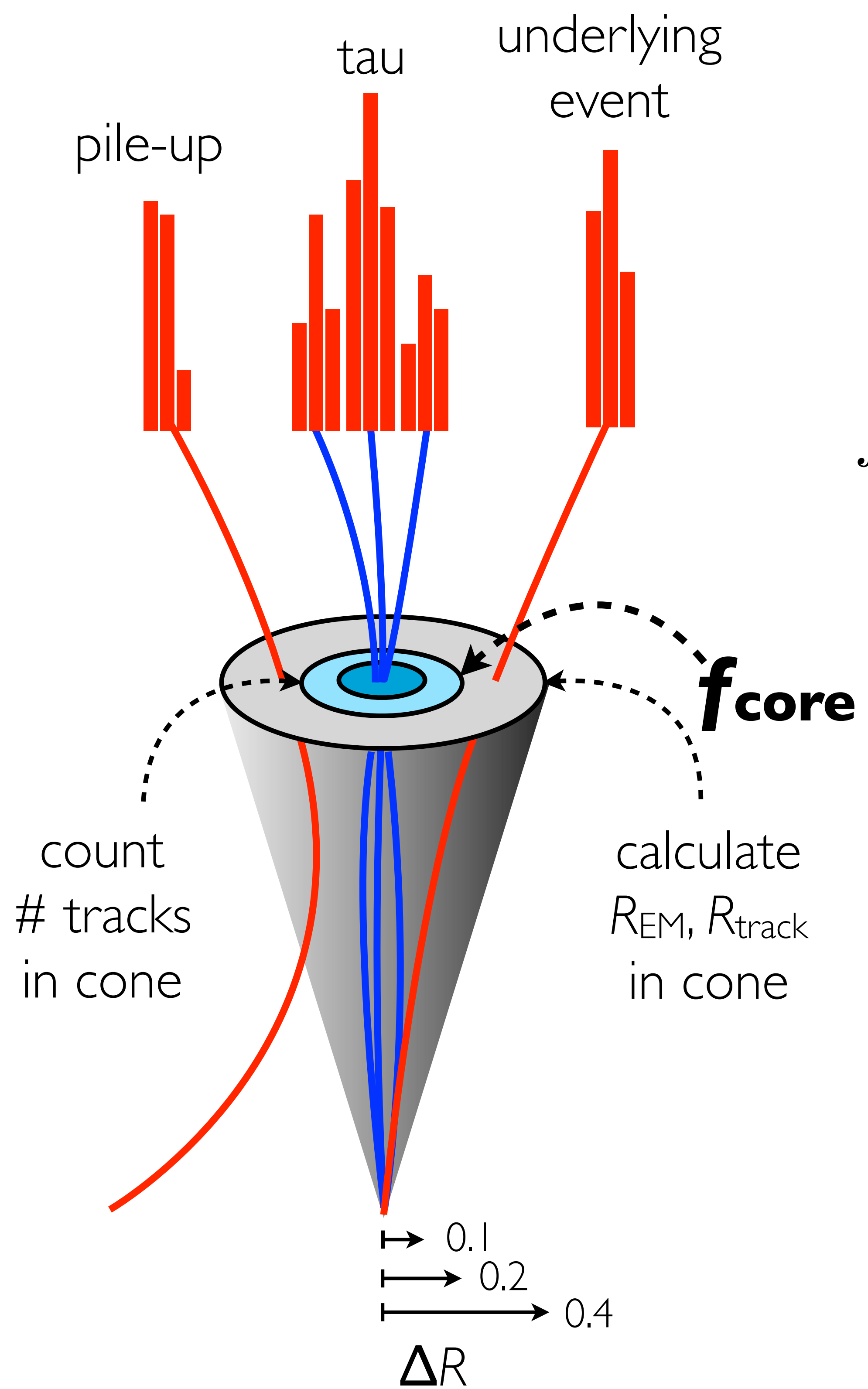




- In 2011, the track selection for tau candidates cut on the d_0 and z_0 with respect to the vertex with the highest $\sum p_T^2$.
- Selecting the vertex with the highest JVF recovers efficiency in high pile-up (Tau Jet Vertex Association).

Pile-up robust variables

2011

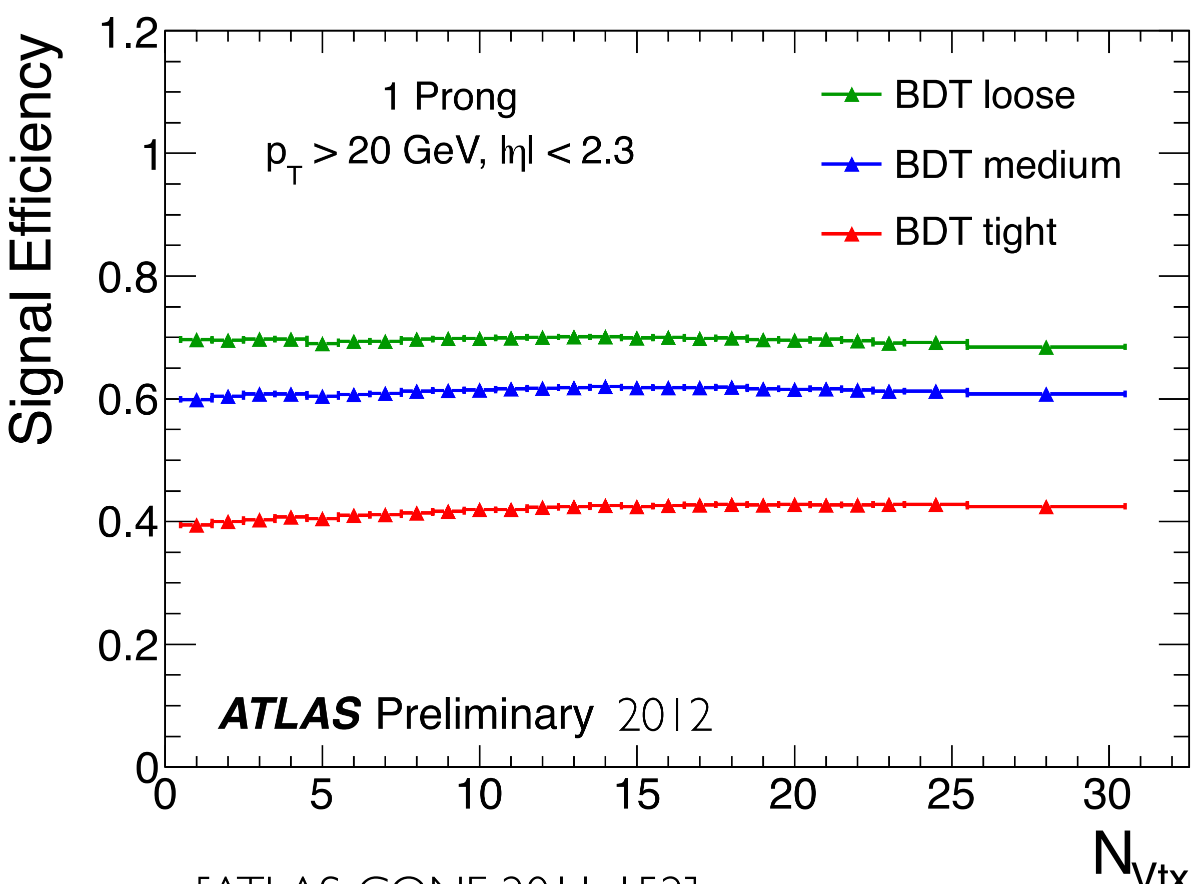


- Beginning in 2012, the core energy fraction is used instead of R_{EM}, which has less pile-up dependence by using the ratio of energies in smaller ΔR cones of 0.1 and 0.2.

$$f_{\rm core} = \frac{\sum_{\{\Delta R<0.1\}} E_{\rm T}^{\rm EM}({\rm cell})}{\sum_{\{\Delta R<0.2\}} E_{\rm T}^{\rm EM}({\rm cell})}$$

+ (0.3%/vertex) × N(vertex)

