Search for Supersymmetry in Events with Same-Sign Di-Leptons and Missing Energy with the CMS Detector

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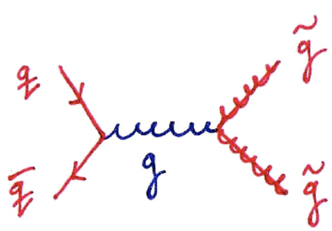
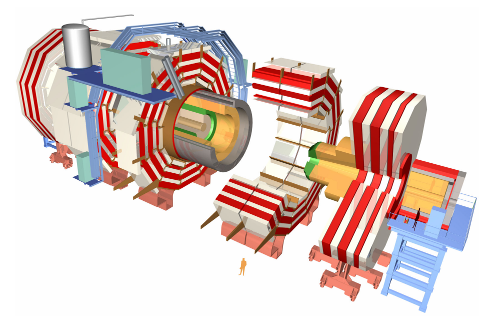


Cornell HEP Seminar

March 2, 2012

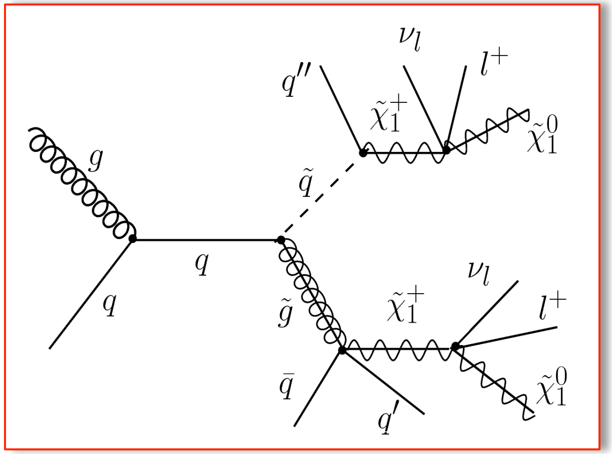


Introduction

- If SUSY exists, it could manifest itself in a variety of ways
  - Numerous particle states become available, diverse phenomenology
- In general we expect:
  - Long cascade decays that begin with colored SUSY particles (squarks/gluinos) and end with an LSP (typically the lightest neutralino)
  - Lots of activity in the event
    - **Jets from squark/gluino decays**
    - **Leptons form intermediate chargino/neutralino decays**
    - **Missing energy from escaping invisible particles**
  - The key is to choose a final state configuration (topology) that is not easily mimicked by the Standard Model

The Same-Sign Di-Lepton Topology

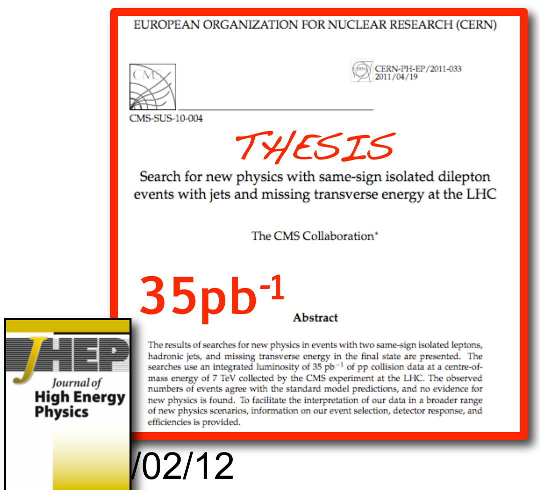
- Events containing two isolated leptons of the same electromagnetic charge (same-sign) are highly suppressed in the Standard Model
  - **Much more natural to produce oppositely charged leptons**
- Same-Sign di-lepton events are easily produced in SUSY scenarios as well as other models of new physics

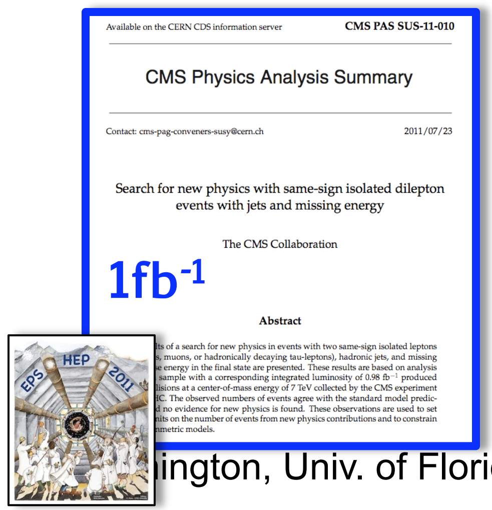


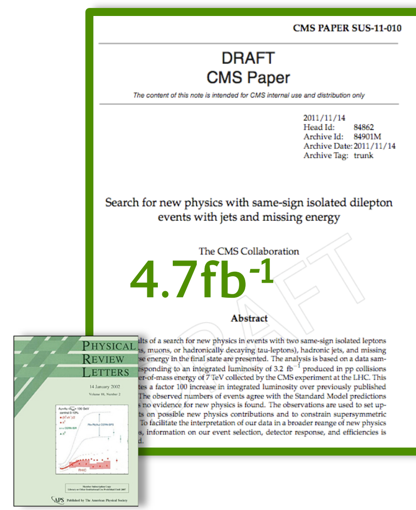
Same-Sign Dileptons in SUSY

Documentation (CMS-SUS-11-010)

- Four Contributions:
  - Florida (e/μ final states)
  - UCSD/UCSB/FNAL (e/μ final states)
  - ETH/Santander/Oviedo/Tehran (e/μ final states)
  - Imperial/Wisconsin/Perugia/Athens (τ final states)
- Original Analysis Results based on 2010 ($35pb^{-1}$)
  - Published in JHEP 1106:077 (2011) [arxiv:1104.3168]
- Second update based on Summer 2011 ($1fb^{-1}$)
  - Presented at EPS 2011 Conference
- Third update based on full 2011 Data ($4.7fb^{-1}$)
  - PRL submission in preparation



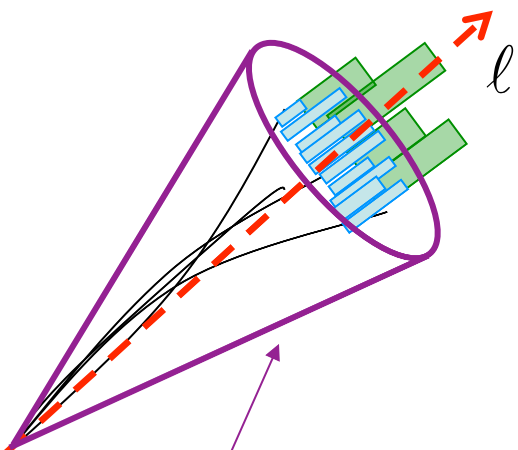




Lepton Selection

Muons (μ), **electrons** (e), and **hadronic taus** (τ) up to $|\eta| < 2.4$ are reconstructed using standard techniques on CMS. Analysis is designed to probe models that could feature "soft leptons"

- $p_T(\mu) > 5$ GeV, $p_T(e) > 10$ GeV, $p_T(\tau) > 15$ GeV



Isolation cone: $\Delta R = \sqrt{(\Delta\eta)^2+(\Delta\phi)^2} < 0.3$

The **relative isolation** (RelIso) observable is used to distinguish prompt from non-prompt leptons:

$$\frac{\sum_{\Delta R<0.3} P_T^{\text{Track}} + E_T^{\text{ECAL}} + E_T^{\text{HCAL}}}{P_T^{\ell}} < 0.15$$

Leptons are ***"prompt" (signal-like)*** if they come from W/Z/χ decays and ***"non-prompt" (fake)*** if the come from hadron decays.

