Higgs and Z → $\tau^+\tau^-$ in CMS

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for the CMS Collaboration

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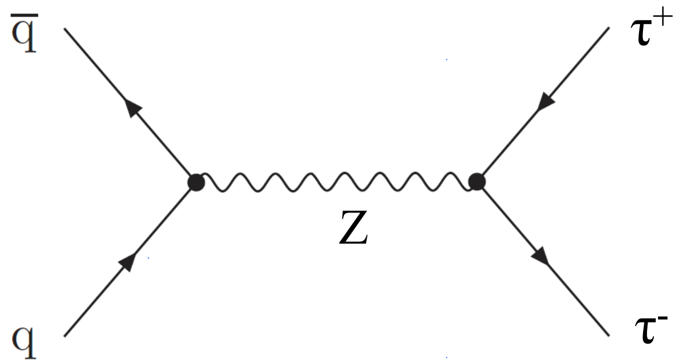
$Z \rightarrow \tau^+\tau^-$ Production @ 7 TeV



CMS Measurement of $Z/\gamma^* \rightarrow l^+l^-$, l = e/μ:

$\sigma \bullet BR(Z/\gamma^* \rightarrow l^+l^-) = 0.931 \pm 0.026$ (stat.) ± 0.023 (sys.) ± 0.102 (lumi.) nb

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NNLO Prediction: 0.972 ± 0.042 nb ($60 < M_{ll} < 120$ GeV)

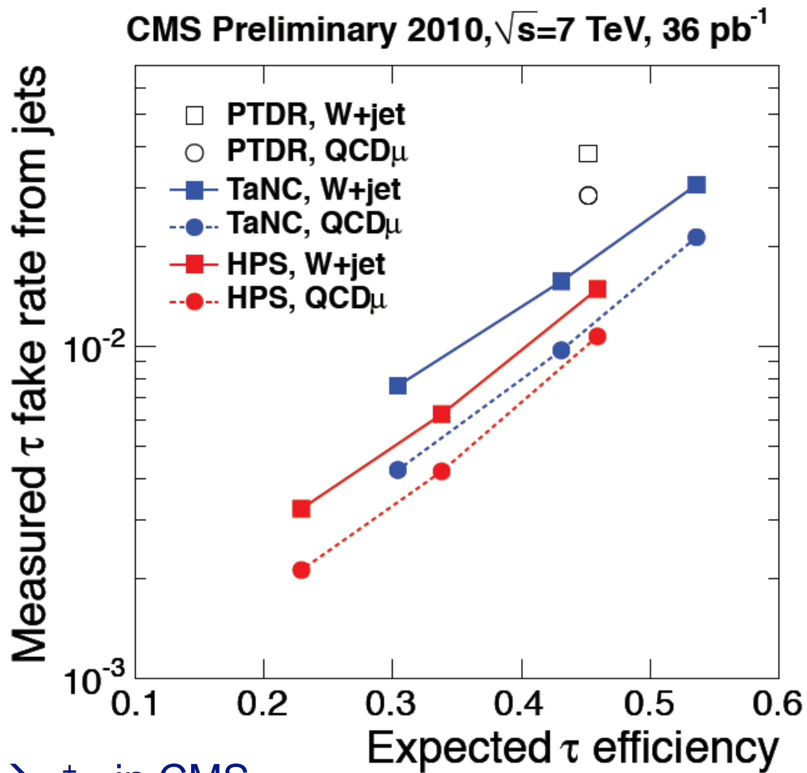
$Z \rightarrow \tau^+\tau^-$ important Source of high energetic τ Leptons in SM:

- Measurement of τ Identification Efficiencies
- Commissioning of τ Triggers
- Important Background in Searches for beyond the SM Physics

CMS τ Identification

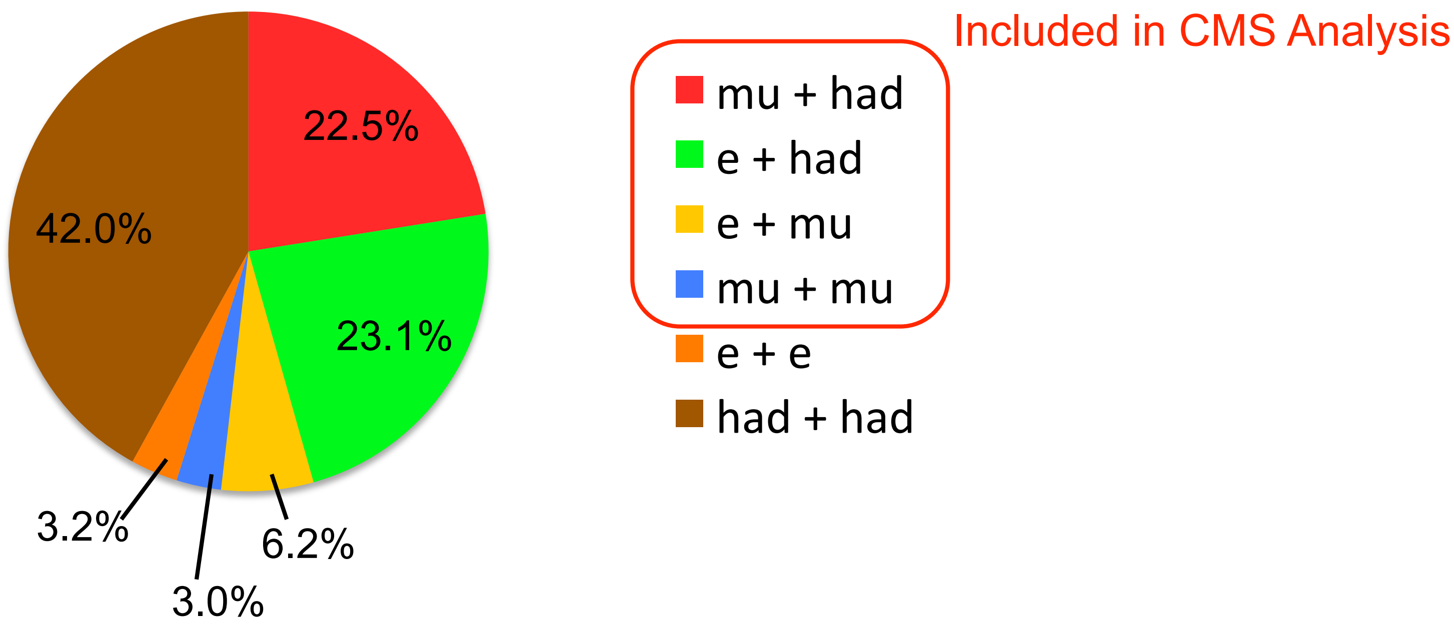
Decay Mode	Resonance	Mass (MeV/c^2)	Branching ratio(%)
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$			17.8 %
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$			17.4 %
$\tau^- \to h^- \nu_\tau$			11.6 %
$\tau^- \to h^- \pi^0 \nu_\tau$	ρ	770	26.0 %
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a1$	1200	10.8 %
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a1$	1200	9.8 %
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8 %
Other hadronic modes			1.7%

Improvement in CMS τ Identification Performance
due to Reconstruction of individual Decay Modes (Vector Meson Resonances), based on Particle Flow



$Z \rightarrow \tau^+\tau^-$ Decay Modes

$Z \rightarrow \tau^+\tau^-$ Analysis based on Combination of Decay Modes:



Variety of semi-leptonic and leptonic Channels analyzed

$\Sigma Br = 54.8\%$

N.B.: Hadronic Channel difficult (Trigger, high Backgrounds)

Event Selection

For $\mu + \tau_{had}$, $e + \tau_{had}$ and $e + \mu$ Channels, $\mu + \mu$ Channel different (Backup)

Trigger

Events triggered by single Electron/Muon Triggers

P_T thresholds 9-15 GeV, depending on instantaneous Luminosity

Lepton Selection

Electrons	Muons	had. τ Decays
$P_T > 15$ GeV	$P_T > 15$ GeV	$P_T > 20$ GeV
$\lvert\eta\rvert < 2.1$ (2.4 for $e + \mu$)	$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.3$
isolated	isolated	Tau Id.
		Veto against e/μ

Opposite Charge Lepton Pair

Transverse Mass

$e + \tau_{had}$, $\mu + \tau_{had}$: $M_T(l + MET) < 40$ GeV

$e + \mu$: $M_T(e + MET) < 50$ GeV && $M_T(\mu + MET) < 50$ GeV

Veto Events with additional isolated Leptons

Cross-section Extraction

$$\sigma(pp \to ZX) \times \mathcal{B}(Z \to \tau^+\tau^-) = \frac{N}{\mathcal{A} \cdot \epsilon \cdot \mathcal{B}' \cdot \mathcal{L}}$$

- $N = N_{obs} - N_{bgr}$
  Background Contribution N_{bgr} estimated from Data
  (using 1-3 complementary Methods, depending on Channel)
- Acceptance taken from Monte Carlo
  (POWHEG + TAUOLA, PYTHIA with CMS Z2 tune for Hadronization)
- Efficiency factorized into independent Terms
  Each Term either measured directly in Data or taken from Monte Carlo and applying Data/MC Correction factor measured from Data
- Branching Ratios for $\tau^+\tau^-$ to decay into $\mu + \tau_{had}$, $e + \tau_{had}$, $e + \mu$, $\mu + \mu$ taken from PDG
- Luminosity measured with Precision of 4%

Event Yields

CMS Data, 36 pb^{-1} @ 7 TeV

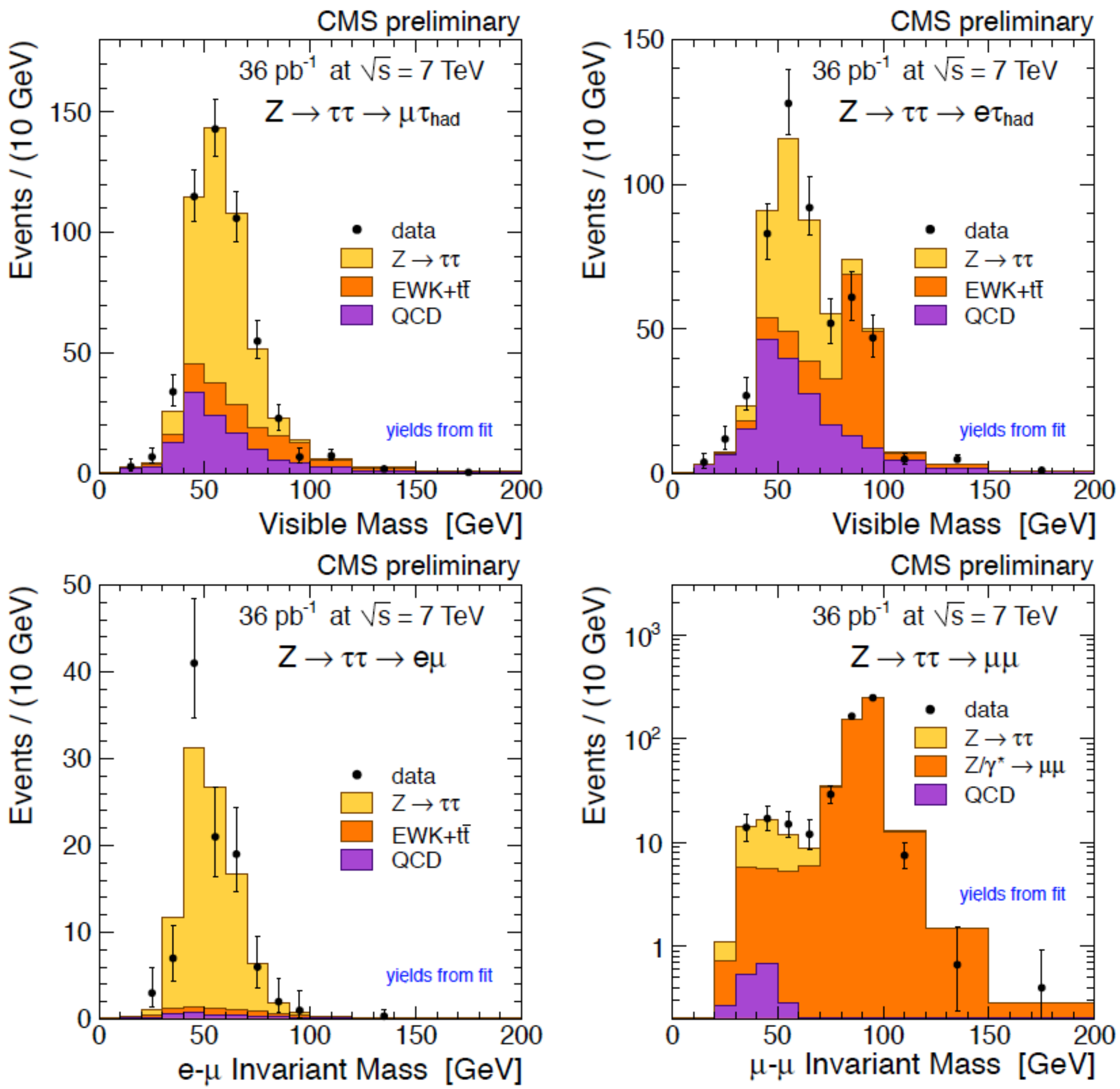
	$\tau_\mu \tau_{had}$	$\tau_e \tau_{had}$	$\tau_e \tau_\mu$	$\tau_\mu \tau_\mu$ ($M_{\mu\mu} < 70$ GeV)
$Z \to \ell^+\ell^-$, jet fake τ_{had}	6.4 ± 2.4	15.0 ± 6.2		
$Z \to \ell^+\ell^-$	12.9 ± 3.5	109.3 ± 28.0	2.4 ± 0.3	20.1 ± 1.3
$t\bar{t}$	6.0 ± 3.0	2.6 ± 1.3	7.1 ± 1.3	0.15 ± 0.03
$W \to \ell\nu$	54.9 ± 4.8	30.6 ± 3.1		
$W \to \tau\nu$	14.7 ± 1.3	7.0 ± 0.7	1.5 ± 0.5	2.5 ± 2.5 (< 5 @95%CL)
QCD	131.6 ± 14.1	181.1 ± 22.5		
WW/WZ/ZZ	1.6 ± 0.8	0.8 ± 0.4	3.0 ± 0.4	
Total Background	228.4 ± 15.8	346.4 ± 36.7	14.0 ± 1.8	22.8 ± 2.8
Total Data	516	540	101	58