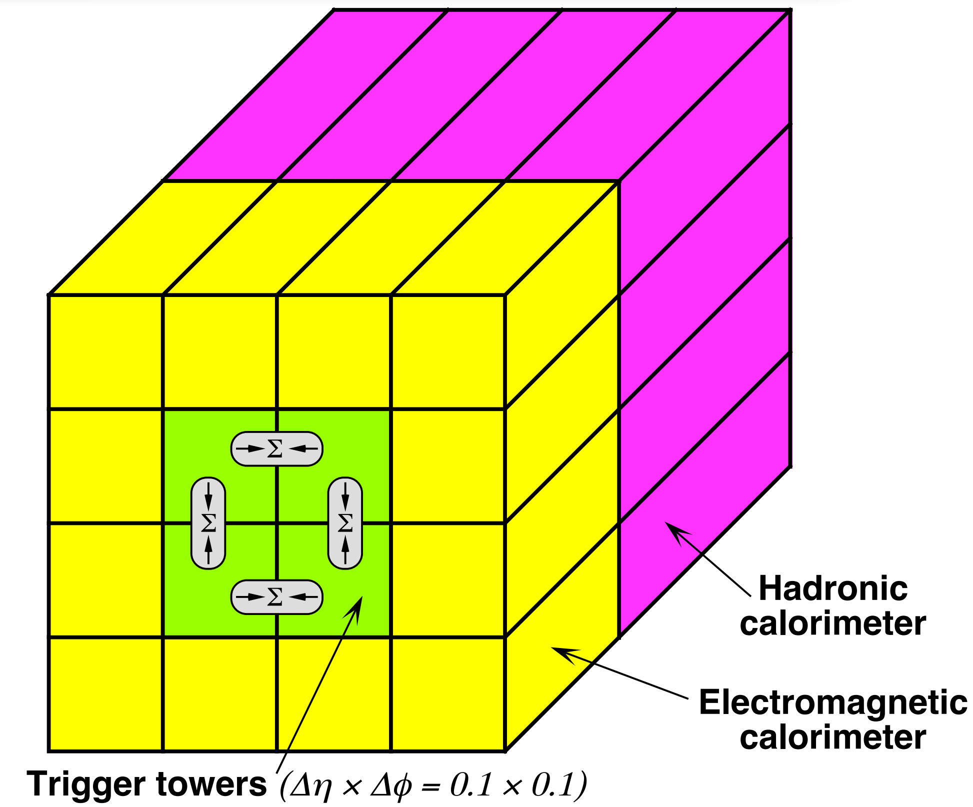
linear pile-up correction

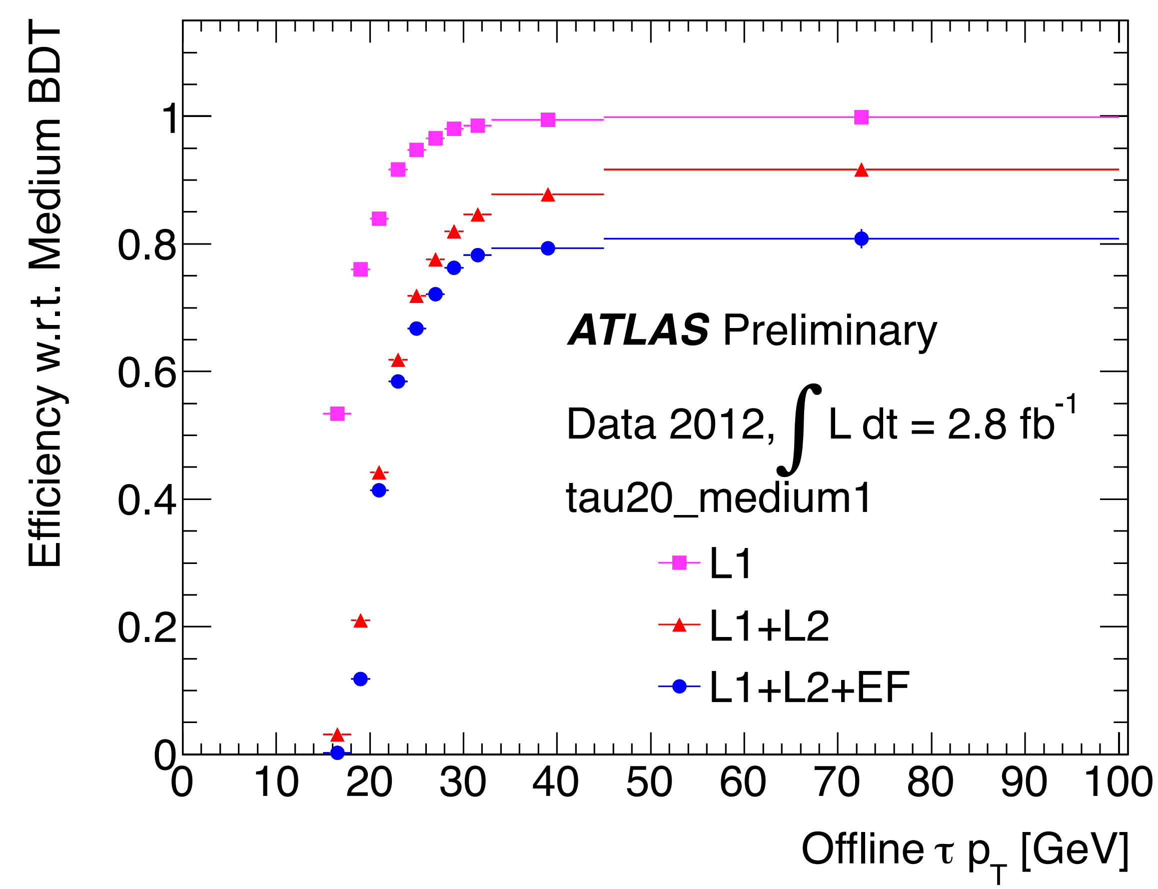


[ATLAS-CONF-2011-152]

Tau triggering

1. **Level 1:** (latency 2.5 μs)
   Coarse EM+Had calorimeter trigger towers $\Delta\eta\times\Delta$ = 0.1×0.1. Candidate passing thresholds on the sum of energies:
   1. highest 2×1 towers
   2. surrounding 4×4 isolation ring
2. **Level 2:** (latency 40 ms)
   Fast tracking. Region-of-interest (RoI) calculation of track- and calorimeter-based ID variables. Similar selection to offline cut-based ID.
3. **Event Filter:** (latency 4 s)
   Beginning in 2012, started using the offline BDT algorithm at the EF trigger.