A requirement is placed on the transverse impact parameter at $d_0 <$ 0.02 cm in order to suppress leptons from heavy-flavor quark decays.

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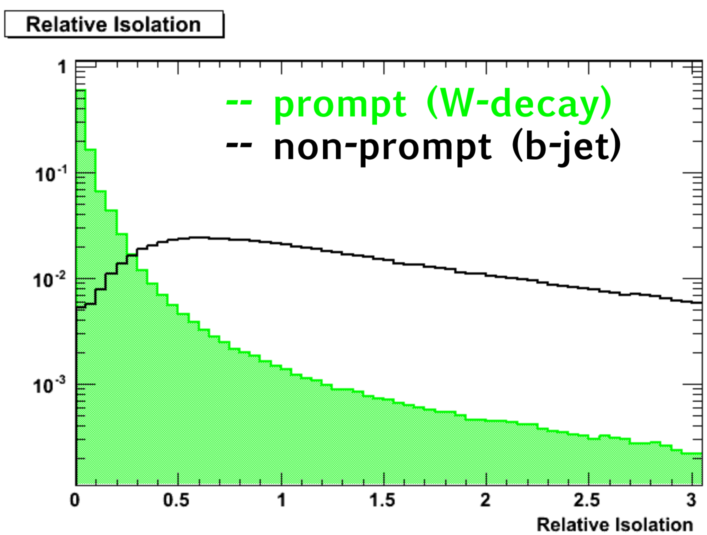

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Jets and Missing Energy

Jets and missing transverse energy (MET or $\not{E}_T$ or E_T^{Miss}) are based on the Particle Flow technique (combined calorimeter + tracking).

- Jet p_T > 40 GeV and $|\eta|$ < 2.5

The total hadronic activity in the event is characterized by the H_T variable:

$$H_T = \sum_j^{\text{all jets}} \left| p_T^j \right|$$

The E_T^{Miss} is calculated by summing vectorially over the transverse momenta of all of the reconstructed particle candidates in the event:

$$\left| \vec{E}_T^{miss} \right| = \left| \sum_j^{\text{all particles}} \hat{x}\left(p_T^j \cdot \cos(\varphi)\right) + \hat{y}\left(p_T^j \cdot \sin(\varphi)\right) \right|$$

Datasets and Triggers

- We pursue 3 online event selection strategies
  - Di-Lepton Triggers
    - Allows for low-H_T cuts, but requires *high-p_T leptons*
  - Di-Lepton + H_T Triggers
    - Allows for *low-p_T leptons*, but requires larger H_T
  - Lepton + H_T + MET Triggers
    - Allows for *hadronic-tau final states* but requires larger H_T and MET

Baseline Event Selection

- 2 isolated same-sign leptons + 2 jets
- Z-Veto: no OS pair within [76,106] GeV
- Di-lepton Mass > 8 GeV
  - Reduces pairs from heavy flavor decays
  - Implemented in logic of Dilepton+H_T triggers

Table 1. Baseline Event Selection (GeV)

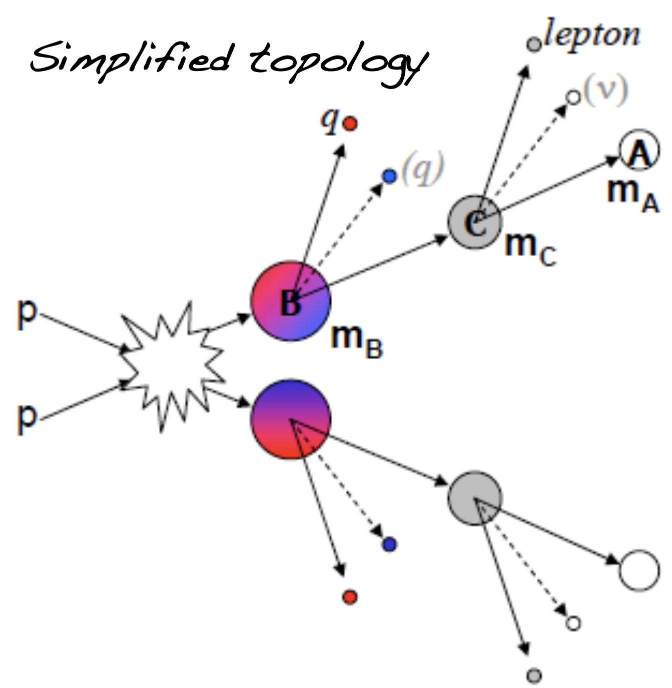
Category	e	μ	τ	Max($p_T^{\ell_1}, p_T^{\ell_2}$)	H_T	$\not{E}_T$
Low-p_T	10	5	-	-	200	30
High-p_T	10	10	-	20	80	30
Tau	10	5	15	-	320	80

Determining the Signal Regions

- In its simplest incarnation, our topology features 3 mass scales, and these can influence our main observables

A: **LSP** [dark-matter motivated; expect E_T^{miss}]
B: **gluino/squark** [large σ; expect jets]
C: **chargino** [gives exclusive same-sign leptons]

Observable	Influenced By
σ_{prod}	m_B
H_T	Δm_{BC}
p_T^{ℓ}	Δm_{CA}
MET	Δm_{BA}

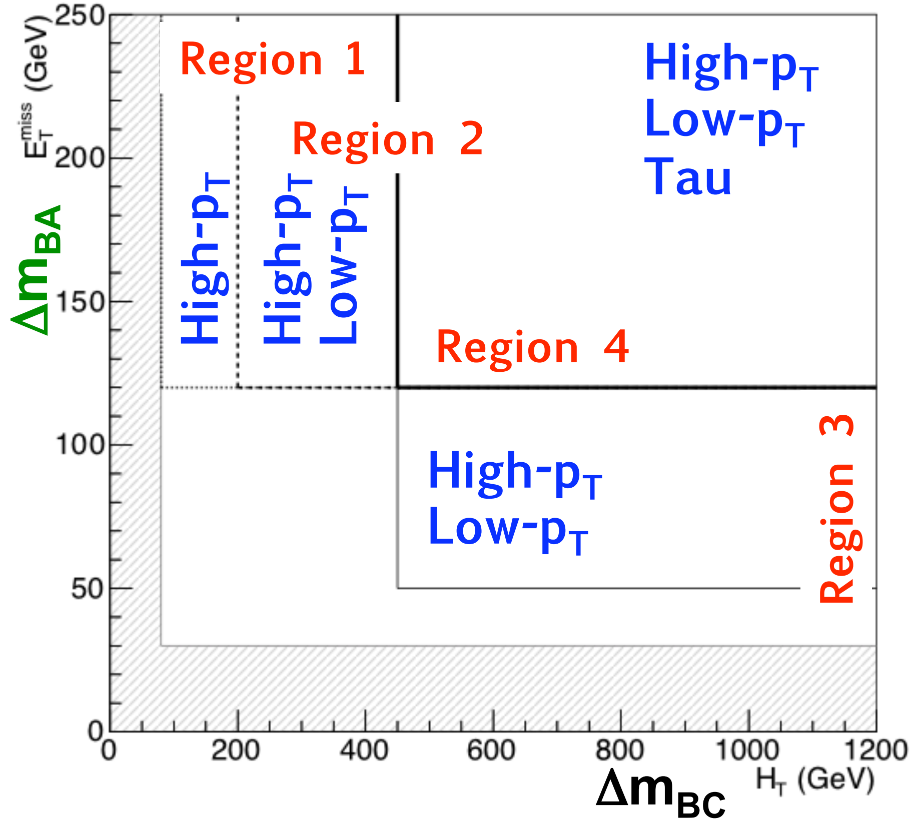


Signal Regions

- Probe various mass-splitting scenarios by targeting regions in the H_T-MET plane