Background Estimates quoted in Table obtained from Data-driven Methods

Difference between "Total Data" and "Total Background" is measured
$Z \to \tau^+\tau^-$ Signal

➔ > 600 $Z \to \tau^+\tau^-$ Signal Events selected in CMS Data

Visible Mass Spectra



➔ Clear Z ➔ $\tau^{+}\tau^{-}$ Signal established in all Channels

$Z \rightarrow \tau^+\tau^-$ Cross-section Results

Individual Channels:

$$\sigma(\mathrm{pp} \to \mathrm{ZX}) \times \mathcal{B}(\mathrm{Z} \to \tau^+\tau^-)_{\mu\tau} = 0.83 \pm 0.07\,(\mathrm{stat.}) \pm 0.04\,(\mathrm{syst.}) \pm 0.03\,(\mathrm{lumi.}) \pm 0.19\,(\tau\text{-ID})\,\mathrm{nb}$$
$$\sigma(\mathrm{pp} \to \mathrm{ZX}) \times \mathcal{B}(\mathrm{Z} \to \tau^+\tau^-)_{e\tau} = 0.94 \pm 0.11\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.}) \pm 0.04\,(\mathrm{lumi.}) \pm 0.22\,(\tau\text{-ID})\,\mathrm{nb}$$
$$\sigma(\mathrm{pp} \to \mathrm{ZX}) \times \mathcal{B}(\mathrm{Z} \to \tau^+\tau^-)_{e\mu} = 0.99 \pm 0.12\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.}) \pm 0.04\,(\mathrm{lumi.})\,\mathrm{nb}$$
$$\sigma(\mathrm{pp} \to \mathrm{ZX}) \times \mathcal{B}(\mathrm{Z} \to \tau^+\tau^-)_{\mu\mu} = 1.15 \pm 0.25\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{syst.}) \pm 0.05\,(\mathrm{lumi.})\,\mathrm{nb}.$$

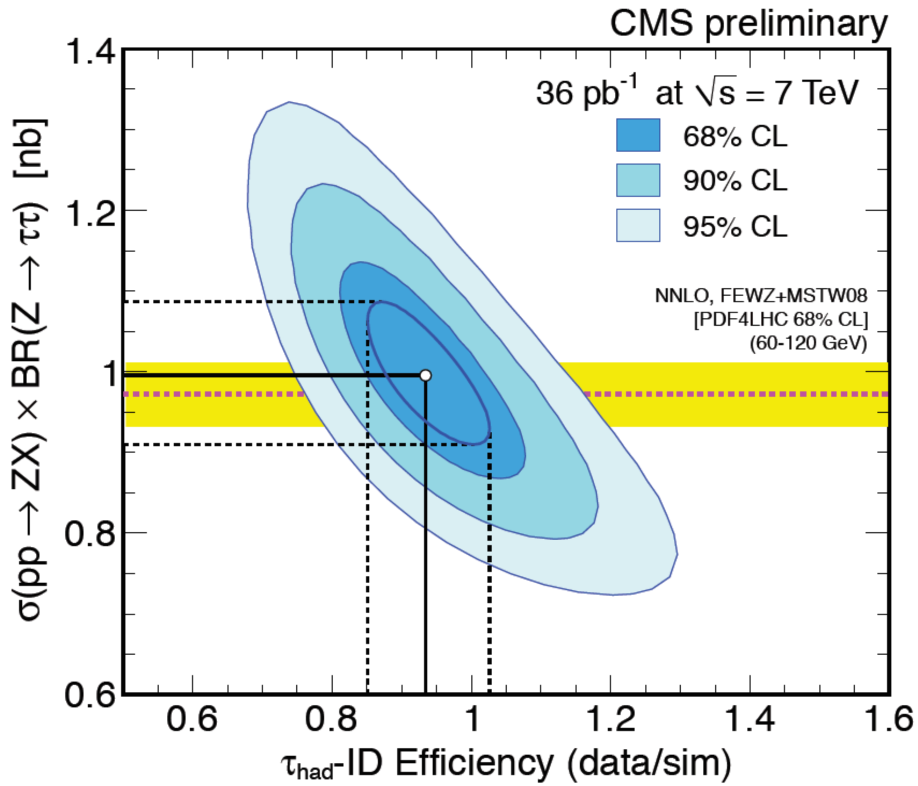
Good Agreement between all four Channels

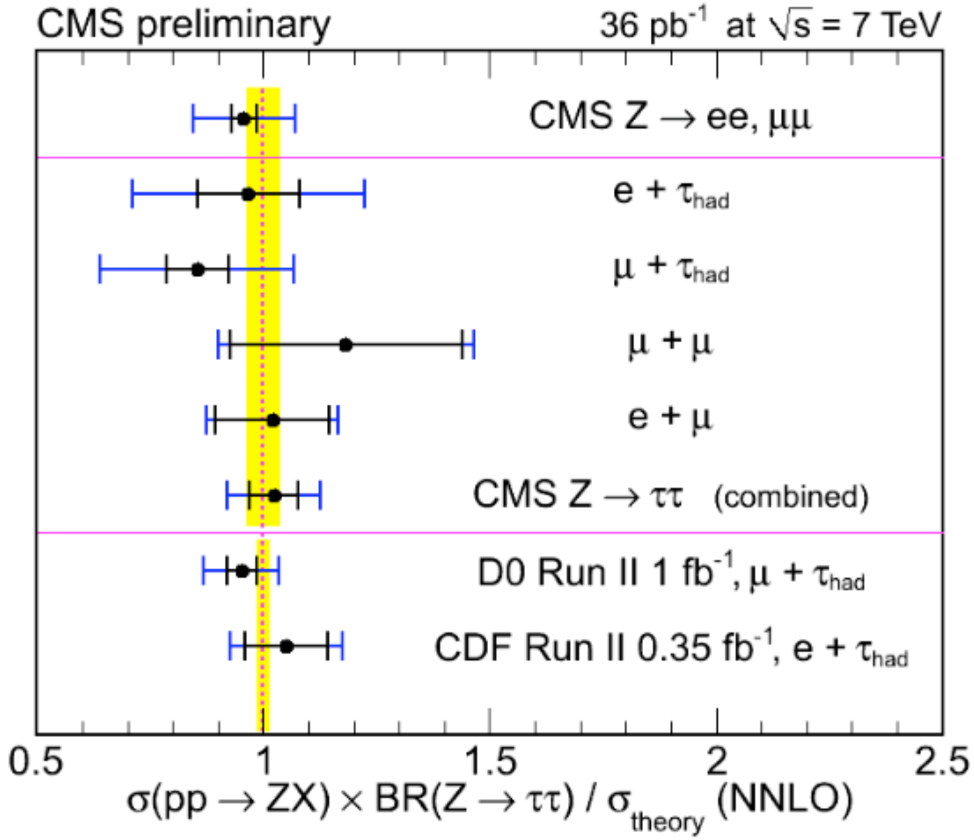
Largest Uncertainty: hadronic Tau Identification Efficiency

τ_{had} Identification Efficiency constrained by Ratio of Event Yields in semi-leptonic/leptonic Channels

➔ Determine $Z \rightarrow \tau^+\tau^-$ Cross-section by simultaneous Fit of all four Channels

Simultaneous Fit Results





Combined:

$\sigma \cdot BR(Z/\gamma^* \to \tau^+\tau^-) = 1.00 \pm 0.05$ (stat.) ± 0.08 (sys.) ± 0.04 (lumi.) nb

Measured Cross-Section in good Agreement with Theory Prediction (NNLO) and CMS Measurement of $Z/\gamma^* \to l^+l^-$, l = e/μ Cross-section

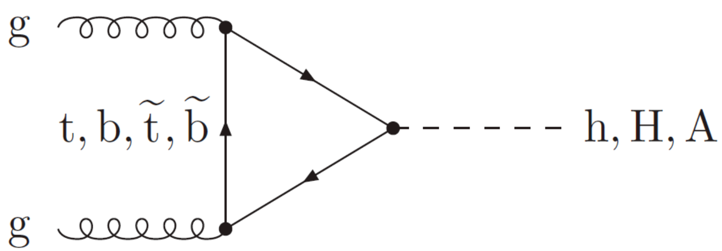
Data/MC Correction factor for τ Id. Efficiency = 0.94 ± 0.09, compatible with 1

And the Higgs ?

MSSM Higgs Phenomenology

Minimal Supersymmetric Standard Model

- 2 Higgs doublets → 5 physical Higgs Bosons:
  - 2 CP-even neutrals: h, H — scalar
  - 1 CP-odd neutral: A — pseudo-scalar
  - 2 charged: H^+, H^-
- CP-odd and 1 CP-even Higgs Boson degenerate in Mass
- At Born level MSSM described by 2 Parameters: tan β, m_A
  (Dependency on SUSY Parameters via radiative Corrections)
- 2 main Production Processes:



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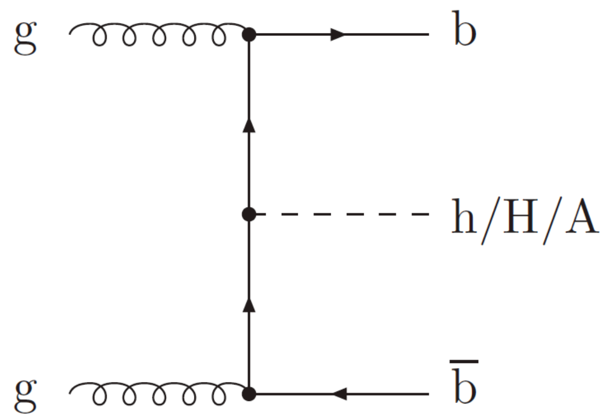
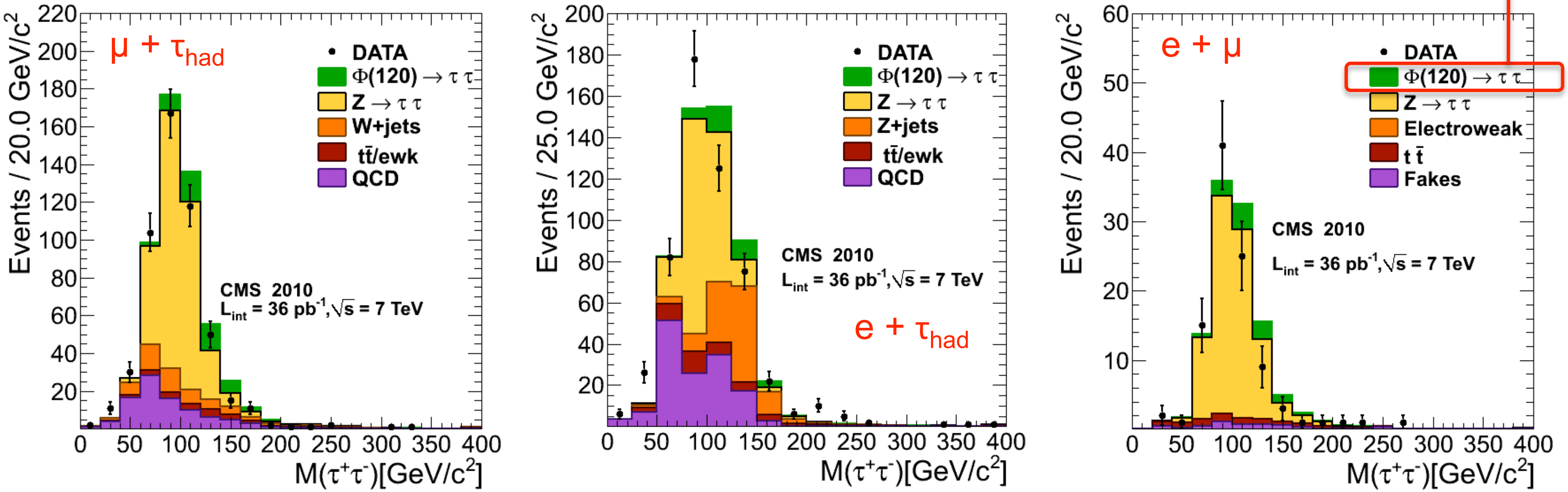


- Cross-section increases ~tan β^2

$\tau^+\tau^-$ Mass Reconstruction

- Likelihood Fit of momenta of visible Decay Products and of Neutrinos produced in τ Decays
- At present uses Likelihood Terms for τ Decay kinematics and missing E_T
- Yields "physical" Solution for every Event
- Improvement in Resolution wrt. previous Techniques