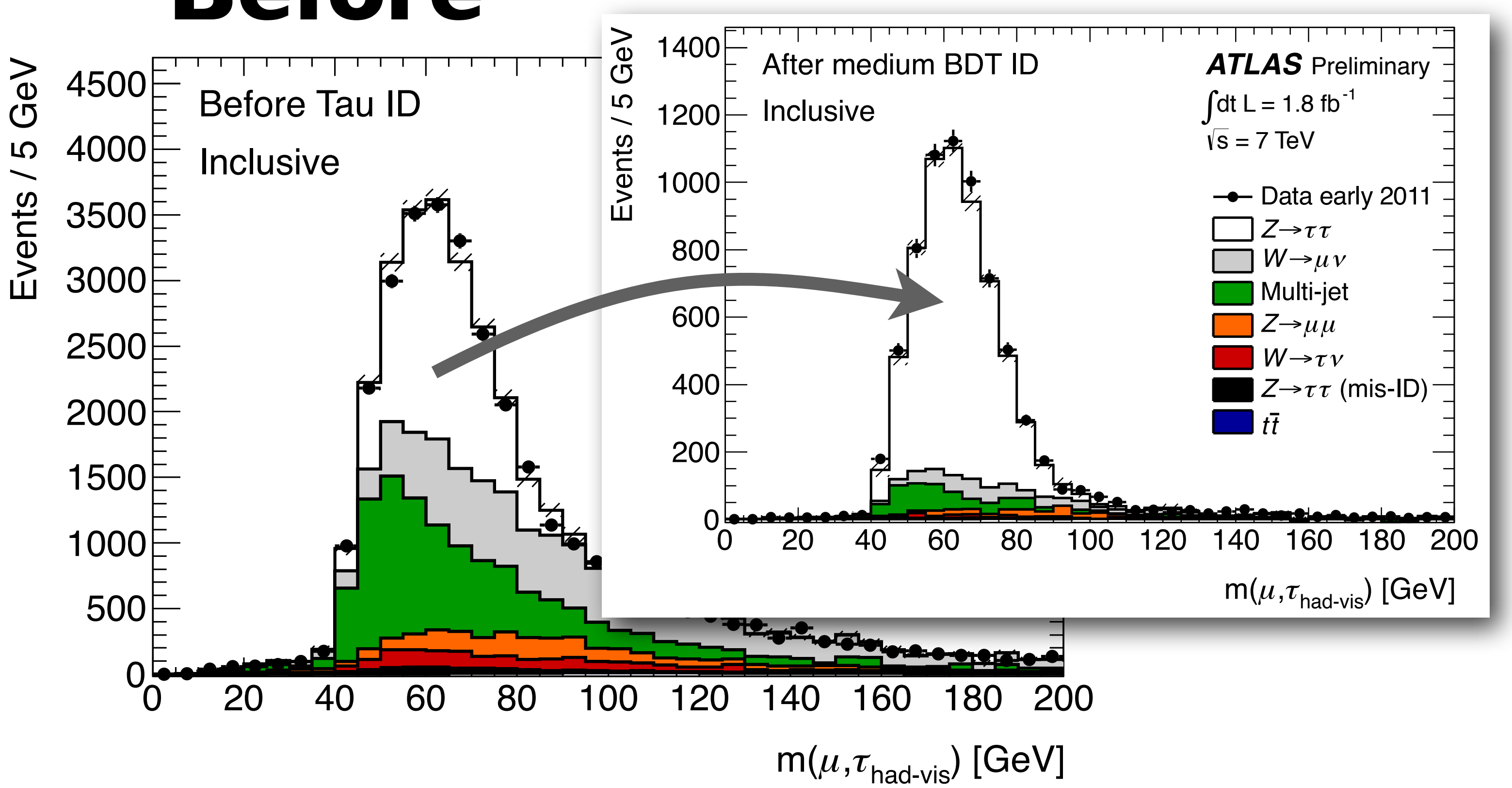


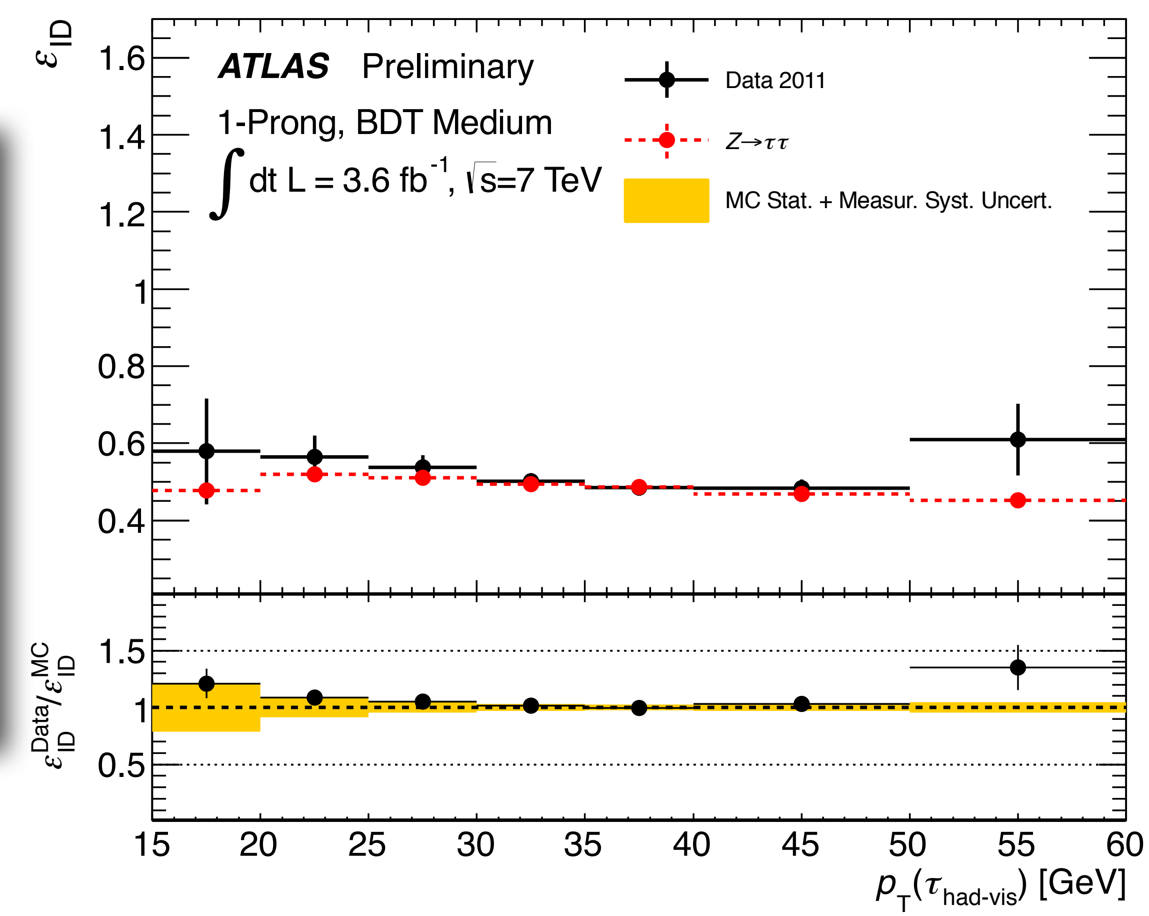
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauTriggerPublicResults

Identification efficiency

- ***Tag-and-probe:*** selecting a sample of a known composition without some ID, so one can probe its efficiency.
- For the case of tau ID, select $Z\to\tau\tau\to\mu\tau_h 3\nu$ by triggering on the muon and selecting events with muon + tau candidate.