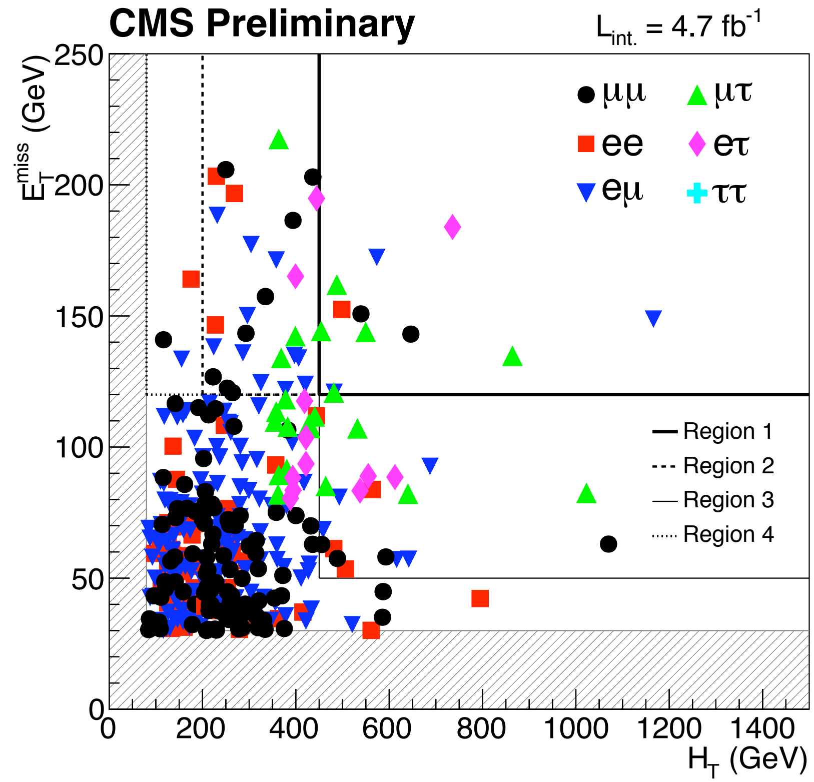
Region	H_T	MET
1	80	120
2	200	120
3	450	50
4	450	120

8 overlapping regions in total. We do track yields in exclusive H_T-MET boxes as well, to be used for combined limit-setting in the future



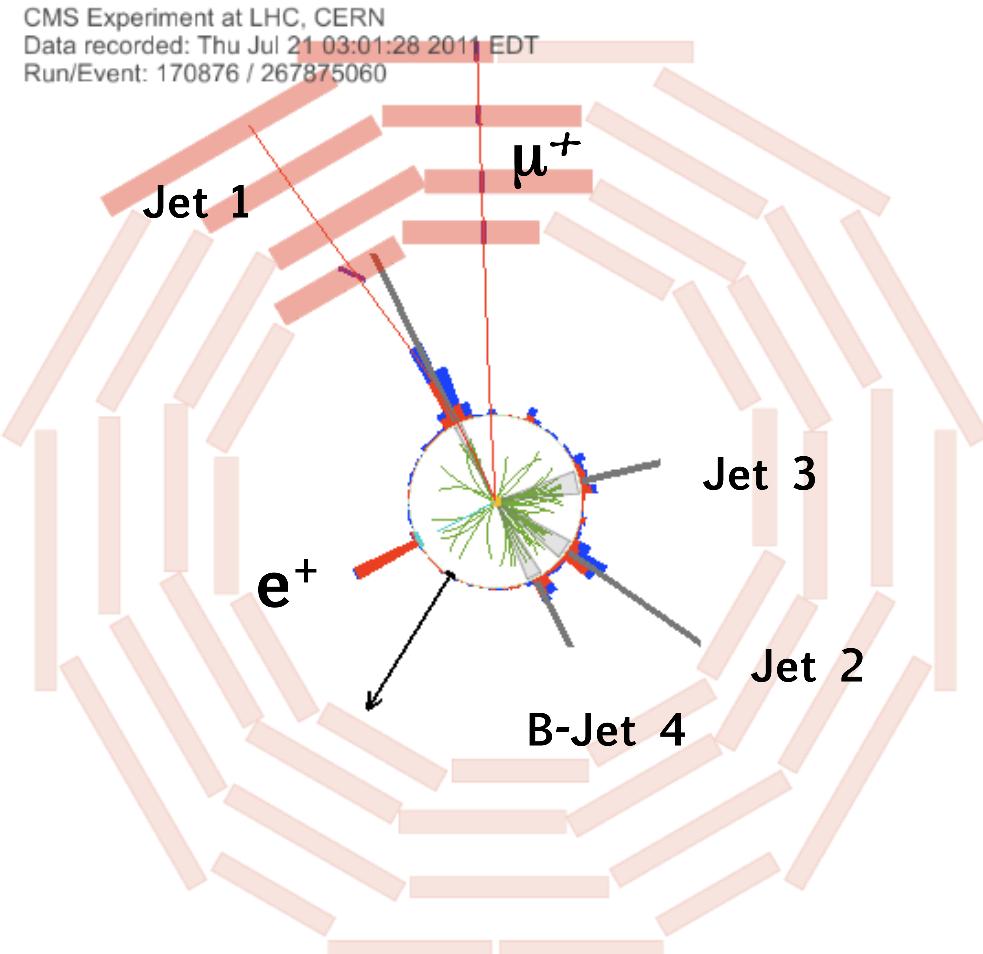
Signal Region Yields

		80/120	200/120	450/50	450/120
High-p_T	ee	5	4	4	1
	μμ	7	6	2	0
	eμ	12	11	5	3
	Tot	24	21	11	4
Low-p_T	ee	–	4	4	1
	μμ	–	10	6	2
	eμ	–	14	8	3
	Tot		28	18	6
Tau	eτ	–	–	–	1
	μτ	–	–	–	5
	ττ	–	–	–	0
	Tot				6



Fundamental challenge of the analysis: ***Can we predict these event counts using our understanding of the SM?***

Candidate Signal Event



H_T = 579 GeV
MET = 172 GeV

	p_T	η	ϕ	Iso	d_0
μ^+	130	0.05	1.6	0.00	0.00
e^+	79	-0.4	-2.7	0.01	0.00

	p_T	η	ϕ	TCHE (hp)
Jet 1	215	-0.85	2.0	0.8
Jet 2	185	-0.97	-0.6	0.5
Jet 3	91	-0.92	0.2	0.8
Jet 4	83	-0.32	-1.1	10.8