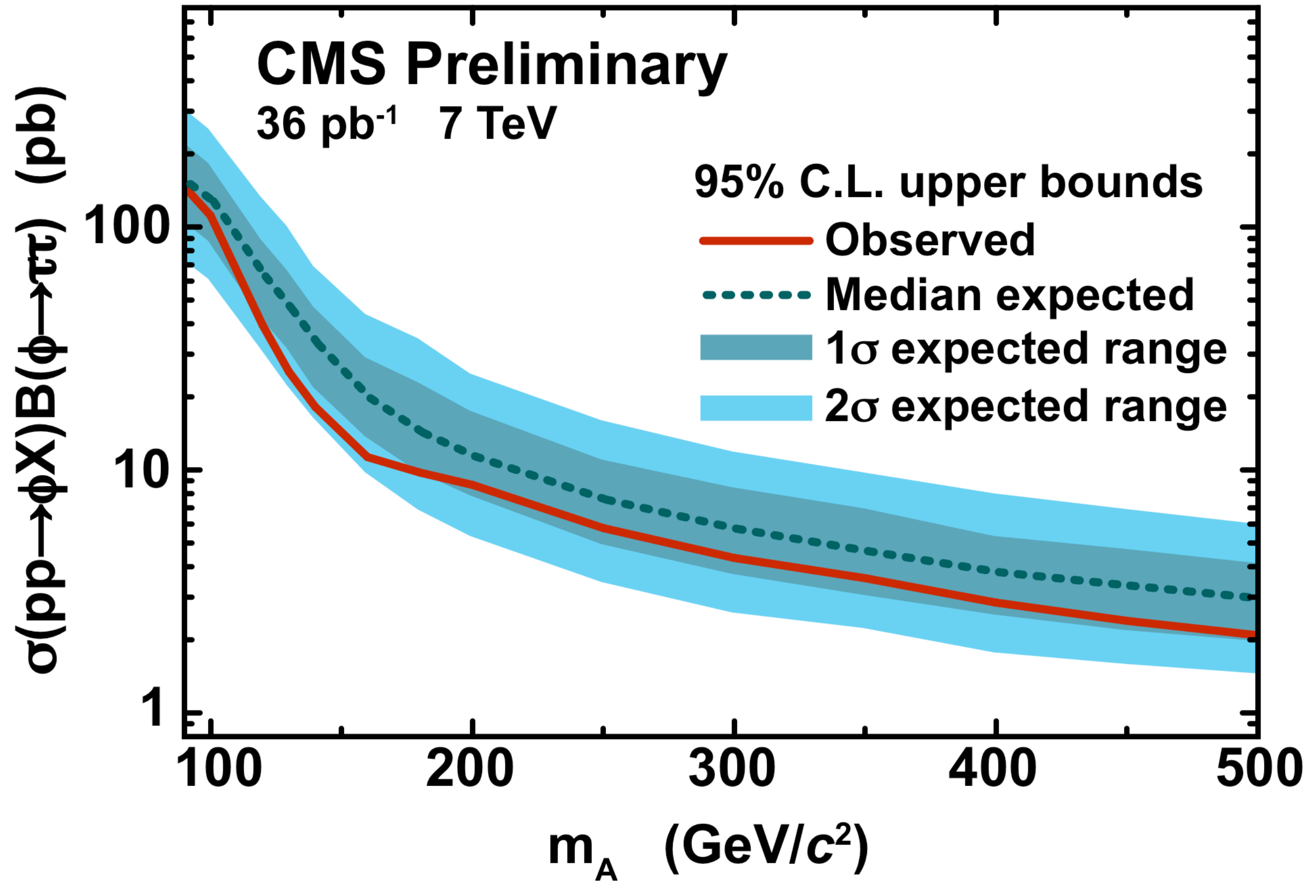
Normalization for tan β = 30



➔ Clear Z Mass Peak seen in CMS Data

Higgs → $\tau^+\tau^-$ Cross-section Limit

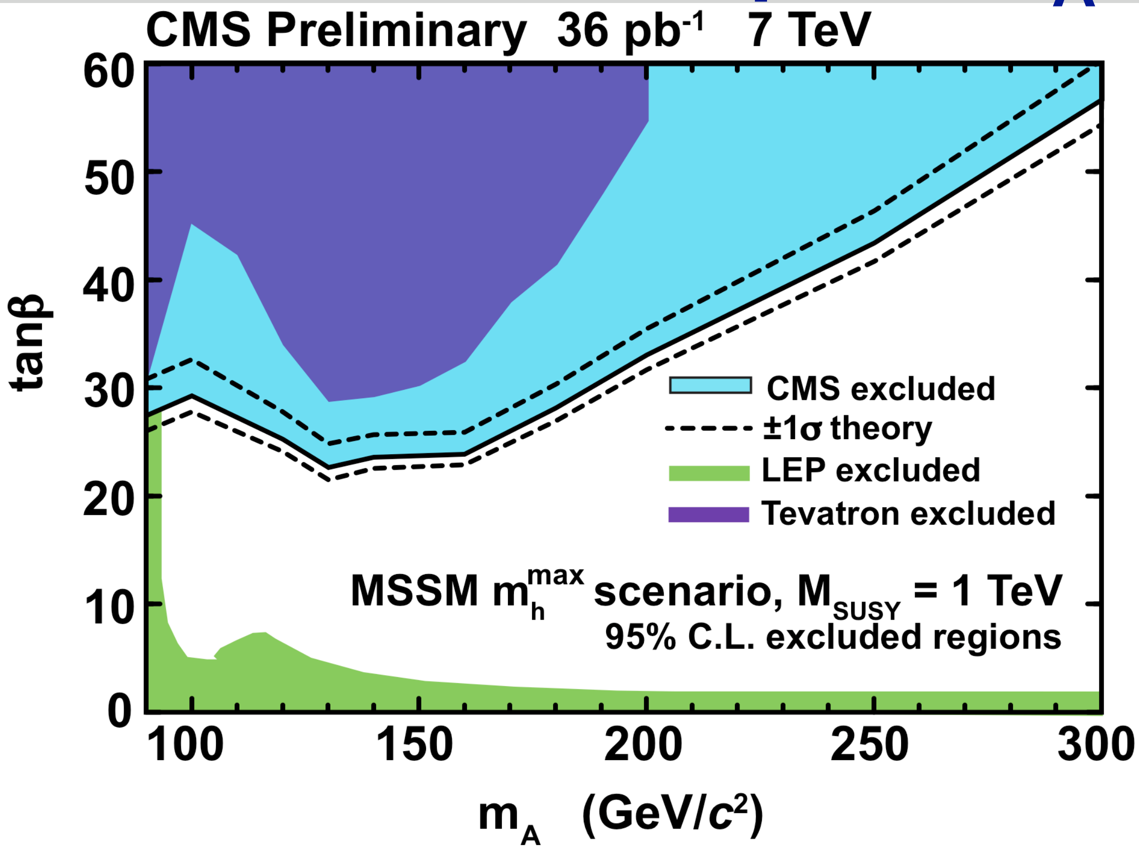
ϕ: Sum of pseudo-scalar + scalar Higgs of ~same Mass



Observed and expected Limit on $\sigma \times$ Br computed for different Mass Hypotheses m_A via combined Likelihood Fit of $M_{\tau\tau}$ Spectrum in $\mu + \tau_{had}$, $e + \tau_{had}$, $e + \mu$ Channels using Bayesian Inference

➔ No Evidence for Signal, observed Limit agrees with expected Sensitivity

Limit on tan β vs. m_A



Upper Limit on $\sigma \times$ Br converted into Limit on MSSM Parameter tan β:

- Relation between σ, Br and tan β taken from LHC Higgs Cross Sections Working Group (for m_h^{max} SUSY benchmark scenario) hep-ph 1101.0593v2
- Theory Uncertainty estimated according to WG Recommendations

➔ CMS Limit more stringent than TeVatron Limit over whole Mass range

Summary

$Z \rightarrow \tau^+\tau^-$ Production has been analyzed in four Channels: $\mu + \tau_{had}$, $e + \tau_{had}$, $e + \mu$ and $\mu + \mu$

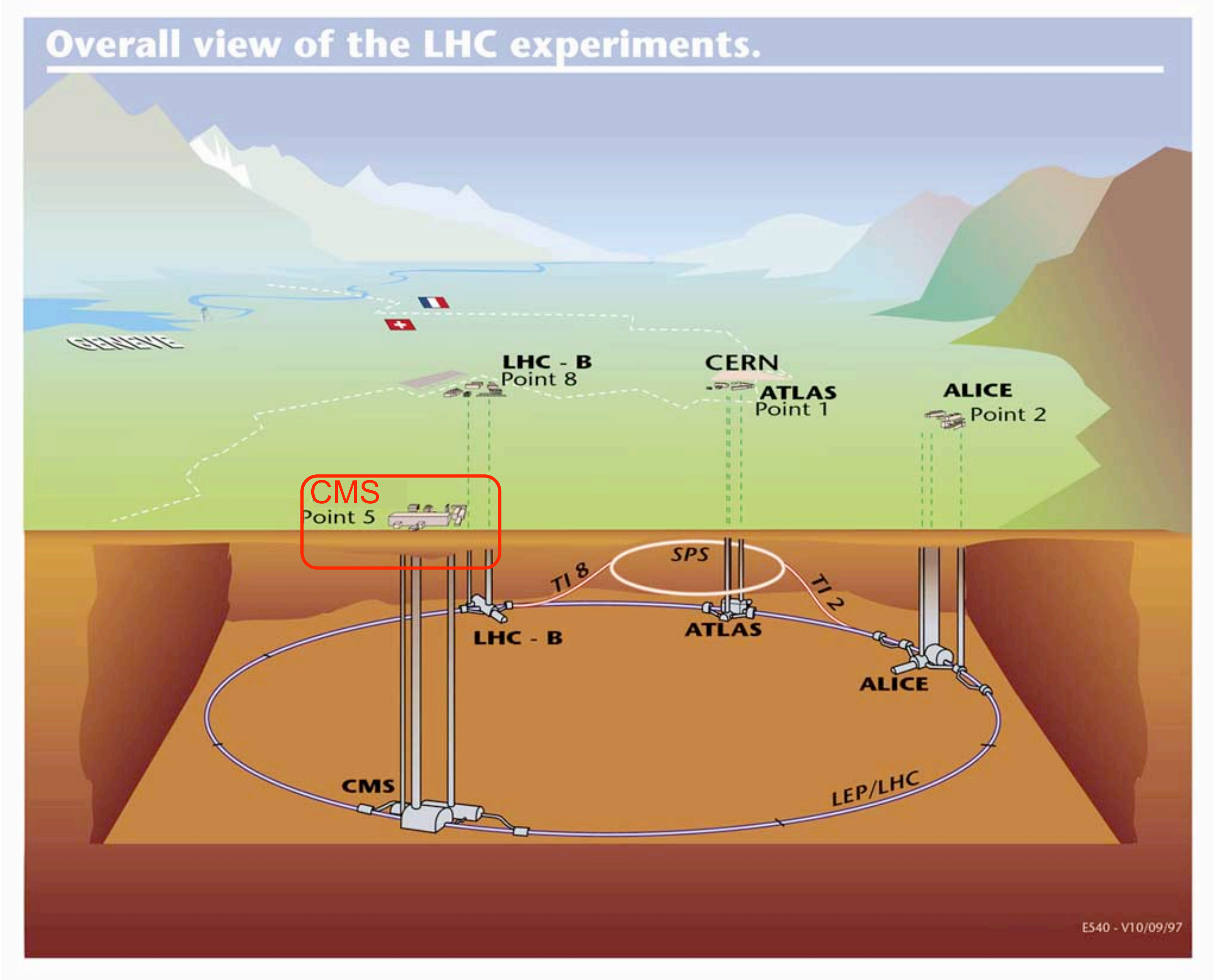
- An unambiguous Signal is established in all Channels
- The $Z \rightarrow \tau^+\tau^-$ Cross-section is measured @ 7 TeV center-of mass Energy and found to be in good Agreement with $Z \rightarrow l^+l^-$, $l = e/\mu$ Cross-section measured by CMS as well as with Theory Predictions (NNLO)

No evidence for Higgs $\rightarrow \tau^+\tau^-$ Signal observed in CMS Data

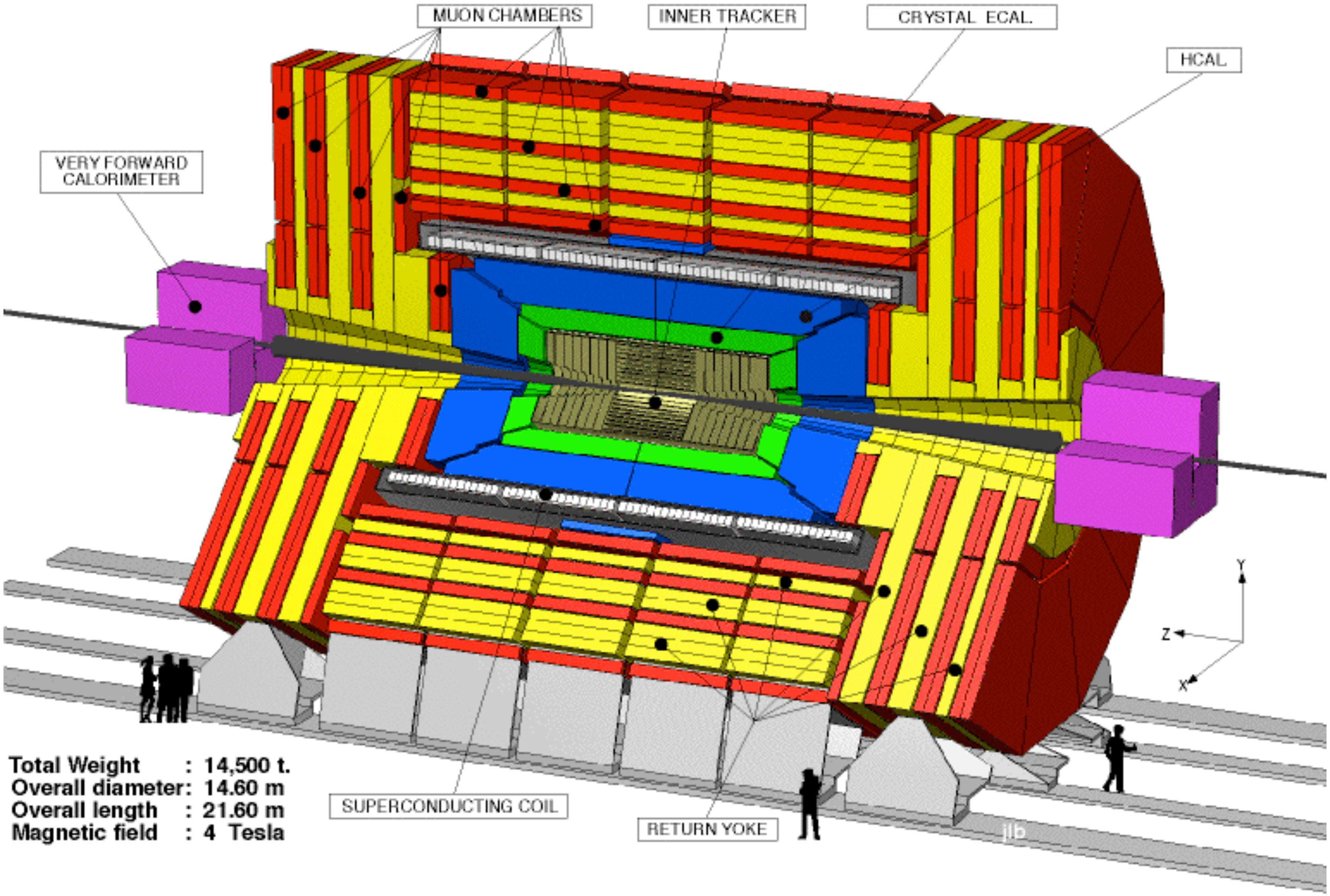
- Observed Limit tracks expected Limit
- $\tau^+\tau^-$ Mass reconstructed using novel Likelihood Technique
- Stringent Limits are set on MSSM Higgs $\rightarrow \tau^+\tau^-$ Production