Before **After Tau ID**

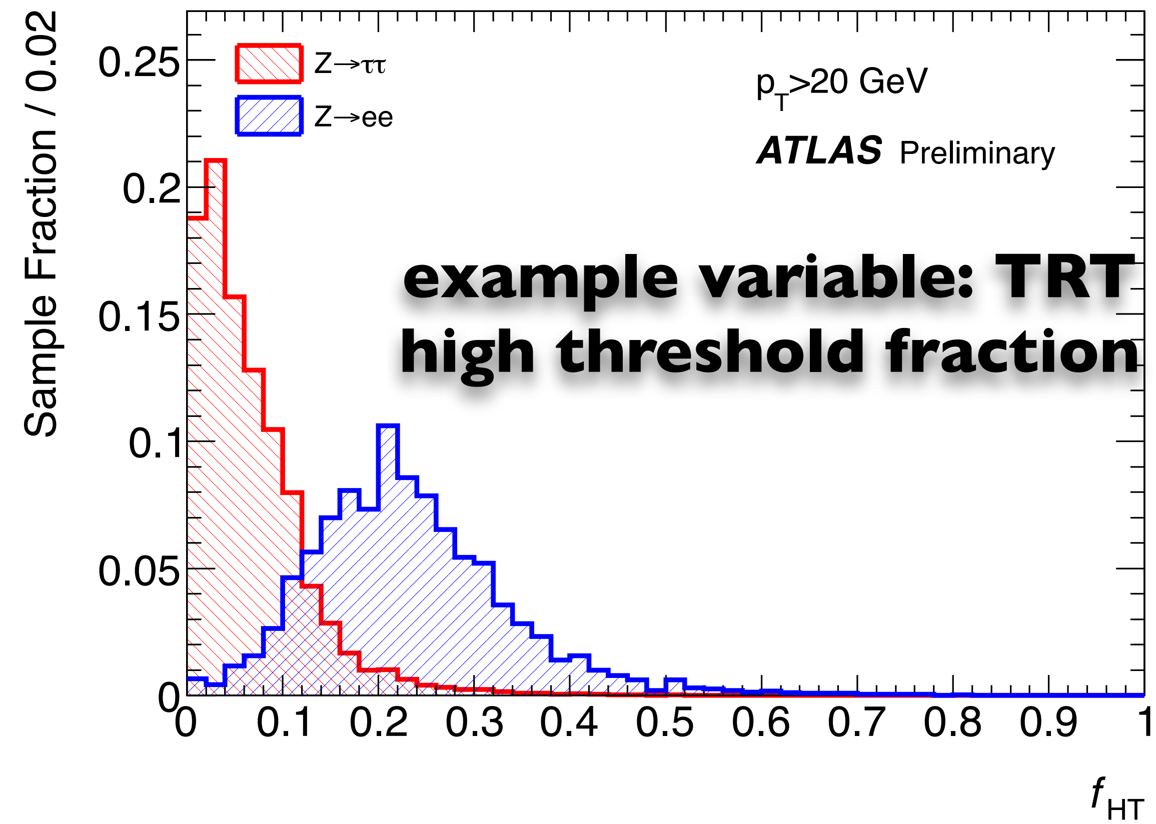


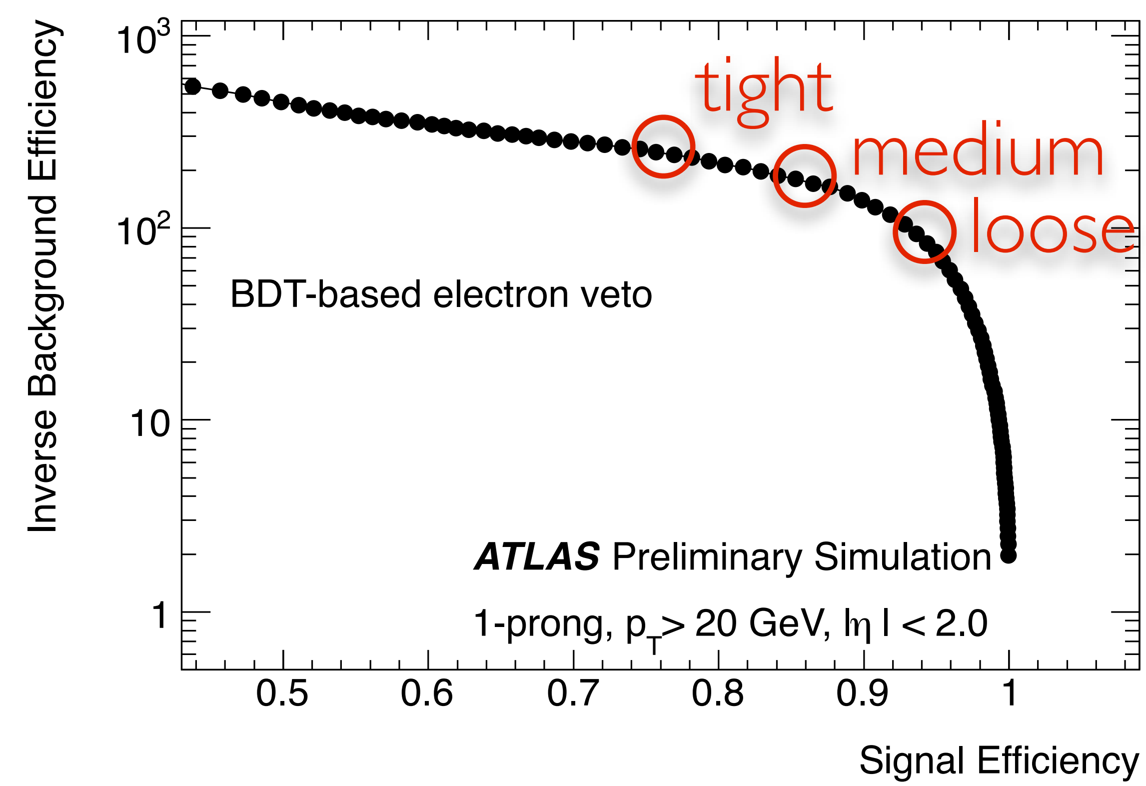


- Scale factor ≈ 1, known to a few percent, 2-3% (1-prong), 5-6% multi-prong.

Electron veto

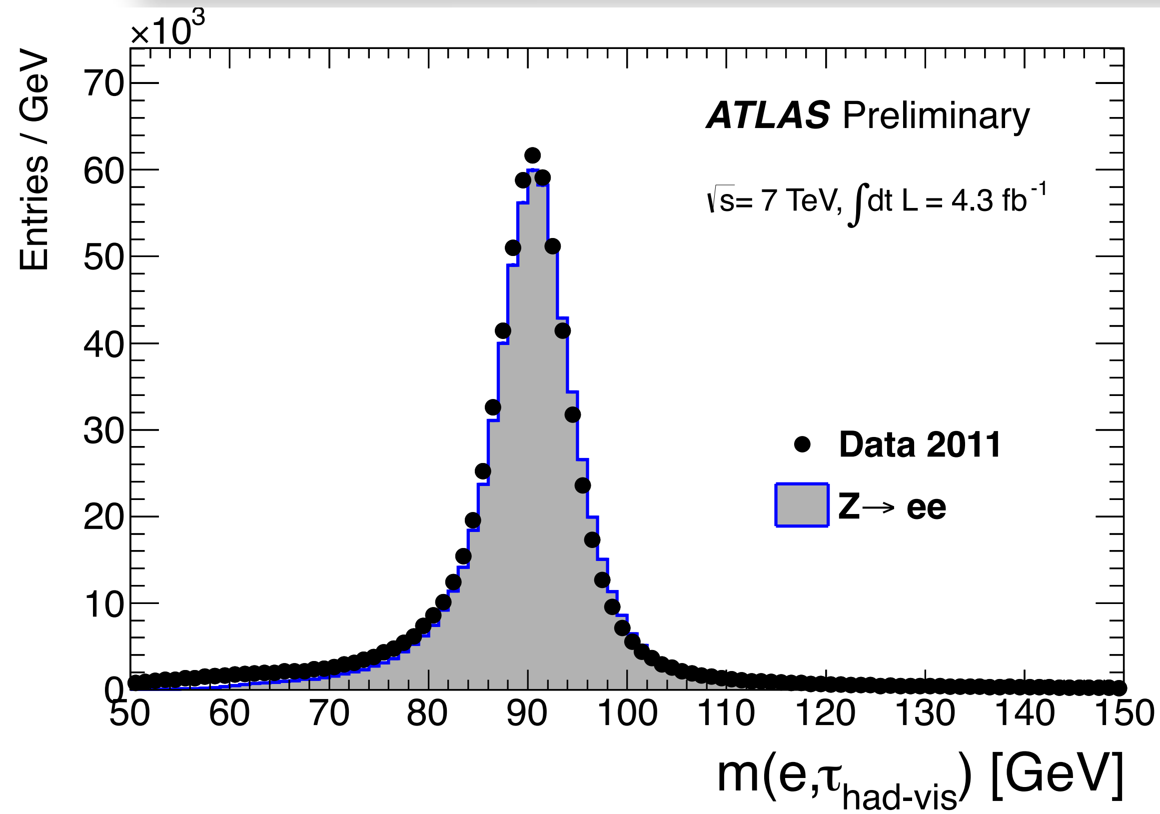
- Electrons provide a track and calorimeter deposit that can fake hadronic tau decay identification.
- ATLAS provides a BDT to discriminate electrons from tau candidates, even after removing overlaps with selected electrons.
- Tight/Medium/Loose working points are defined (≈75%, 85%, 95% efficient).
- In 2012, the BDT is being re-optimized to have better efficiency at high-p_T.