Mass(J2,J3) = 105 GeV
Mass(J2,J3,J4) = 188 GeV

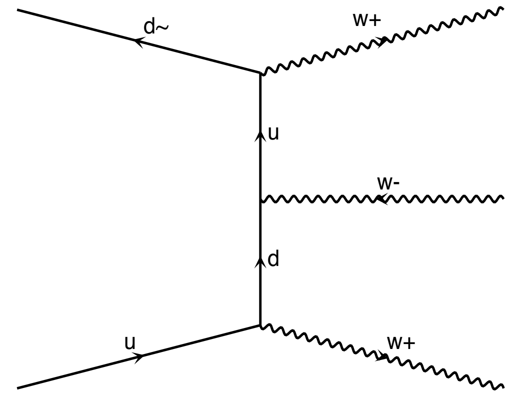
Background Classification

Type	Sources
2 same-sign prompt leptons: N^{SS}_{p-p} – small, but irreducible, contribution – reasonably well understood → *taken from MC*	$qq \to qqW^{\pm}W^{\pm}$, $WZ, ZZ, WWW, t\bar{t}W, t\bar{t}Z$ double parton scattering $2\times(qq \to W^{\pm})$
2 opposite-sign prompt leptons + charge misidentification (appears as same-sign) N^{OS}_{p-p} – small contribution – relying on MC is not safe → *derive from data*	$t\bar{t}$, tW, Drell-Yan, $W^{\pm}W^{\mp}$, WZ, ZZ
1 prompt lepton + 1 fake lepton N^{SS}_{p-f} – dominant contribution – relying on MC is not safe → *derive from data*	$(t\bar{t}, tW, tb) \to \ell\nu$ + jets W + jets, Drell-Yan + jets VV $\to \ell$ + jets
2 fake leptons N^{SS}_{f-f} – sub-dominant contribution – relying on MC is impossible → *derive from data*	QCD $t\bar{t}$ (all-hadronic)

$$N^{\text{tot}}_{\text{bgd}} = N^{SS}_{p-p} + N^{OS}_{p-p} + N^{SS}_{f-f} + N^{SS}_{p-f}$$

$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

Irreducible Backgrounds



- These backgrounds include:
  - Di-boson production: $q\bar{q} \to WZ, ZZ$
  - Double "W-sstrahlung": $qq \to q'q'W^{\pm}W^{\pm}$
  - Double-parton scattering: $2 \times (qq \to W^{\pm})$
  - Tri-Boson production: $q\bar{q} \to WWW, WWZ, WZZ, ZZZ$
  - Top-Antitop+Boson production: $q\bar{q}' \to t\bar{t}\,W, t\bar{t}\,Z$
- Many of these rare SM processes have not been well-measured or established directly at the LHC, so Monte-Carlo—based estimates are necessary
  - Several of these samples produced specifically for this analysis*
  - 50% uncertainty to cover incomplete knowledge of NLO σ's
  - Accounts for 12-75% of the total bgd, depending on search region

Expected Contribution for 4.7fb^{-1}

	80/120	200/120	450/50	450/120
High-pT	13.4	10.2	6.4	3.0
Low-pT		11.2	6.8	3.3
Tau				0.9

*https://indico.cern.ch/contributionDisplay.py?contribId=3&confId=168540

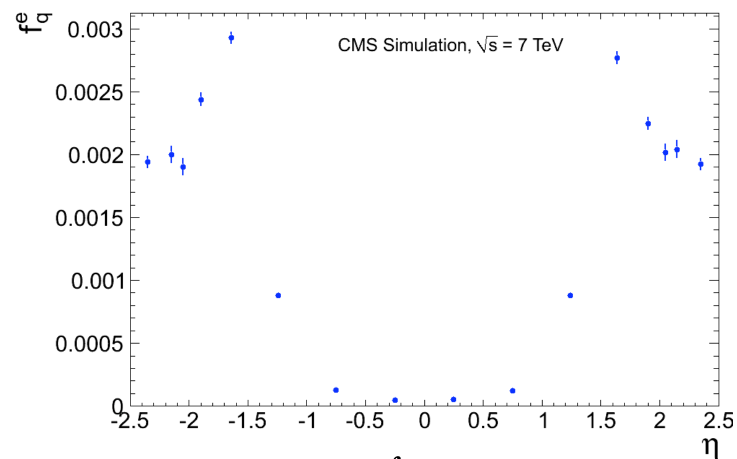
$$N_{\rm bgd}^{\rm tot} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

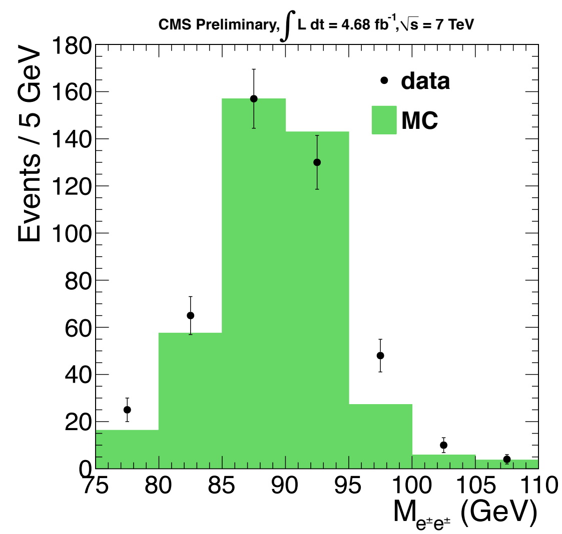
Electron Charge Mis-ID

- We estimate the probability f^e_q to mis-assign the charge for electrons using Z→ee events (ie, look for SS events in the Z-peak)
- Mis-Id rate agrees well with simulation
  - 0.02% in the barrel and 0.28% in endcaps
- Estimate contribution to signal regions by inverting charge requirement and multiplying by the probability

$$N(e^{\pm}e^{\pm}) = 2 f_q^e \cdot N(e^{\pm}e^{\mp})$$
$$N(e^{\pm}\mu^{\pm}) = f_q^e \cdot N(e^{\pm}\mu^{\mp})$$

Accounts for ~1% to 5% of total background





Tau-Charge Mis-Id in backup

$$N_{\mathrm{bgd}}^{\mathrm{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

Fake Leptons (single & double)

- Dominant background for most search regions
- Main source (e/μ) : Heavy-Flavor decays
  - ***~95% of our non-prompt muons***
  - ***~80% of our non-prompt electrons***
- Main source (τ) : Hadronic jets
- Important to derive these estimates from data as simulation does not model these well enough
- We present a diverse set of approaches to measuring contributions from fakes
- All methods rely on some type of a loose-to-tight extrapolation in the respective lepton selection variables
  - *Measure loose-to-tight probabilities in well-defined control region in data*
  - *Apply to sideband next to signal region*
- Systematic uncertainties on various methods ~50%

$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + \underline{N_{f-f}^{SS} + N_{p-f}^{SS}}$$