Backup Material

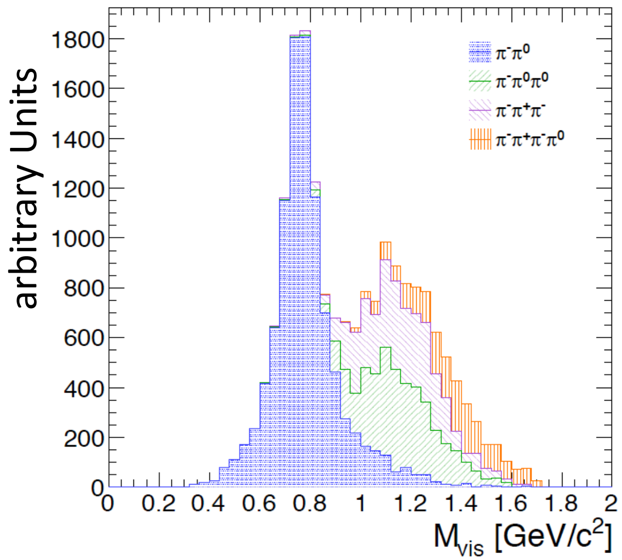
The CMS Experiment



The CMS Detector



τ Decay Modes

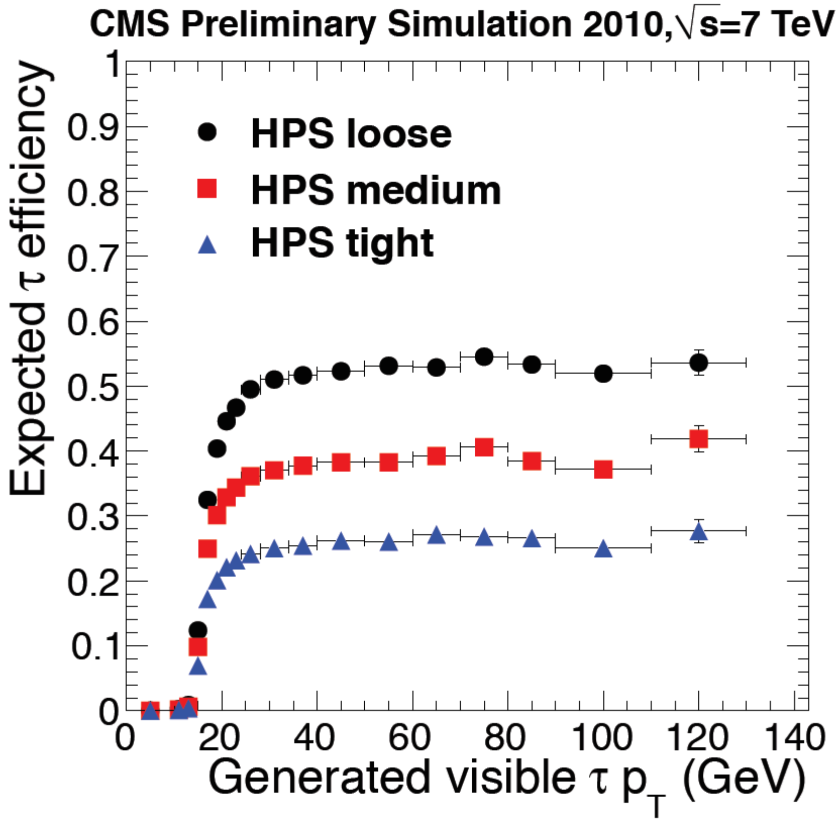


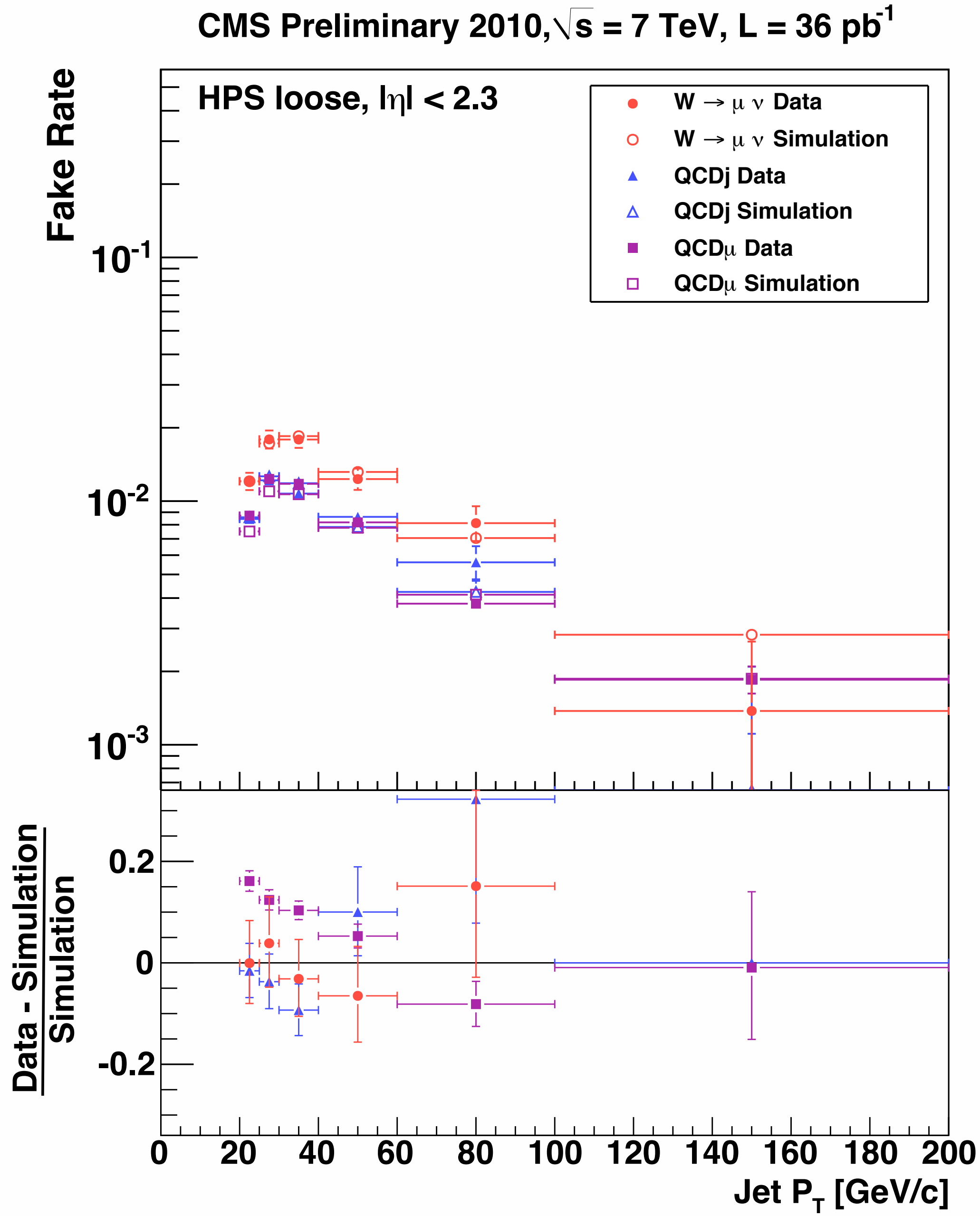
Decay Mode	Resonance	Mass (MeV/c^2)	Branching ratio(%)
$\tau^- \to e^-\bar{\nu}_e\nu_\tau$			17.8 %
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$			17.4 %
$\tau^- \to h^-\nu_\tau$			11.6 %
$\tau^- \to h^-\pi^0\nu_\tau$	ρ	770	26.0 %
$\tau^- \to h^-\pi^0\pi^0\nu_\tau$	$a1$	1200	10.8 %
$\tau^- \to h^-h^+h^-\nu_\tau$	$a1$	1200	9.8 %
$\tau^- \to h^-h^+h^-\pi^0\nu_\tau$			4.8 %
Other hadronic modes			1.7%

Tau Identification ≅ Reconstruction of well-known Vector Meson resonances

CMS τ Id. Performance

Z → $\tau^+\tau^-$ Simulation





Event Selection μ + μ Channel

Trigger

Events triggered by single Muon Triggers

P_T threshold 9-15 GeV, depending on instantaneous Luminosity

Lepton Selection

1st Muon	**2nd Muon**
$P_T > 19$ GeV	$P_T > 10$ GeV
$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.1$
isolated	isolated

1st + 2nd Muon of opposite Charge

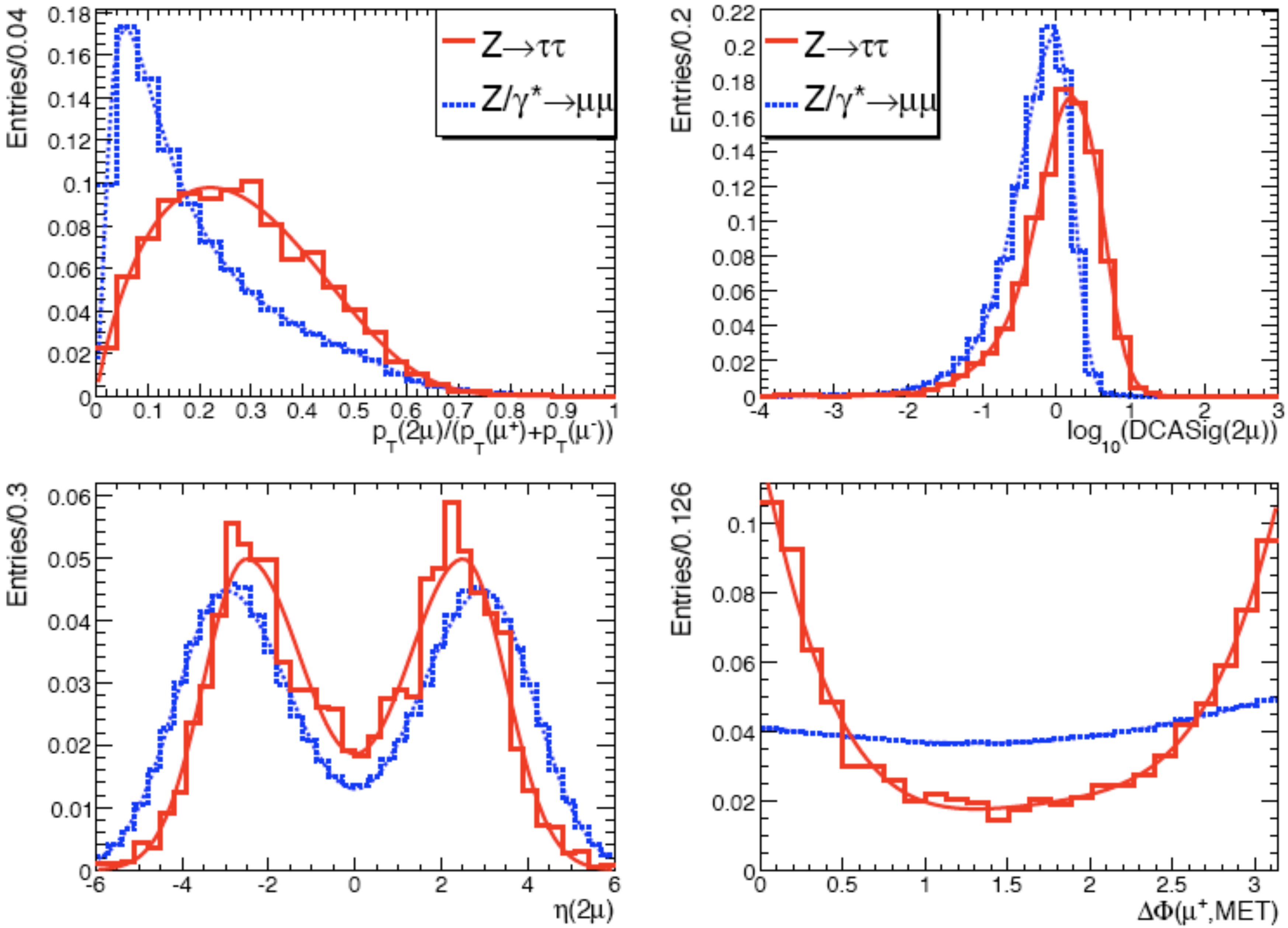
$\Delta\phi(\mu,\mu) < 2.0$ rad

Missing $E_T < 50$ GeV

$Z \rightarrow \tau^+\tau^- \rightarrow \mu^+\mu^-/Z \rightarrow \mu^+\mu^-$ Likelihood > 0.87