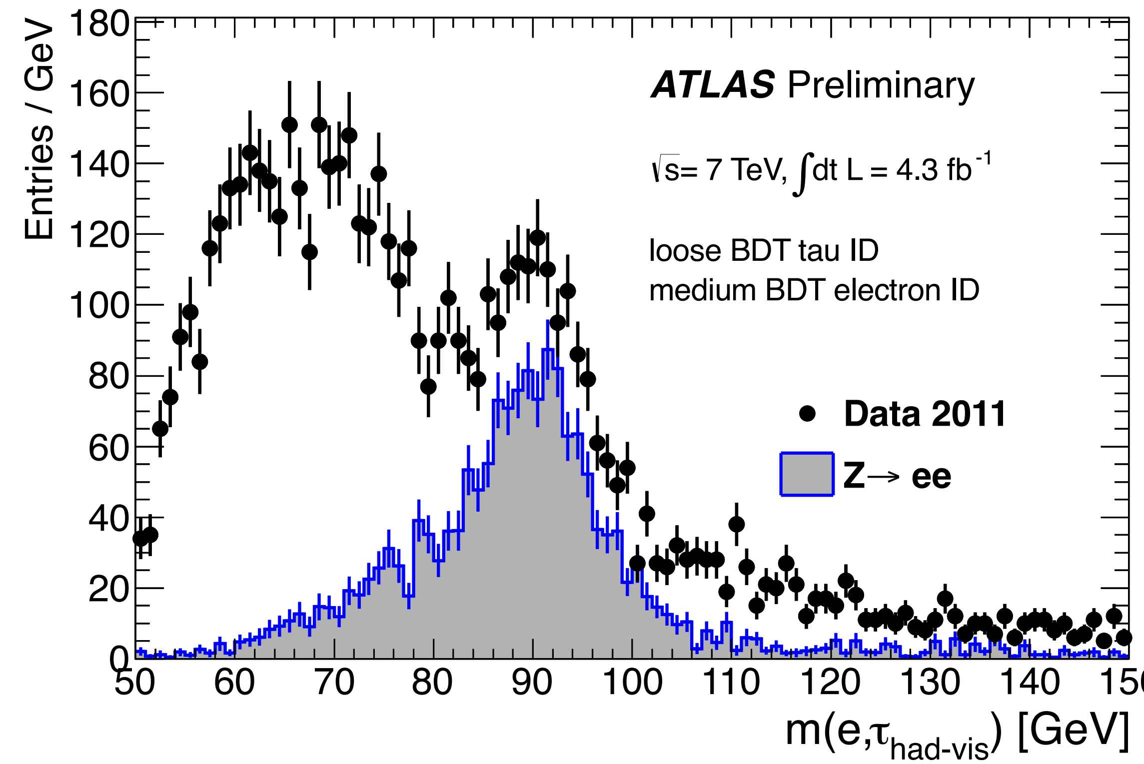




 [ATLAS-CONF-2011-152, ATLAS-CONF-2012-142]

Electron veto fake rate





- Tag e + tau candidates
- Probe the e-veto efficiency after removing overlap with selected electrons.

data/MC scale factor and uncertainty

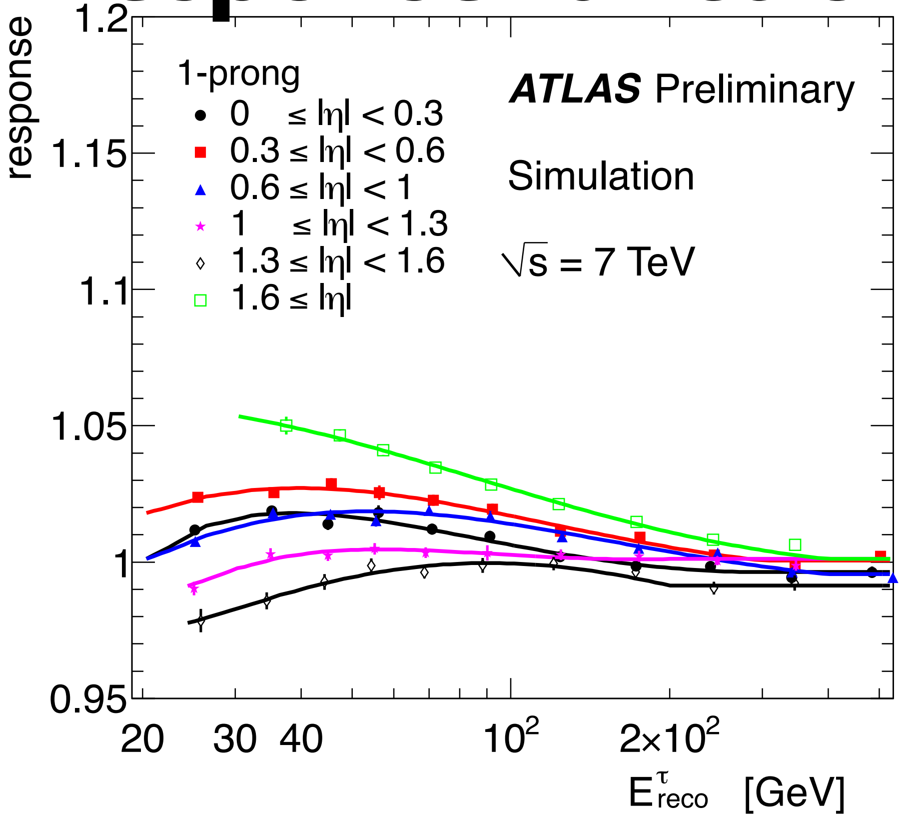
from Z→ee tag-and-probe with 2.6/fb from 2011

	$\|\eta\| <$.	. $< \|\eta\| <$.	. $< \|\eta\| <$.	$\|\eta\| >$.
loose	±	±	±	±
medium	±		±	±

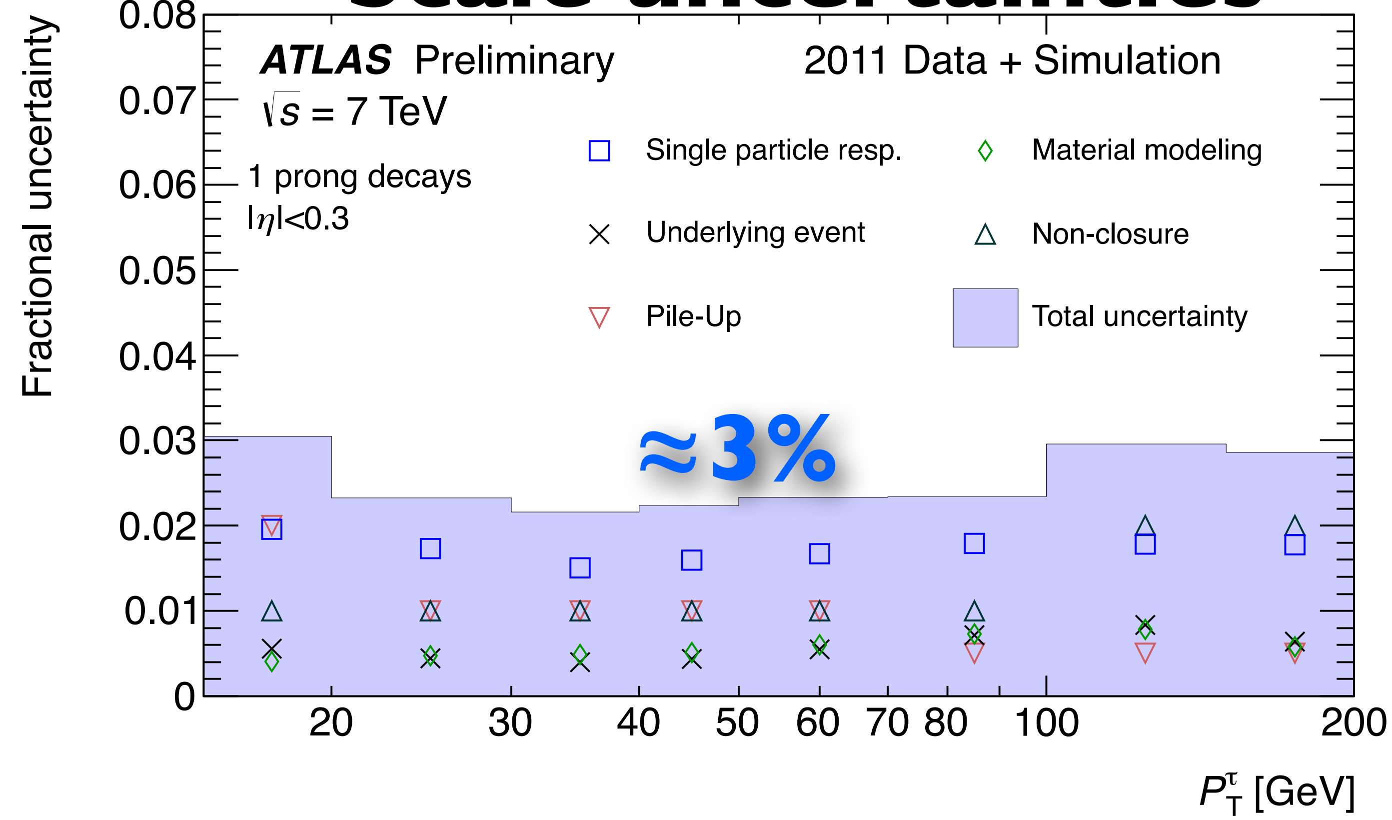
- Statistically limited by the sample that pass the veto, giving uncertainties ≈ 50-100%.
- Improving with the data added in 2012.