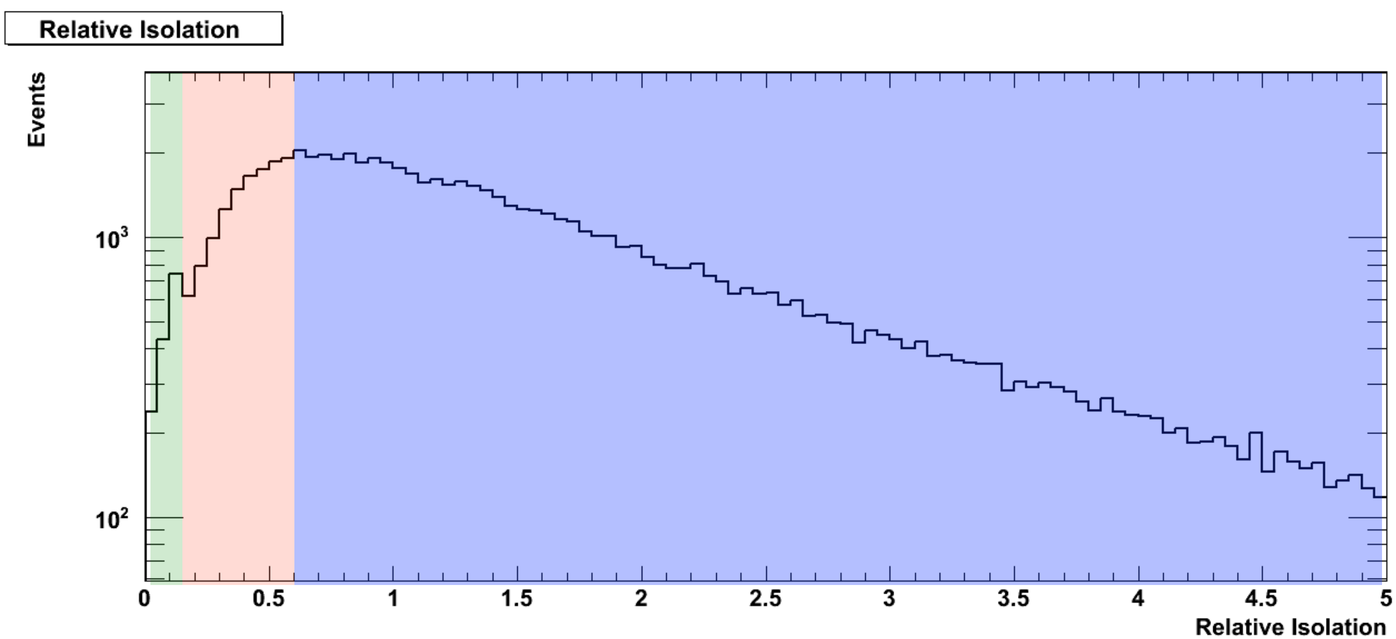
Notation

The conditional probability for a lepton candidate to pass the **tight selection criteria** given that it has passed some **loose selection criteria** is called a "Tight-To-Loose" ratio or the T/L ratio

Consider the *RelIso* selection variable. Depending on the value of this parameter a lepton may either be classified as

I. Loose [a.k.a. the sideband]
II. Tight [a.k.a. the signal region]
III. Neither Loose, nor Tight [a.k.a. junk]

T/L ratio =



$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$

Diversified Approaches

Each group chooses a different collection of *extrapolation variables* and varying lengths for the sideband. The T/L ratio must be derived from a *control region*. This region may need to be *transformed* to the signal region. This is achieved by *binning* the T/L ratio as a function of *appropriate observables*. Additionally, some groups assume *universality* of the T/L ratio (i.e., the origin of the lepton does not influence the T/L ratio).

Group	Extrapolation Variables	Transformation Variables	T/L Universality Assumption	Sideband Length
Florida	RelIso, MET	p_T^{ℓ}, NJets	No	Large
ETH, et. al.	RelIso, e-ID	None	Yes	Medium
UCSD, et. al.	RelIso, e-ID, d_0, χ^2	p_T^{ℓ}, η^{ℓ}	Yes	Small
Imperial, et. al.	RelIso, τ-ID	p_T^{ℓ}, η^{ℓ}	Yes	Medium

Control regions are selected independently by each group. Most feature inverted cuts on MET and M_T in order to suppress events w/ signal leptons

$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

T/L Algebra and Application

Notation : T/L Ratio = Probability for loose lepton to also pass tight selection

- General Formula, assuming true cut efficiencies f and p for fake and prompt leptons respectively:

(1 fake)

$$N_{pf} = \frac{pf}{(p-f)^2}\left[-2fpN_{ll} + \left[f(1-p)+p(1-f)\right]N_{tl} - 2(1-p)(1-f)N_{tt}\right]$$

(2 fakes)

$$N_{ff} = \frac{f^2}{(p-f)^2}\left[p^2N_{ll} - p(1-p)N_{tl} + (1-p)^2N_{tt}\right]$$

- If one assumes no prompt leptons in the sideband, then p→1

$$N_{pf} \approx \frac{f}{(1-f)^2}\left[-2fN_{ll} + (1-f)N_{tl}\right]$$

$$N_{ff} \approx \frac{f^2N_{ll}}{(1-f)^2}$$

- Each group uses some variation of this formula
- Universality assumption: f is the same in N_{pf} and N_{ff}

$$N_{\rm bgd}^{\rm tot} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

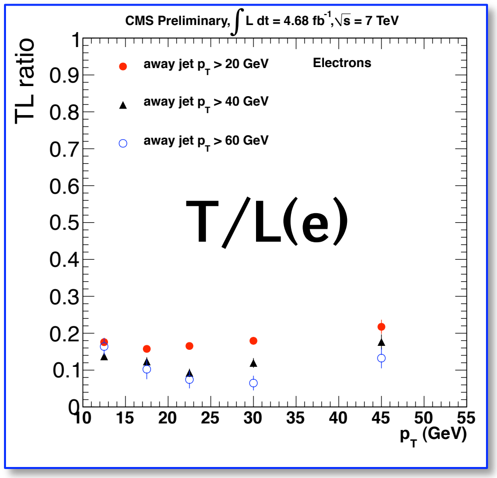
T/L Ratios from Data (e/μ)

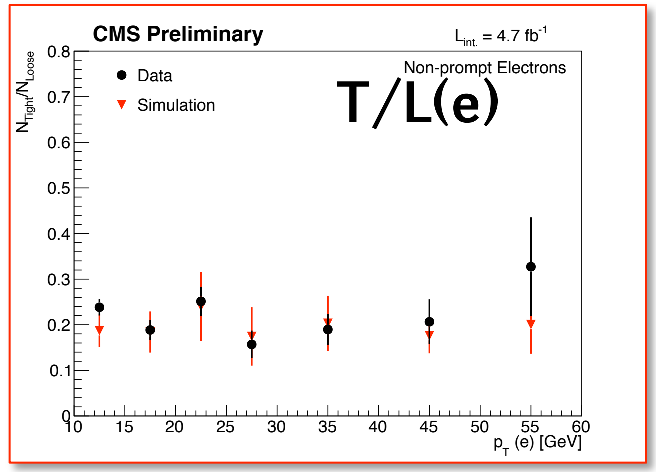
Notation : T/L Ratio = Probability for loose lepton to also pass tight selection

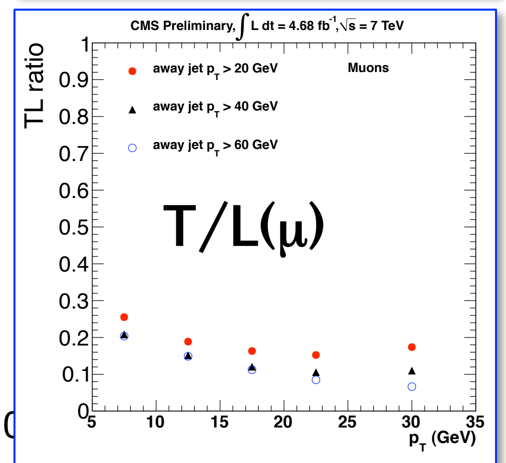
Measure T/L ratio in events with Jets + “away” lepton

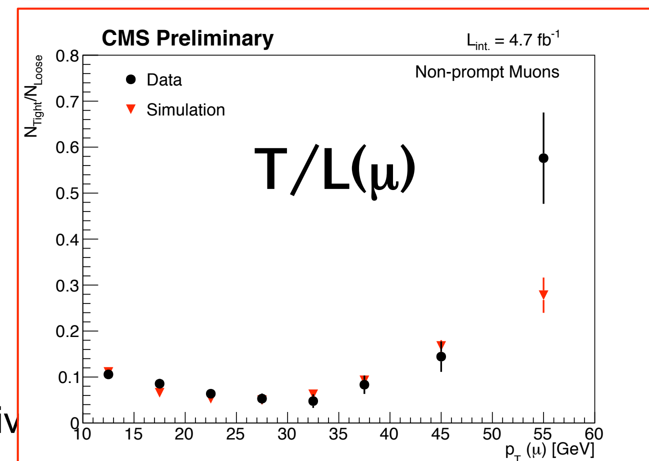
“Short Sideband”
UCSD/UCSB/FNAL

“Medium Sideband”
ETH, et. al.