- $P_T(\mu^+ + \mu^-)/(P_T^{\mu+} + P_T^{\mu-})$
- DCA between μ^+, μ^- Tracks
- η of di-Muon system
- $\Delta\phi(\mu^+$, MET)

$Z \rightarrow \tau^+\tau^- \rightarrow \mu^+\mu^-$ / $Z \rightarrow \mu^+\mu^-$ Likelihood



$Z \rightarrow \tau^+\tau^-$ Acceptance × Efficiency

	$\tau_\mu \tau_{\mathrm{had}}$	$\tau_e \tau_{\mathrm{had}}$	$\tau_e \tau_\mu$	$\tau_\mu \tau_\mu$
Acceptance: $\mathcal{A}$	0.13	0.12	0.074	0.16
Selection efficiency: ϵ	0.37	0.23	0.55	0.17
Mass window correction: f_c	0.97	0.97	0.98	0.99

- Acceptance taken from $Z \rightarrow \tau^+\tau^-$ Monte Carlo (POWHEG + TAUOLA) Fraction of Events generated with $60 < M_{\tau\tau} < 120$ GeV for which visible Decay Products of both τ Leptons are within |η| Range and above P_T thresholds (depending on Decay Mode/Channel)

- Efficiency defined as Fraction of $Z \rightarrow \tau^+\tau^-$ Events within Acceptance that passes all Event Selection criteria, measured either directly in Data or taken from Monte Carlo and applying Data/MC Correction factor measured from Data

- Mass window Correction factor corrects for $Z/\gamma^* \rightarrow \tau^+\tau^-$ Events which pass Event Selection, but are not generated within Mass window $60 < M_{\tau\tau} < 120$ GeV

$Z \rightarrow \tau^+\tau^-$ Systematic Uncertainties

Source	$\tau_\mu \tau_{had}$	$\tau_e \tau_{had}$	$\tau_e \tau_\mu$	$\tau_\mu \tau_\mu$
trigger	0.2 %	3 %	0.2 %	0.3 %
lepton identification and isolation	1.0 %	1.1 %	1 %	1 %
τ_{had} identification	23 %		-	
efficiency of topological selections	2 %		-	
likelihood selection efficiency	-			2 %
acceptance due to τ energy scale, 3 %	3.5 %		-	
acceptance due to e energy scale, 2 %	-	1.6 %	1.6 %	-
acceptance due to μ momentum scale, 1 %	1 %	-	1 %	2 %
luminosity	4 %			
parton distribution functions	2 %			

Largest Uncertainty: hadronic Tau Identification Efficiency

➔ τ_{had} Identification Efficiency constrained by Ratio of Event Yields in semi-leptonic/leptonic Channels

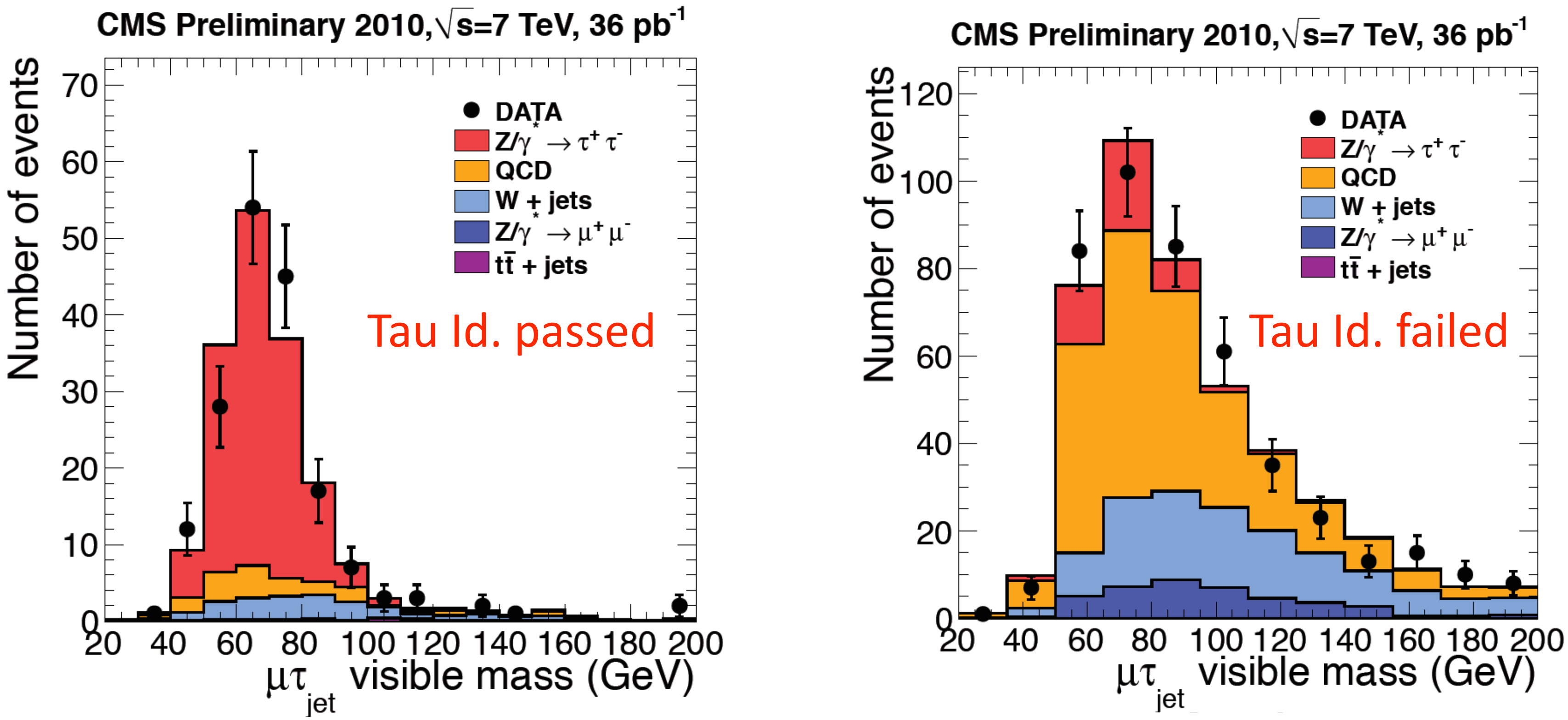
➔ Determine $Z \rightarrow \tau^+\tau^-$ Cross-section by simultaneous Fit of all four Channels

τ Id. Efficiency Measurement

Select Sample of $Z \rightarrow \tau^+\tau^- \rightarrow \mu + \tau_{had}$ Candidate Events without applying τ Id.

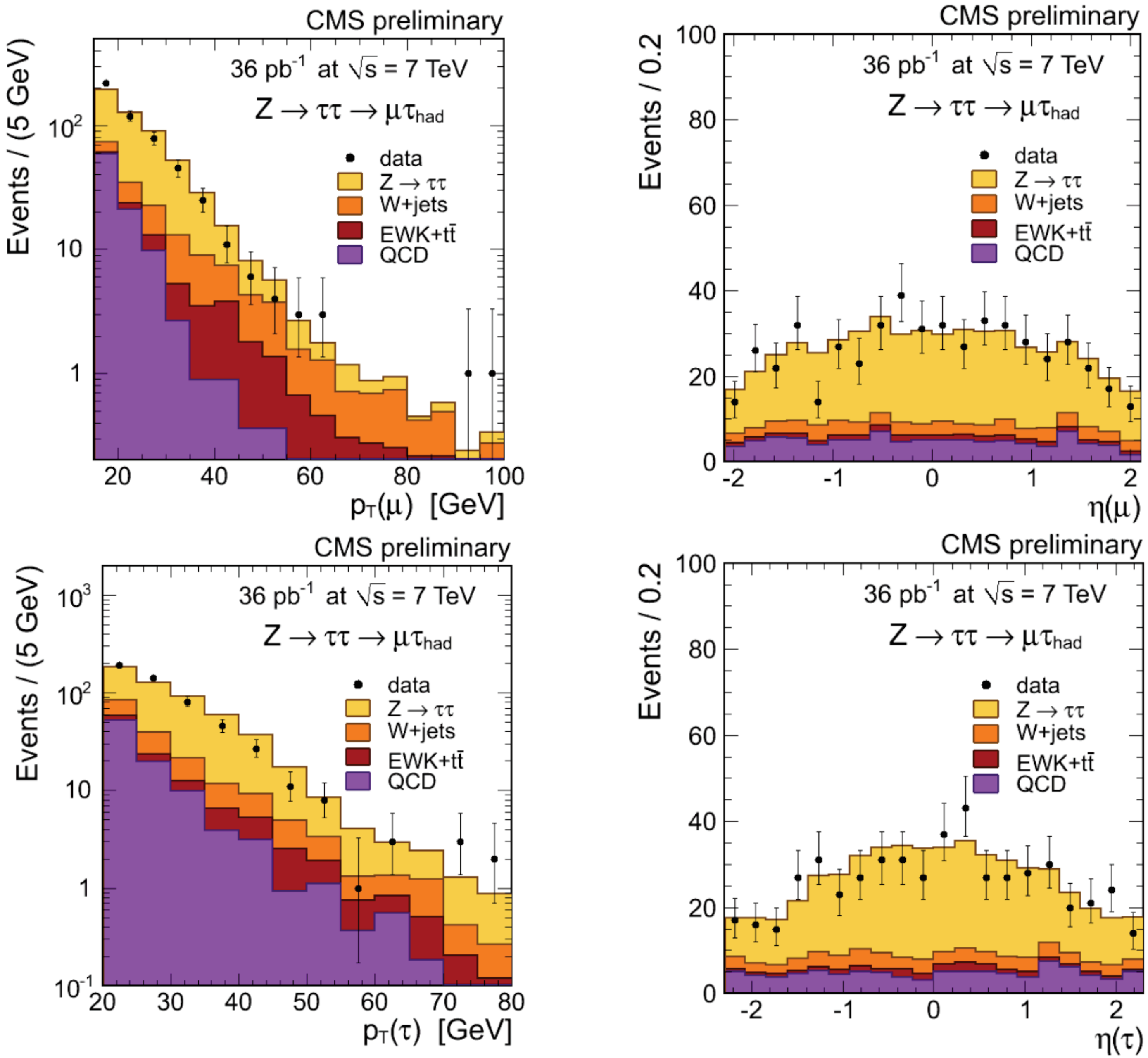
Challenge: sizeable Background Contributions

➔ Determine $Z \rightarrow \tau^+\tau^- \rightarrow \mu + \tau_{had}$ Signal Contribution by fitting $\mu + \tau_{had}$ visible Mass Distribution in Tau Id. passed/failed Samples

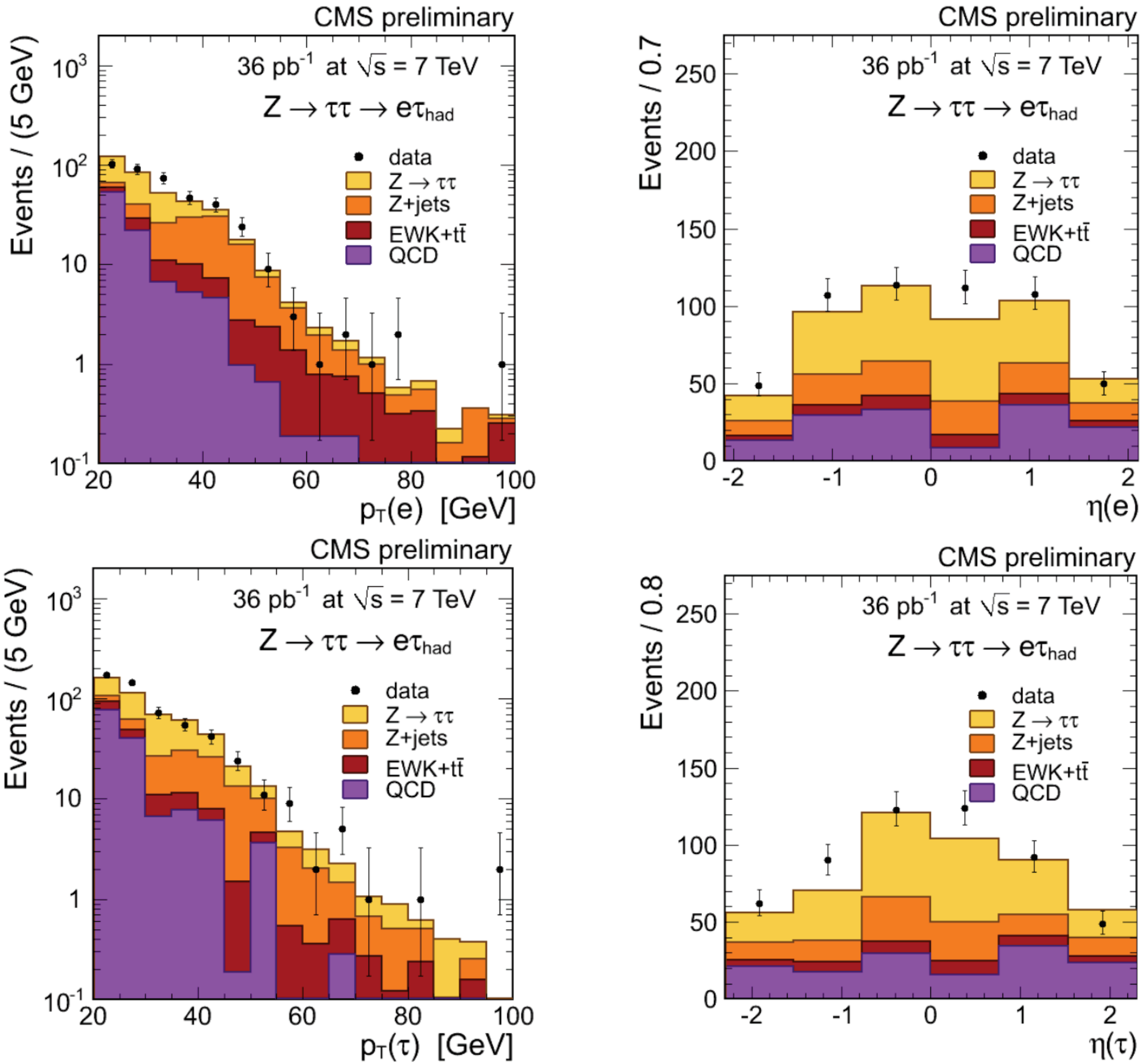


➔ ε = ($Z\tau\tau$ | passed) / ($Z\tau\tau$ | passed + $Z\tau\tau$ | failed)