Energy scale

Response functions



Scale uncertainties



- Tau candidates are first brought from the EM to the Jet Energy Scale with LC calibration of the clusters within $\Delta R < 0.2$ (from 0.4 to be pile-up robust).
- Then response functions are calibrated with tau Monte Carlo to make final corrections of a few percent.
- Uncertainties are determined by smearing the Monte Carlo truth according the tau decays true composition, using uncertainties constrained by single particle response measurements (CTB, E/p, $Z \rightarrow ee$/π^0-resp.)

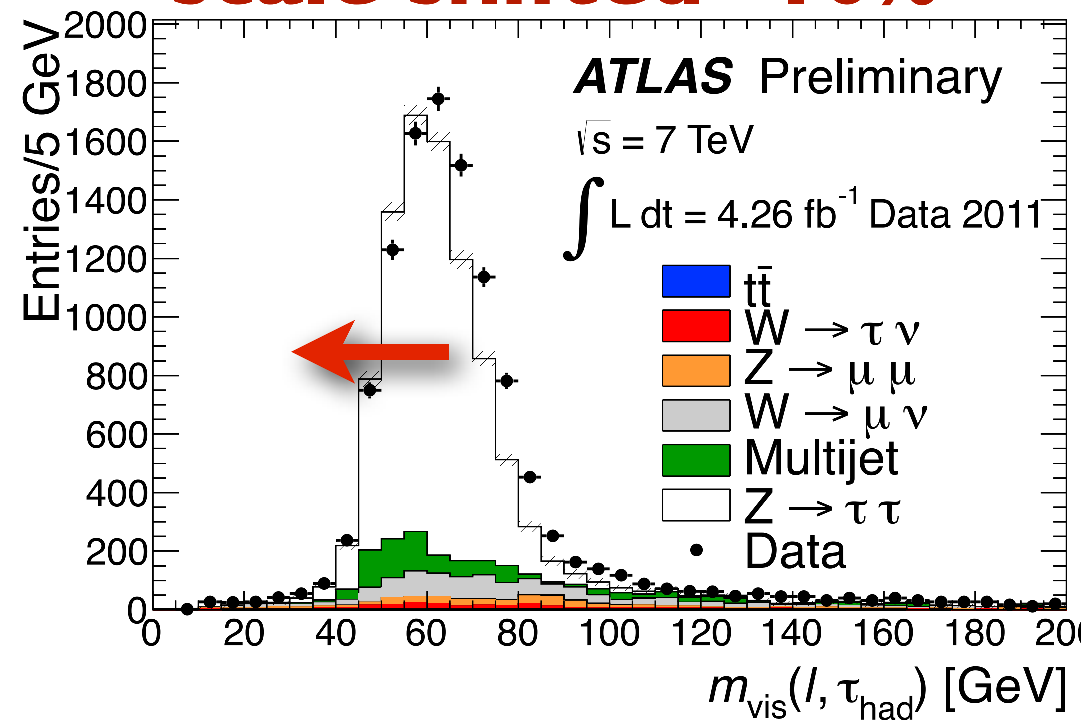
Energy scale cross

- Tau energy scale is manually shifted in the modeling.
- Median of the visible mass peak is used to decide which scale matches the data.
- Toy experiments are used to estimate the uncertainty.

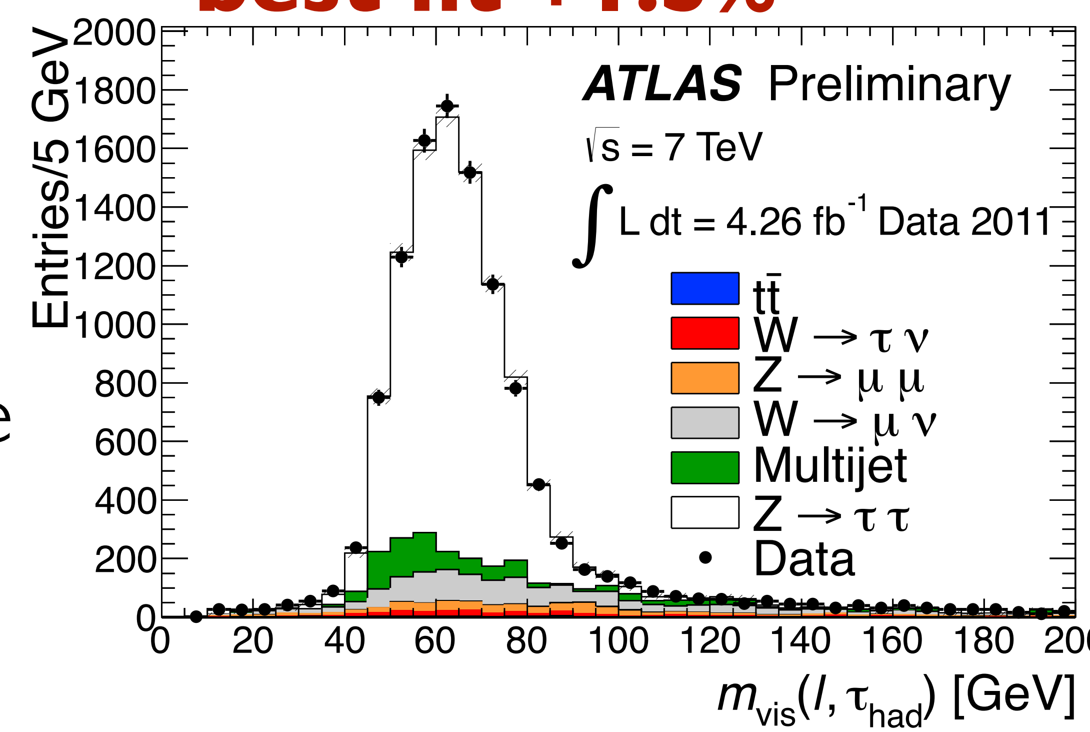
$\|\eta\|$	best scale	uncert.
0.0-0.8	-1.5%	3.3%
0.8-2.5	+1.5%	2.8%

- Scale consistent with 1 within single-particle-response uncertainties ≈ 3%.
- May become primary method with more data.