$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

Non-Universal T/L Ratios (e/μ) *(Florida)*

- Use knowledge that **single-fake** events primarily come from **top events** and **double-fakes** come from **QCD**
- The T/L ratios may not be identical in QCD events and top events
  - **Different Heavy-Flavor proportions**
  - **Different jet multiplicities**
  - **Different kinematics**
- Goal: Measure two sets of T/L ratios
  - ***BTag-And-Probe Method (measures single-fakes ttbar/single-top)***
  - ***Factorization Method (measures double-fakes from QCD)***
- Use both methods together to derive the total contribution from fake leptons

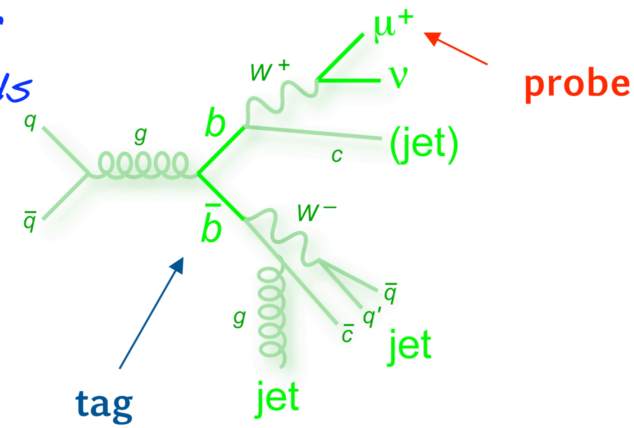
$$N^{tot}_{bgd} = N^{SS}_{p-p} + N^{OS}_{p-p} + N^{SS}_{f-f} + N^{SS}_{p-f}$$

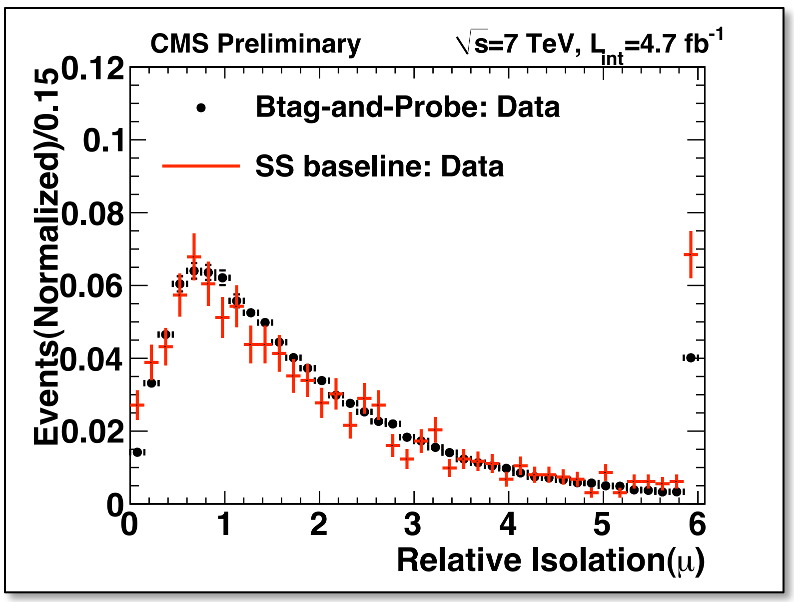
T/L Ratios for top events

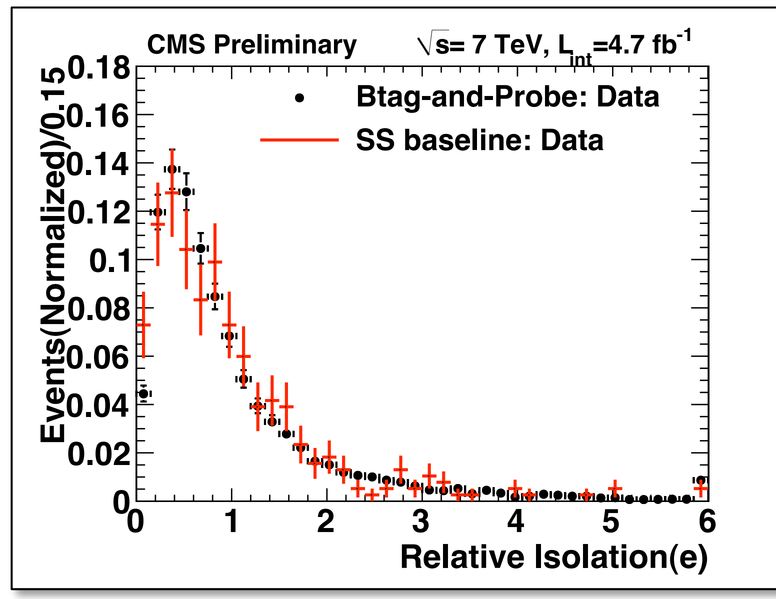
(Florida)

"BTag-And-Probe"
w/ Long sidebands

Measure T/L ratios in B-enriched control sample (B-tagged jet + "away" lepton)







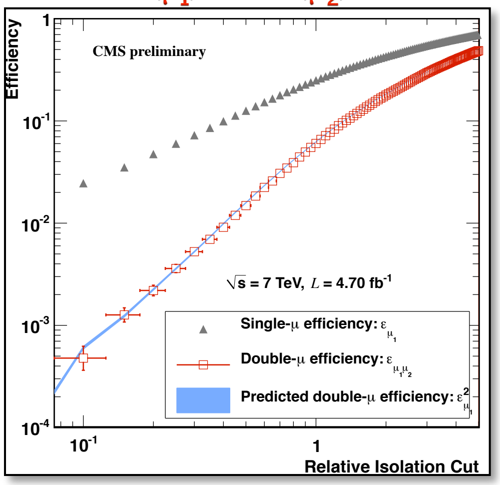
First bin represents the T/L ratio

$$N_{\rm bgd}^{\rm tot} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

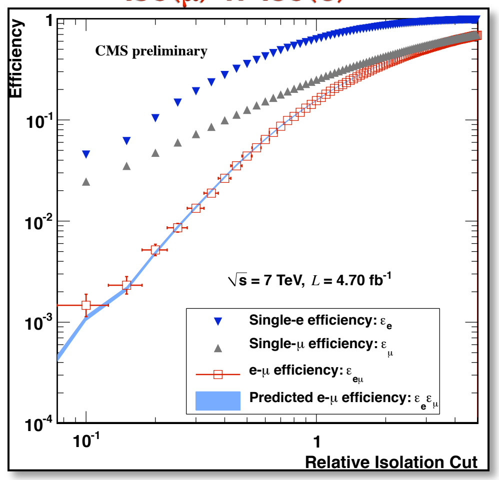
T/L Ratios for QCD *(Florida)*

"Factorization Method"