Lepton P_T and η: μ + τ_{had} Channel



Lepton P_T and η: $e + \tau_{had}$ Channel

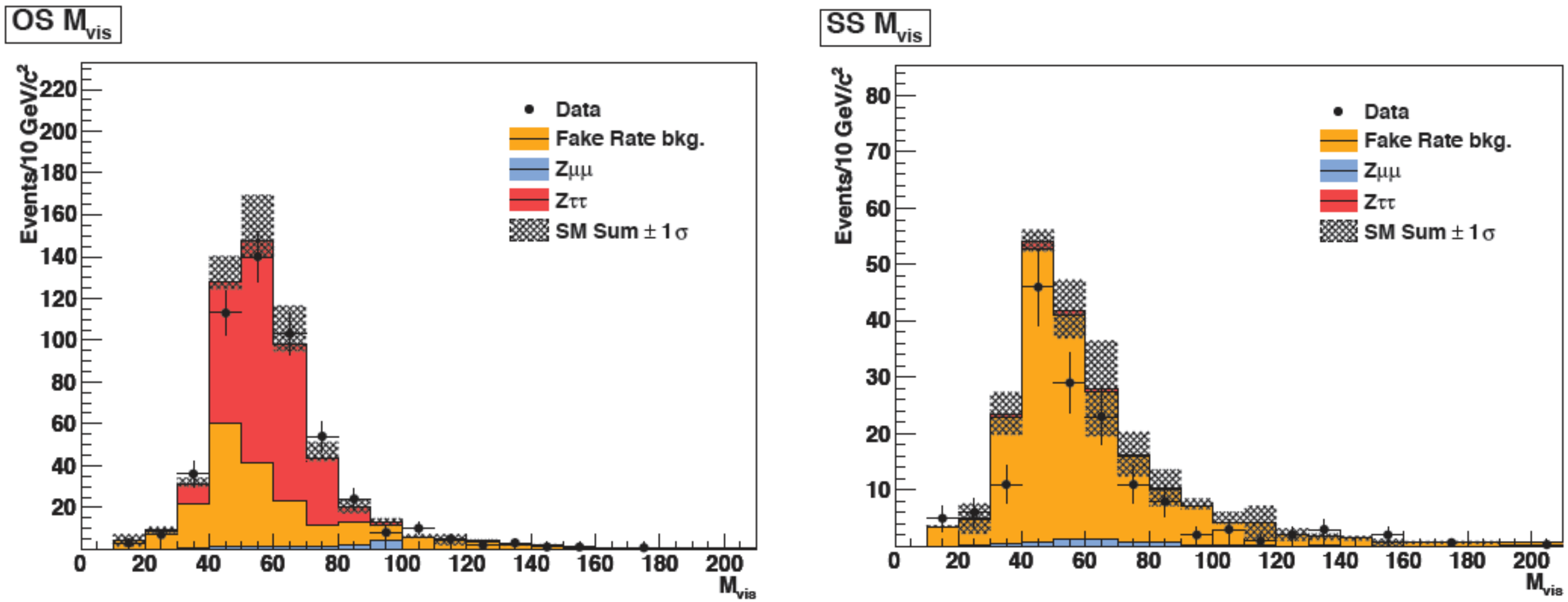


Data-driven Background Estimation

Fake-rate Technique

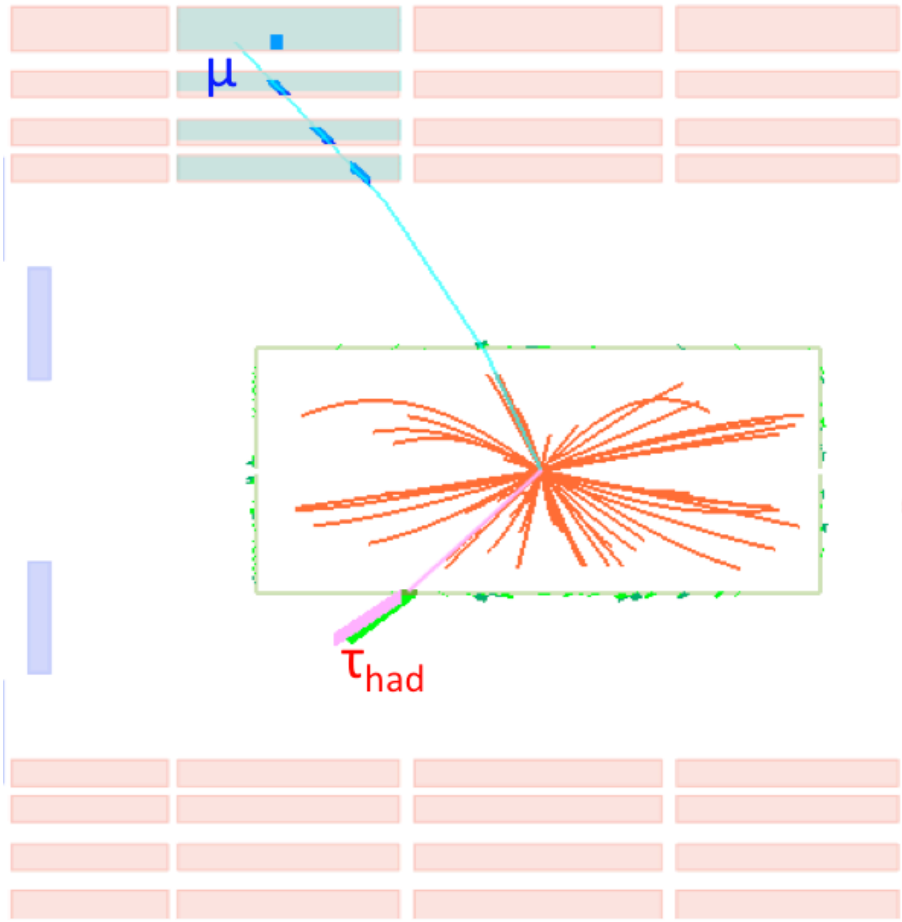
- Probability of quark/gluon Jets to fake hadronic τ Signature measured in QCD multi-jet, QCD μ-enriched and W + Jets Events
- Select sample of Events passing all Event Selection Criteria except τ Id.
- Weight selected Events by measured Fake-rates

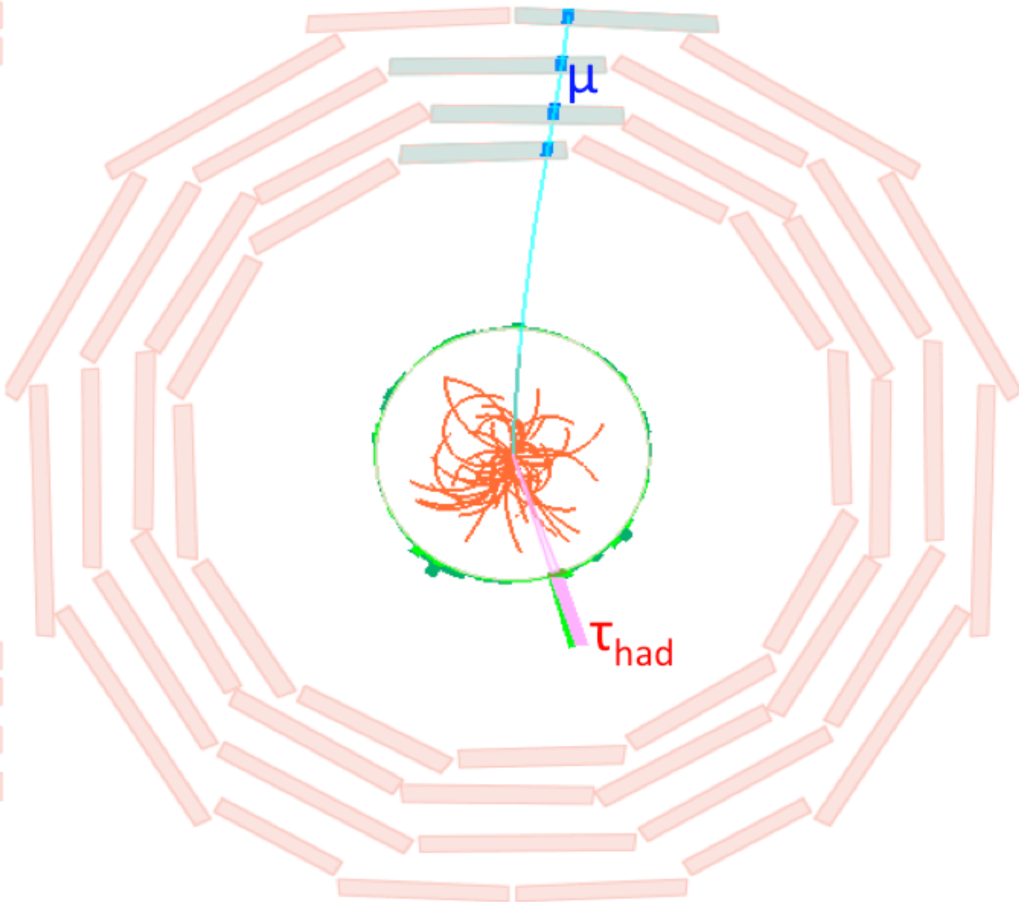
Results for Z → μ + τ_{had} Channel



➔ Data-driven Background Estimate agrees with Monte Carlo Predictions

$Z \rightarrow \tau^+\tau^- \rightarrow \mu^+ + \rho^-$ Candidate
$\quad \llcorner \pi^- \pi^0$



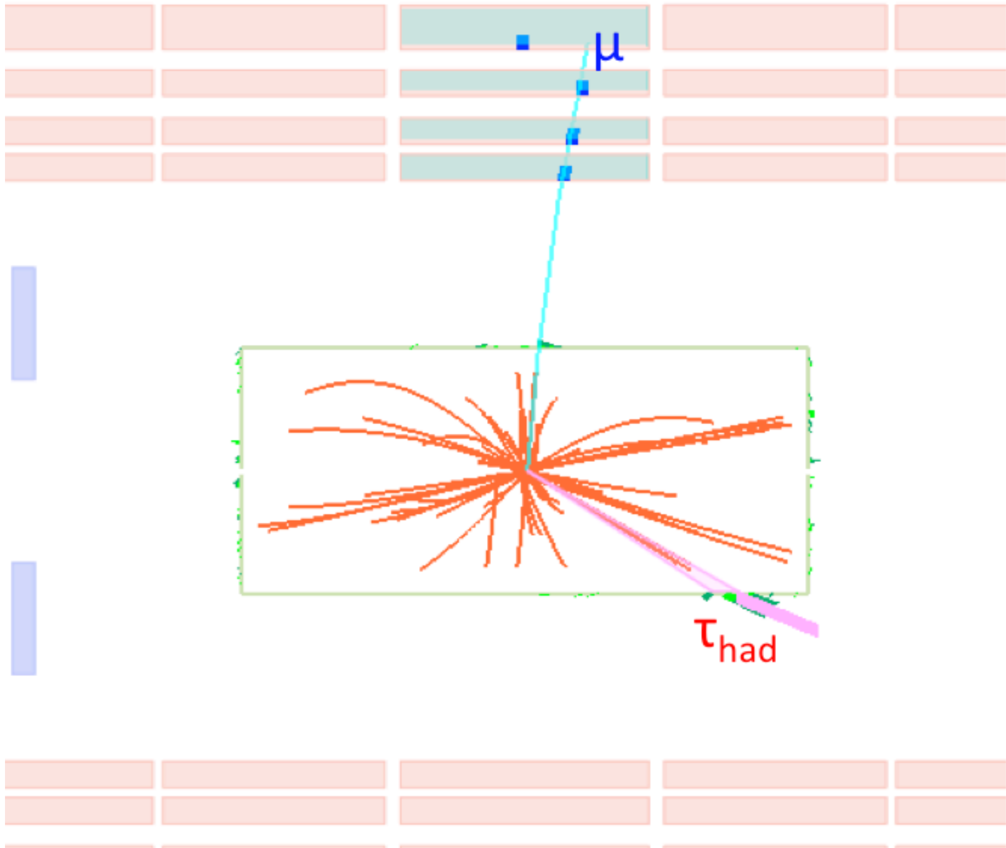


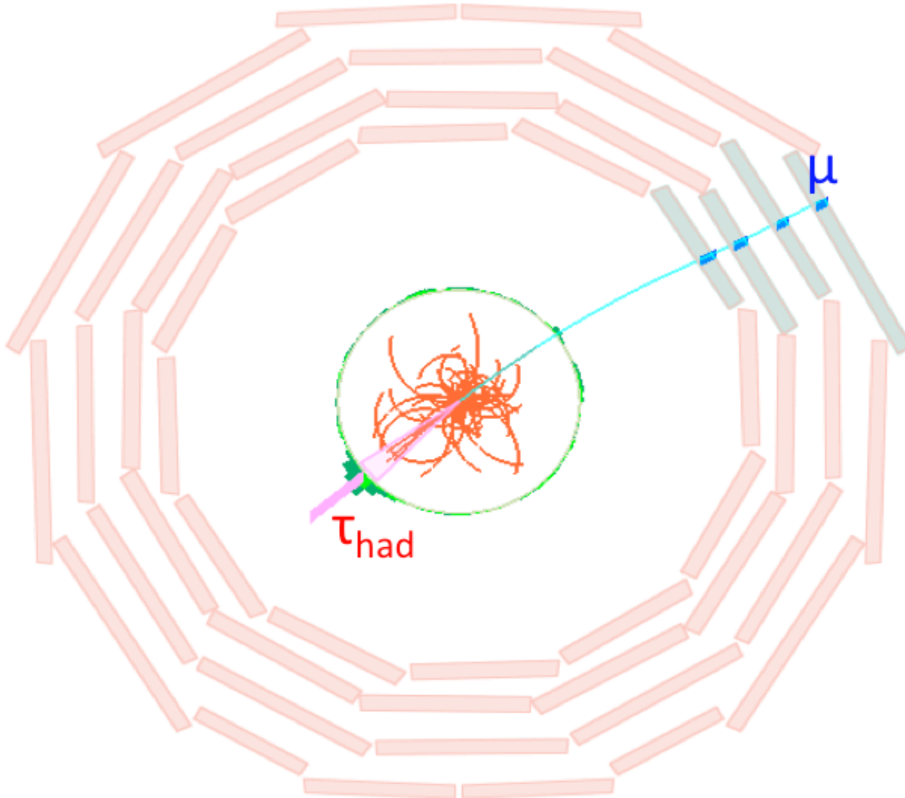
P_T^{μ} = 39.3 GeV

P_T^{had} = 28.2 GeV, lead. Track P_T = 3.3 GeV

M_{vis} = 67.0 GeV, MET = 19.9 GeV, $M_{\tau\tau}$ = 90.3 GeV

$Z \rightarrow \tau^+\tau^- \rightarrow \mu^+ + a_1^-$ Candidate
$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \pi^- \pi^+ \pi$