scale shifted -10%



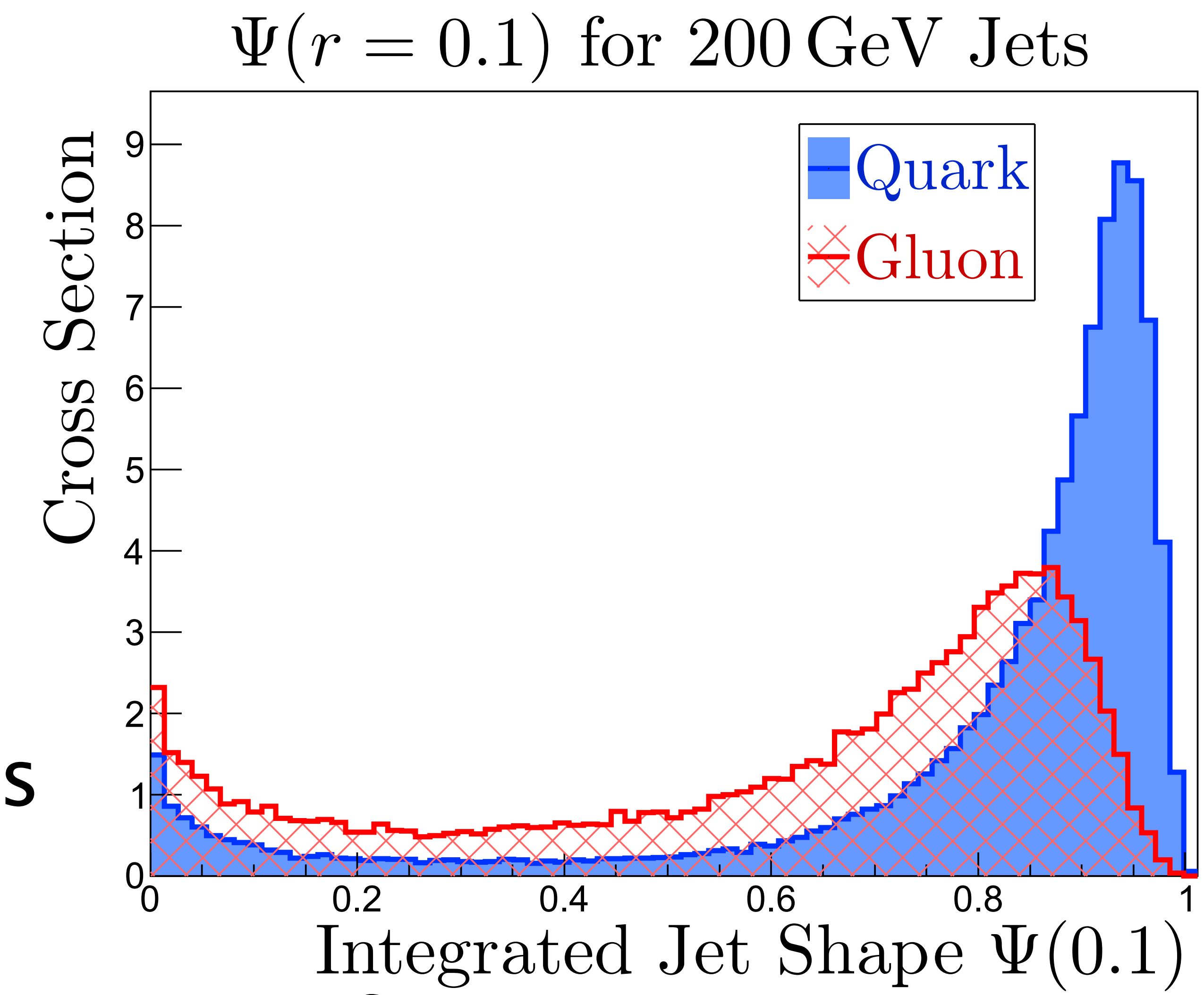
best fit +1.5%



Jet width for quark/

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.



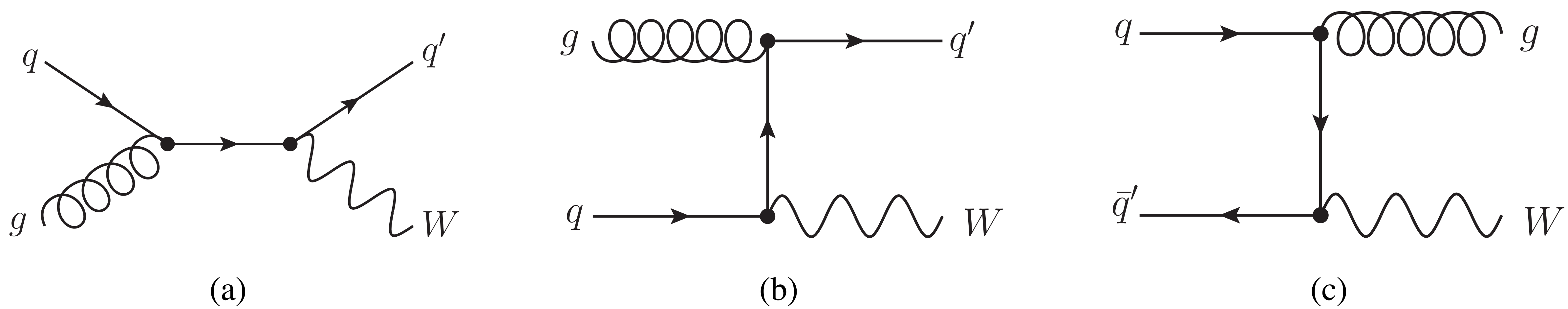
- This is consistent with samples of quark-enriched jets, like W+jet, having higher fake-rates.

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?

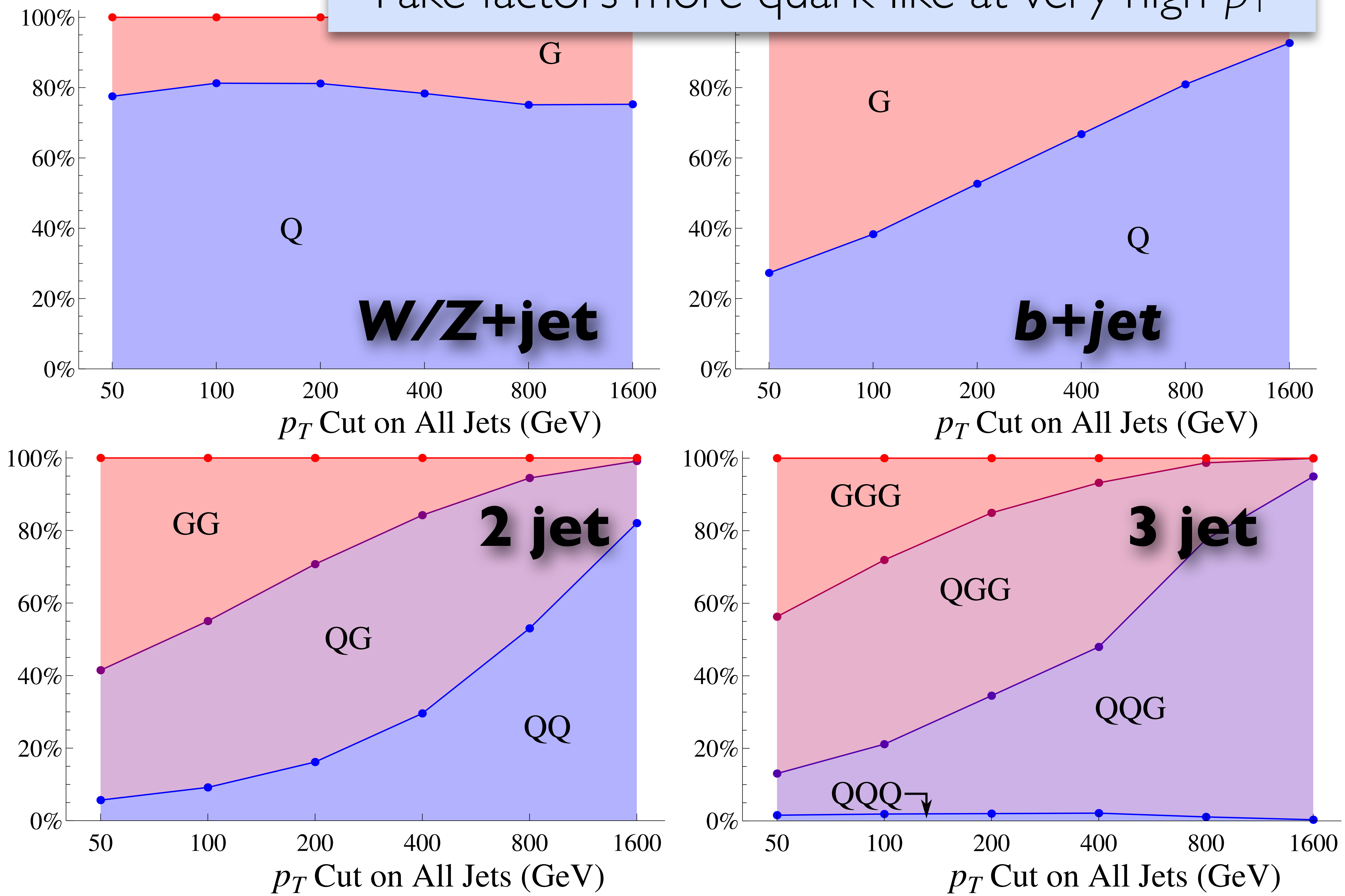
Leading order *W*+jet production:



- 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

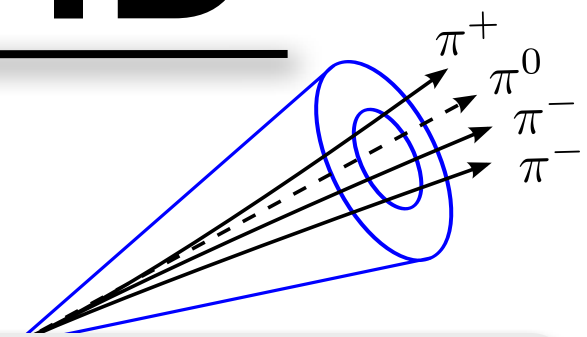
Fake factors more quark-like at very high-p_T



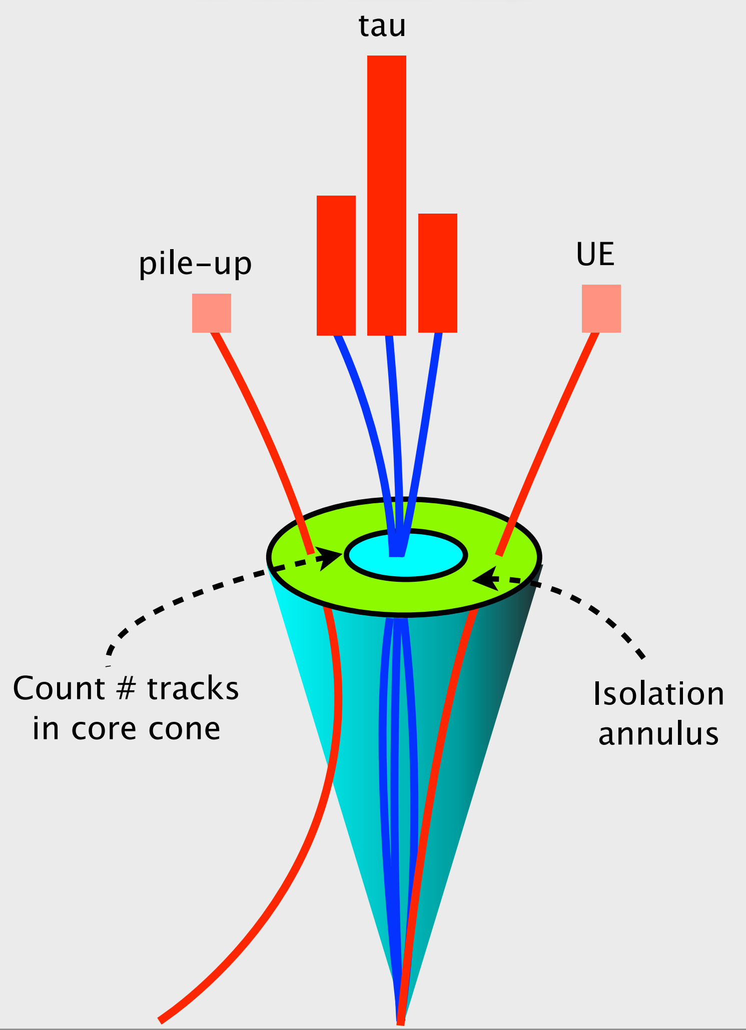
J. Gallicchio, M. Schwartz. "Pure Samples of Quark and Gluon Jets at the LHC". arXiv:1104.1175

CMS vs ATLAS tau ID

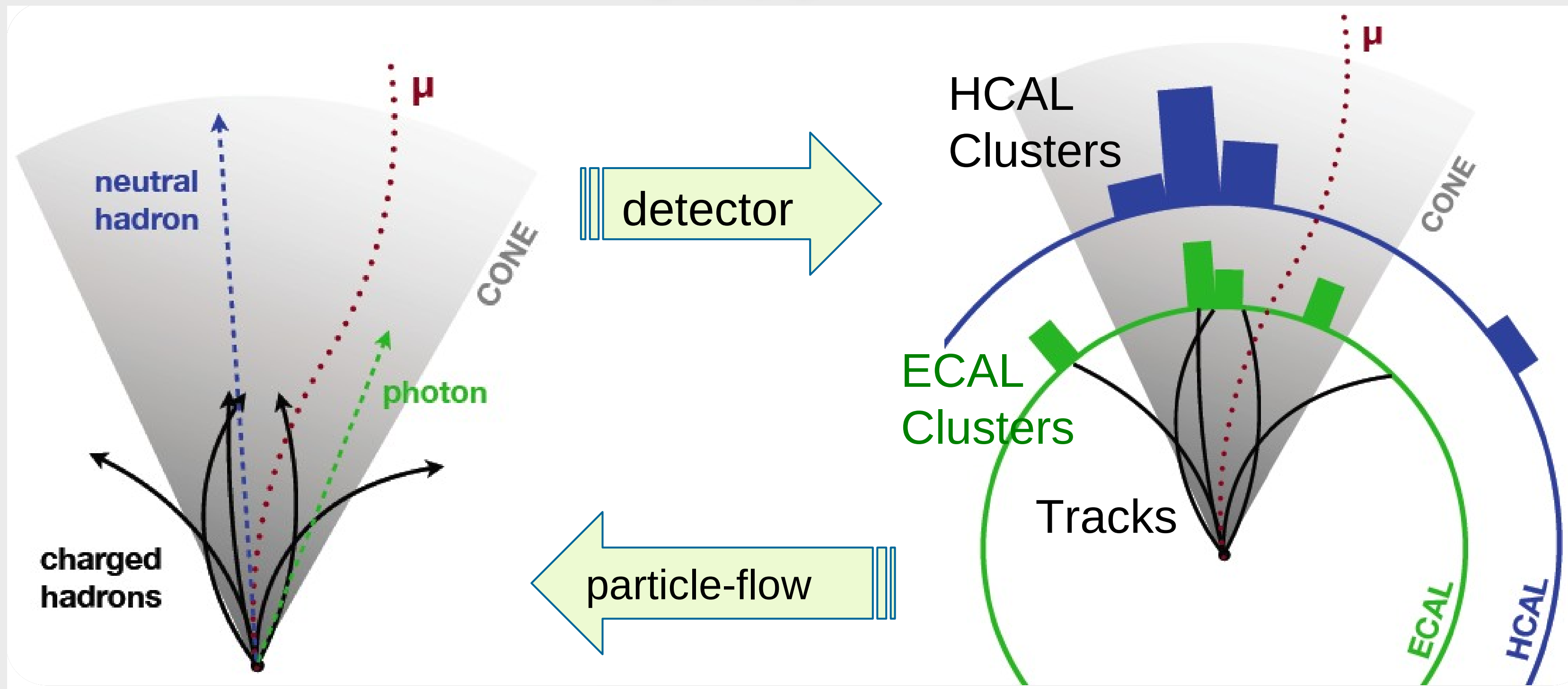
- Hadronic decays dominantly to 1 or 3 $\pi^{\pm}$ and possibly a few additional π^0s
- Decay in beam-pipe: $c\tau \approx 87\ \mu m$



ATLAS



CMS



- 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]