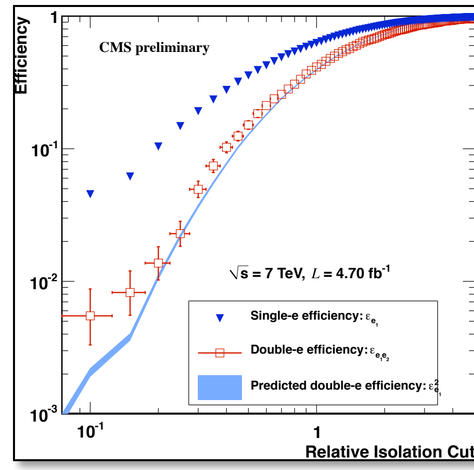
Iso(μ_1) x Iso(μ_2)

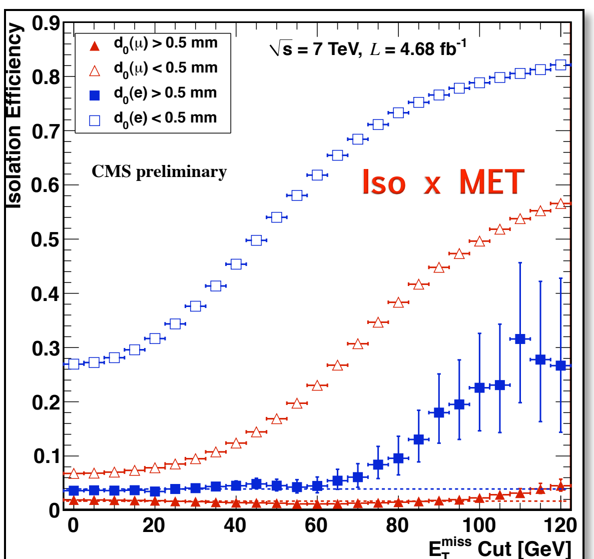


Iso(μ) x Iso(e)



Iso(e_1) x Iso(e_2)





The QCD (double-fake) prediction requires one to extrapolate in three observables sequentially: *Iso(ℓ_1) x Iso(ℓ_2) x MET*. This can only be done if the three are factorizable (i.e., the T/L ratios are uncorrelated). We demonstrate this in data using QCD-dominated regions of our baseline selection.

$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

Fake Lepton Predictions in Baseline (e/μ)

$H_T > 80$, $ME_T > 30$			ETH	UCSD/SB/FNAL	$N_{obs} - N_{p-p}^{SS} - N_{p-p}^{OS}$
High-p_T	ee	Single-Fake	41.3 ± 21.7	64.6 ± 33.2	**29.8**
		Double-Fake	11.8 ± 6.0	6.8 ± 3.6	
	μμ	Single-Fake	65.9 ± 33.3	57.1 ± 28.9	**38.5**
		Double-Fake	10.5 ± 5.3	4.4 ± 2.3	
	eμ	Single-Fake	109 ± 55	114 ± 58	**75.0**
		Double-Fake	13.0 ± 6.5	10.6 ± 5.4	

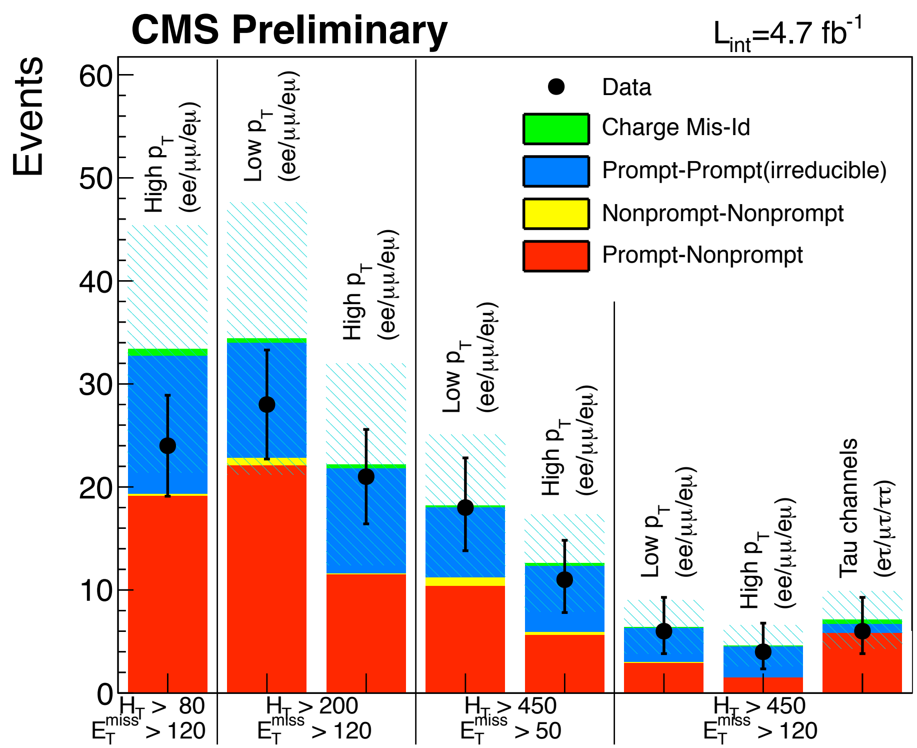
$H_T > 200$, $ME_T > 30$			FLORIDA	UCSD/SB/FNAL	$N_{obs} - N_{p-p}^{SS} - N_{p-p}^{OS}$
Low-p_T	ee	Single-Fake	12.7 ± 8.7	22.9 ± 12.0	**17.5**
		Double-Fake	3.0 ± 3.0	2.4 ± 1.3	
	μμ	Single-Fake	58.1 ± 27.6	53.1 ± 27.6	**70.8**
		Double-Fake	26.1 ± 9.6	25.5 ± 12.9	
	eμ	Single-Fake	64.6 ± 26.3	82.5 ± 41.8	**67.2**
		Double-Fake	18.5 ± 16.3	11.5 ± 5.9	

Good agreement between methods and with observations

Summary of Backgrounds

- Combine methods by taking avg of predictions and most conservative uncerts.
- Observations in good agreement with predictions in all regions
- Single-Fakes (ttbar) and rare SM processes dominate (ttW and WZ)
- Proceed with limit calculations on signal rate

Region	Mode or p_T threshold			Total	UL 95% CL
	$p_{\mathrm{T}}^{\ell 1,\ell 2} > 20, 10$ GeV				
	ee	$\mu\mu$	$e\mu$		
1	6.7 ± 2.7	8.3 ± 3.1	18.3 ± 6.9	33.2 ± 12.0	
	5	7	12	24	14.0
2	4.2 ± 1.7	5.9 ± 2.3	11.9 ± 4.5	22.1 ± 9.8	
	4	6	11	21	16.3
3	3.7 ± 1.5	3.0 ± 1.2	5.8 ± 2.3	12.5 ± 4.7	
	4	2	5	11	9.9
4	1.1 ± 0.8	1.1 ± 0.6	2.5 ± 1.1	4.6 ± 2.0	
	1	0	3	4	6.1
	$p_{\mathrm{T}}^{e,\mu} > 10, 5$ GeV				
	ee	$\mu\mu$	$e\mu$		
2	4.3 ± 1.7	13.9 ± 6.0	16.1 ± 6.2	34.3 ± 13.2	
	4	10	14	28	17.4
3	3.3 ± 1.5	6.3 ± 2.8	8.6 ± 3.5	18.2 ± 6.9	
	4	6	8	18	14.3
4	1.0 ± 0.8	2.3 ± 1.2	3.1 ± 1.4	6.4 ± 2.6	
	1	2	3	6	7.4
	$p_{\mathrm{T}}^{\tau,e,\mu} > 15, 10, 5$ GeV				
	$e\tau$	$\mu\tau$	$\tau\tau$		
4	2.6 ± 1.0	4.4 ± 2.2	0.0 ± 0.1	7.1 ± 2.8	
	1	5	0	6	7.1