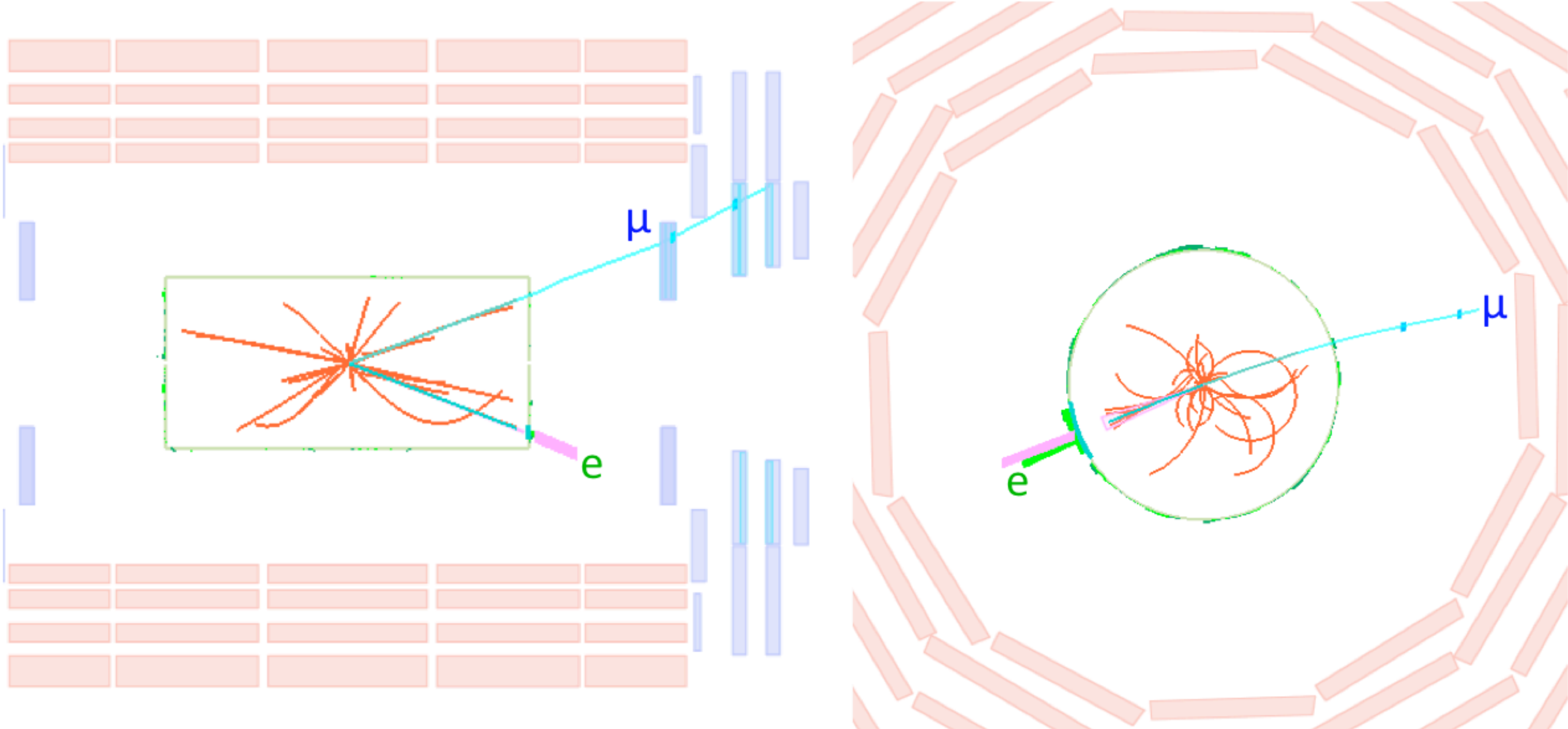


$P_T^{\mu} = 20.5$ GeV

$P_T^{had} = 35.5$ GeV, lead. Track $P_T = 18.5$ GeV

$M_{vis} = 62.7$ GeV, MET = 6.2 GeV, $M_{\tau\tau} = 98.3$ GeV

$Z \rightarrow \tau^+\tau^- \rightarrow e^- + \mu^+$ Candidate

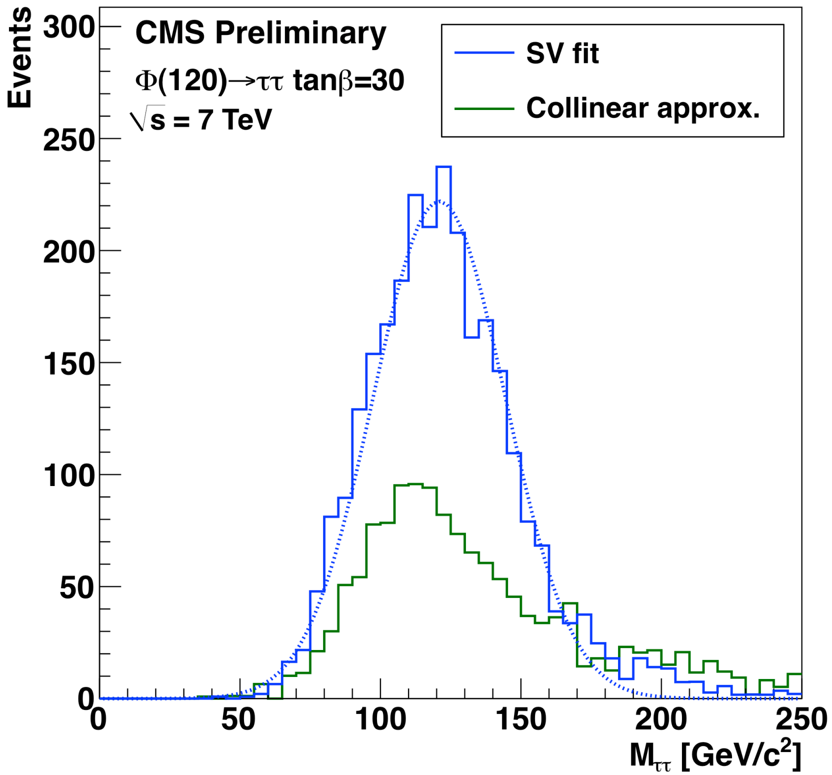


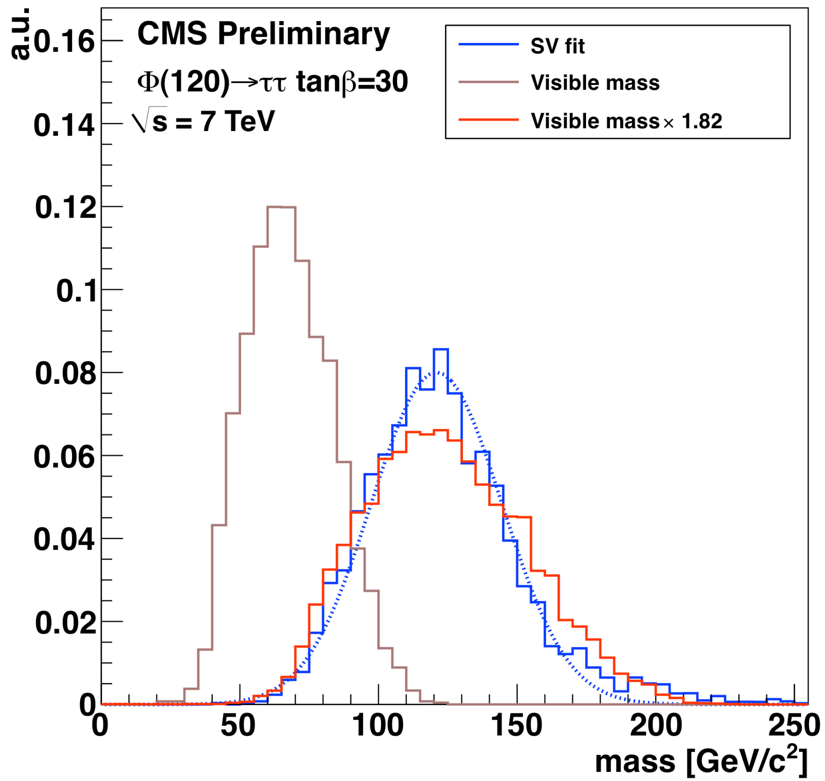
$P_t^e = 29.9$ GeV

$P_T^\mu = 16.3$ GeV

$M_{vis} = 44.2$ GeV, MET = 17.4 GeV, $M_{\tau\tau} = 91.4$ GeV

$M_{\tau\tau}$ Resolution





Compared to collinear Approximation, Likelihood algorithm:

- provides better Resolution
- increases Event Statistics by Factors ~ 2

Compared to visible Mass, Likelihood algorithm:

- improves relative Resolution $\Delta M_{\tau\tau}/M_{\tau\tau}$

Limit Calculation

- Based on fitting $M_{\tau\tau}$ Template histograms to $M_{\tau\tau}$ Distribution observed in Data for 3 Channels: $\mu + \tau_{had}$, $e + \tau_{had}$, $e + \mu$

- 95% Confidence Level upper Limit computed via Bayesian Inference

$$\int_{\sigma=0}^{\sigma_{95\%}} \frac{\int \mathcal{L}(\text{data}, \sigma, \nu)\, \pi(\sigma) \mathrm{d}\nu}{\int \mathcal{L}(\text{data}, \sigma', \nu')\, \pi(\sigma') \mathrm{d}\sigma' \mathrm{d}\nu'} \mathrm{d}\sigma = 0.95$$

using flat Prior Probability $\pi(\sigma)$ on Higgs Cross-section $\sigma > 0$

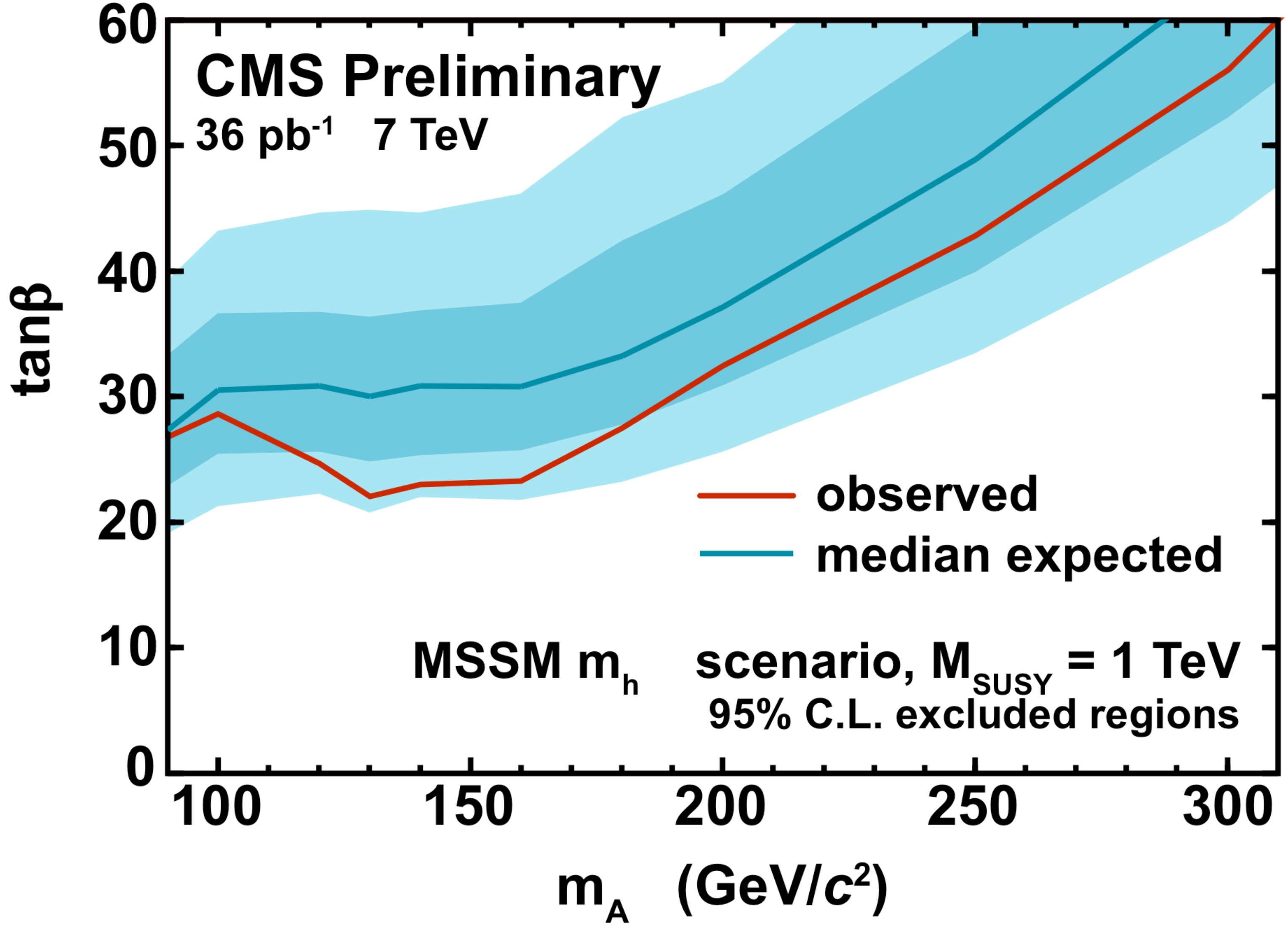
Likelihood: $\mathcal{L}(m_{\tau\tau}; \sigma_{\tau\tau}, \{\nu\}) = \mathcal{L}_{m_{\tau\tau}}(m_{\tau\tau}; \sigma_{\tau\tau}, \{\nu\}) \cdot \prod_n \mathcal{L}_n(\nu_n; \bar{\nu}_n, \Delta\bar{\nu}_n)$

$\mathcal{L}_{m_{\tau\tau}}(m_{\tau\tau}; \sigma_{\tau\tau}, \{\nu\})$: Product over all Bins of the $M_{\tau\tau}$ Distribution of –log(Poisson Probability) to observe N_{obs} Events given N expected

$\mathcal{L}(\nu; \bar{\nu}, \Delta\bar{\nu})$: Constraint on Nuisance Parameter ν (Scale or Shape, e.g. Efficiency, Energy scale, Background Yield) obtained from independent Measurement

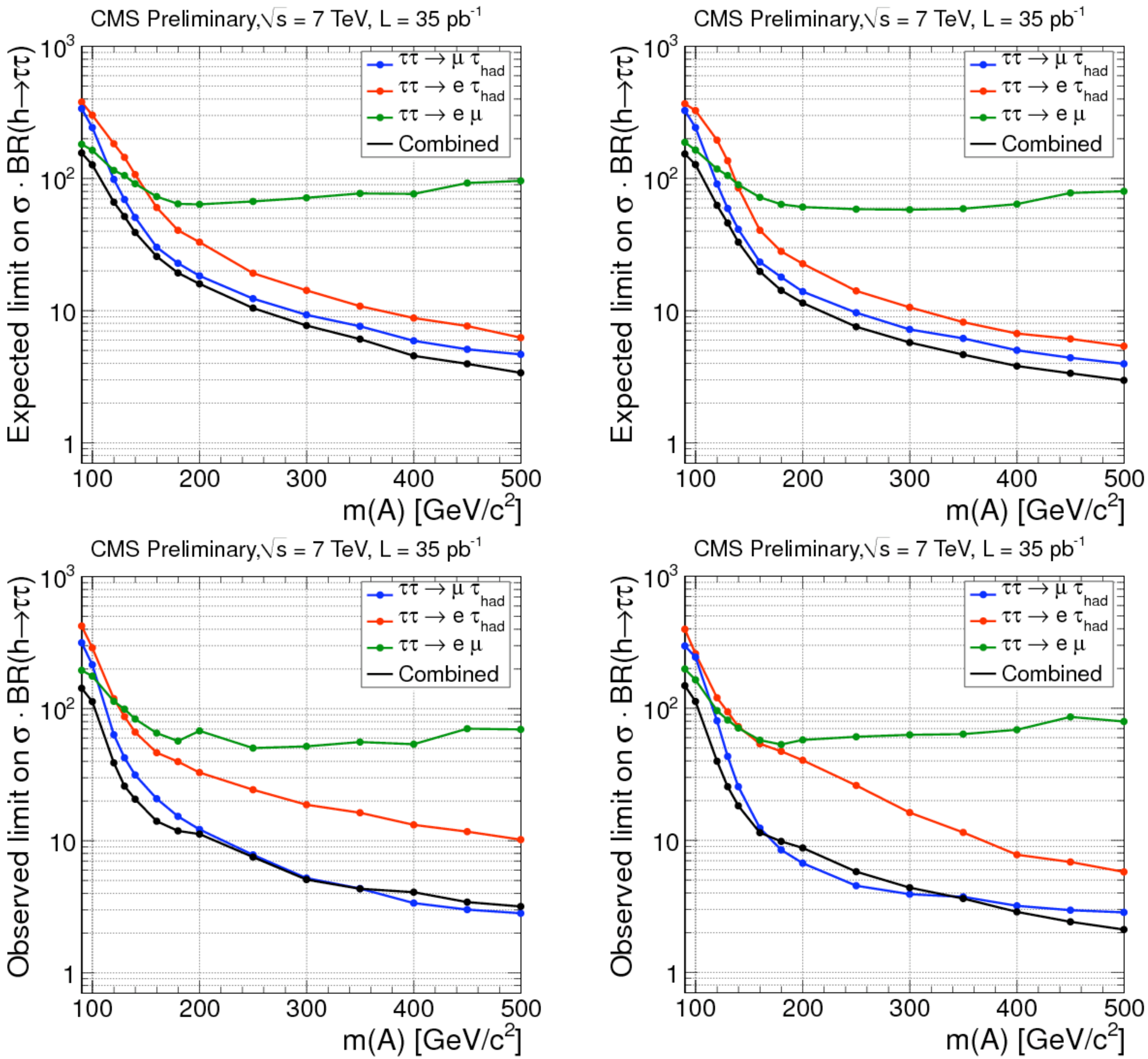
- Expected Limit obtained by “toy” Experiments: Median expected Limit and 68%, 95% CL Intervals computed from Distribution of “toy” Limits

Observed vs. expected Limit



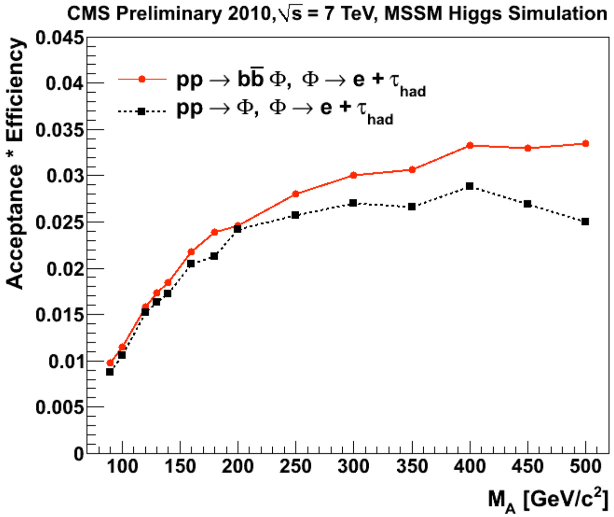
Observed vs. expected Limits by Channel

visible Mass | "full" $\tau^+\tau^-$ Mass

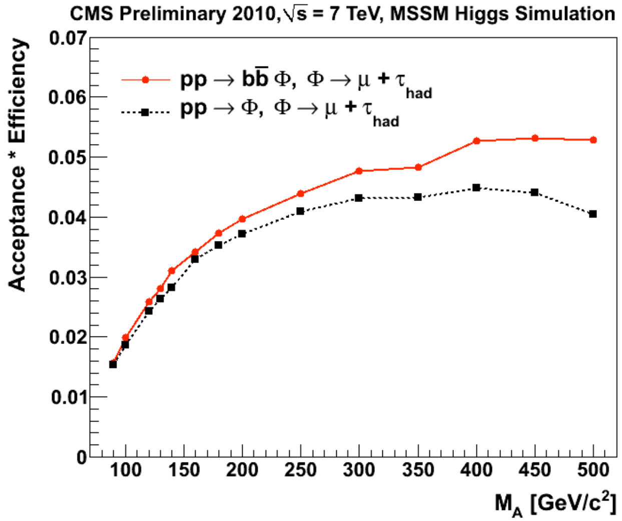


Higgs Acceptance × Efficiency

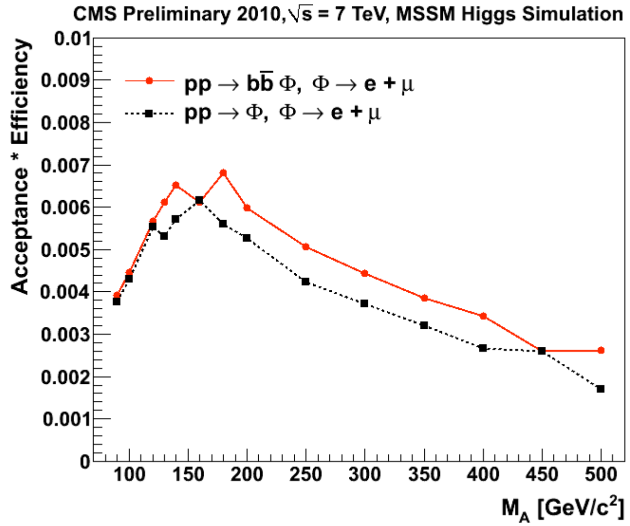
$e\text{-}\tau_{had}$



$\mu\text{-}\tau_{had}$



$e\text{-}\mu$



Approximation

ϕ: Sum of scalar + pseudo-scalar Higgs

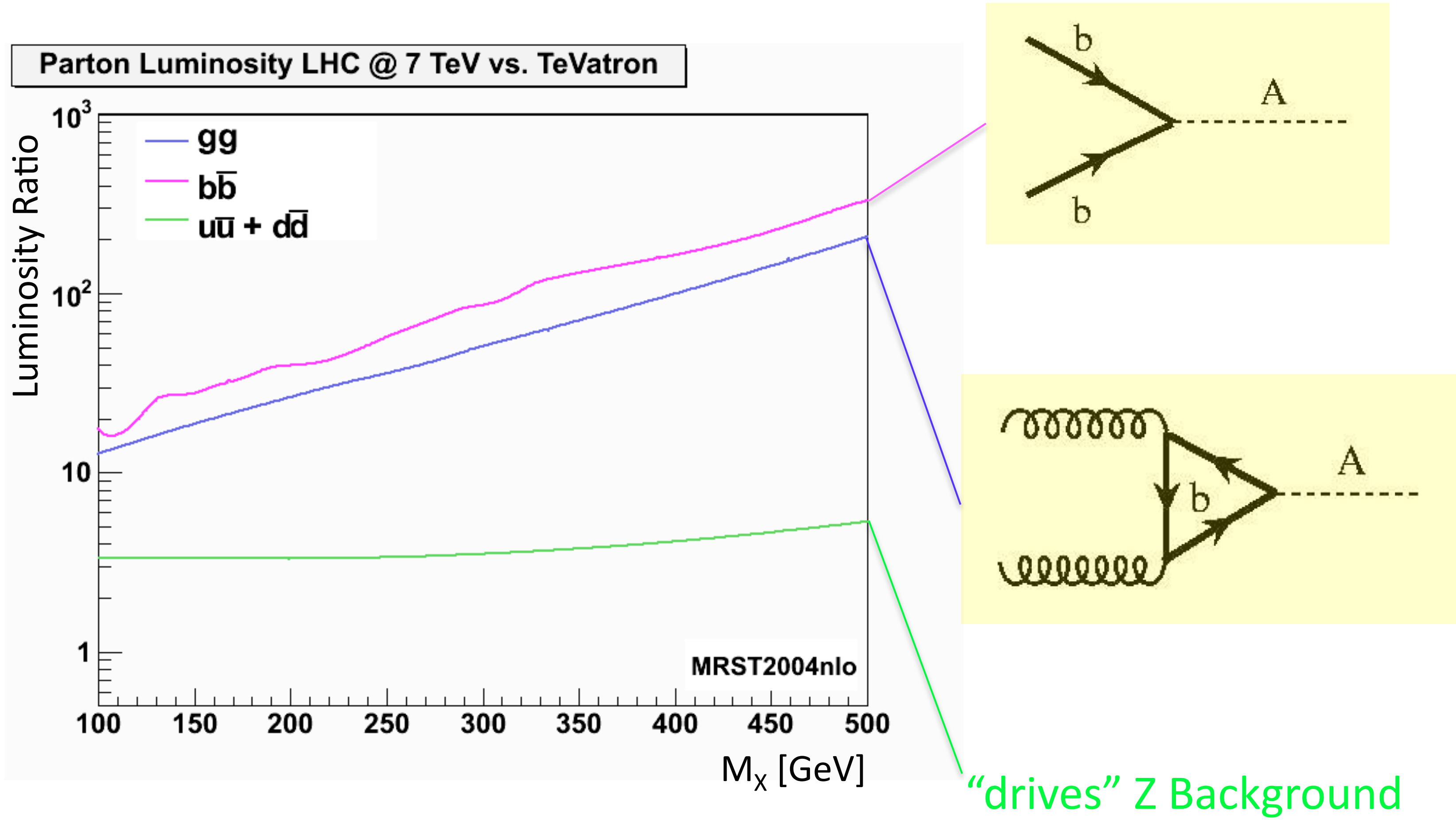
mA ≤ 120 GeV: ϕ = h + A

mA ~ 130 GeV: ϕ = h + H + A

mA ≥ 140 GeV: ϕ = H + A

Acceptance × Efficiency determined for pseudo-scalar A

Parton Luminosities LHC @ 7 TeV



➔ 36pb^{-1} of LHC @ 7 TeV Data correspond to O(1fb^{-1}) of TeVatron Data

Ratio of MSSM Higgs Signal/Z Background Cross-sections in favor of LHC

The Hadron + Strips τ Id. Algorithm

Based on CMS Particle-Flow Algorithm