Systematics & Interpretation of Results

Systematics	
e/μ selection (trigger, id, iso)	6-10%
Tau selection (trigger, id, iso)	10%
Isolation dependence on H_T	10%
Jet energy scale (7.5%)	3-30%
PDF (Acceptance)	2%
Luminosity	4.5%

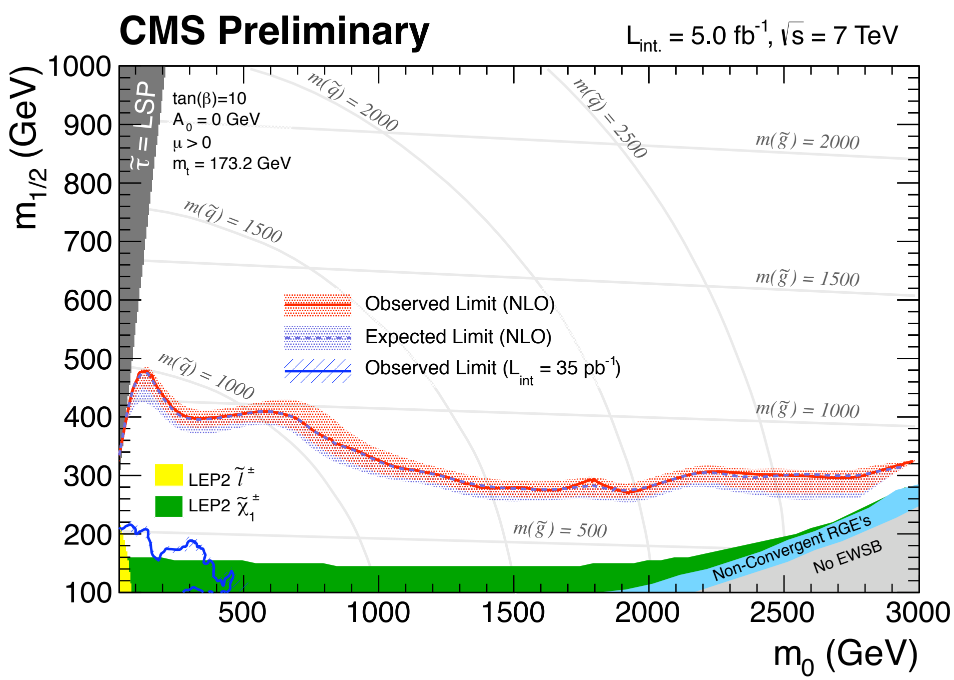
- Signal acceptance and uncertainties are model dependent
- Based on LM6 mSUGRA model uncerts range from 14%-20%
- Theory errors have to be applied (model dependent)

3 approaches to hypothesis testing all based on standard formula:

$$\sigma \times \mathrm{BR} \times \mathrm{Acceptance} = \frac{N_{\mathrm{events}}}{\int L \cdot dt} \overset{?}{>} \frac{N_{\mathrm{UL}}}{\int L \cdot dt}$$

1. cMSSM + FastSim determines LHS as fcn of m_0,$m_{1/2}$ and we compare to N_{UL}
2. SMS + FastSim determine Acceptance as fcn of mass parameters and we absorb σ x BR into the upper limit
3. We parameterize Acceptance = Acc(H_T, MET, p_T^{ℓ}) with parton-level information so that results can be interpreted beyond the models we care to simulate

CMSSM Interpretation



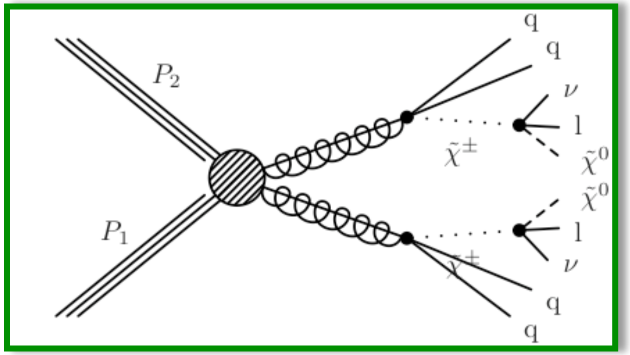
- High-p_T search with MET > 120 GeV and H_T > 450 GeV gives the best expected limits everywhere
- Point-by-point systematics are evaluated and these influence the calculated UL to a small degree

Gluino masses constrained above ~950 GeV for m_0 < 700 GeV

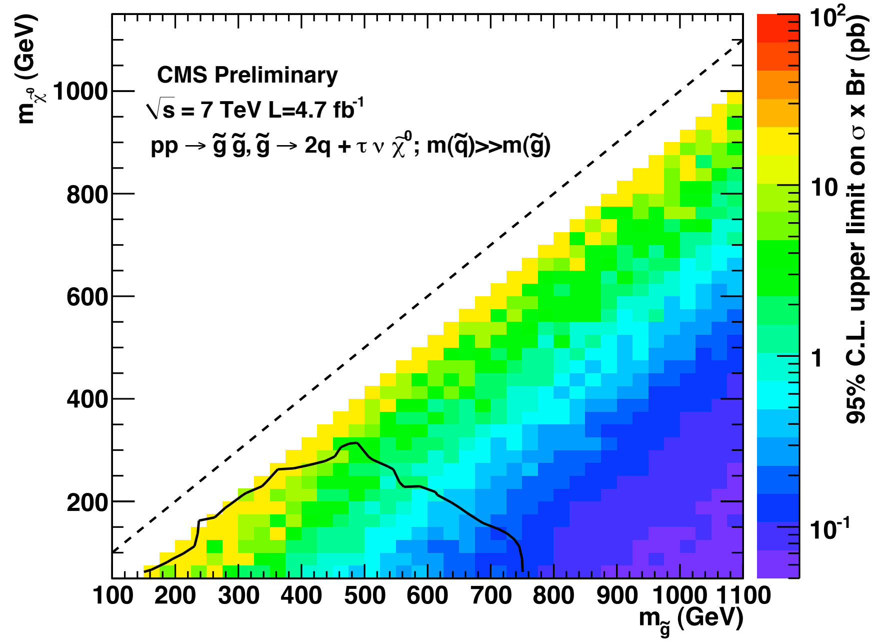
Simplified Model Interpretation

$$M(\tilde{\chi}_1^{\pm}) = \frac{M(\tilde{g}) + M(\tilde{\chi}_1^0)}{2}$$

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow qqqq\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm} \rightarrow qqqq\tau^{\pm}\tau^{\pm}\upsilon\upsilon\tilde{\chi}_1^0\tilde{\chi}_1^0$$

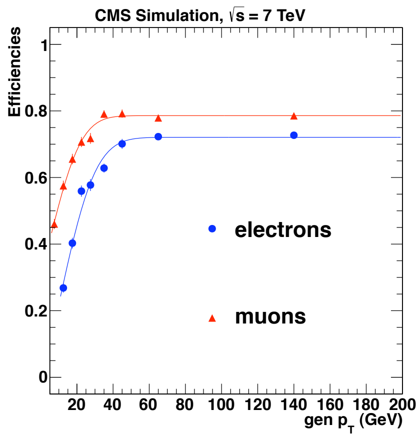


Model: T1-TauNu



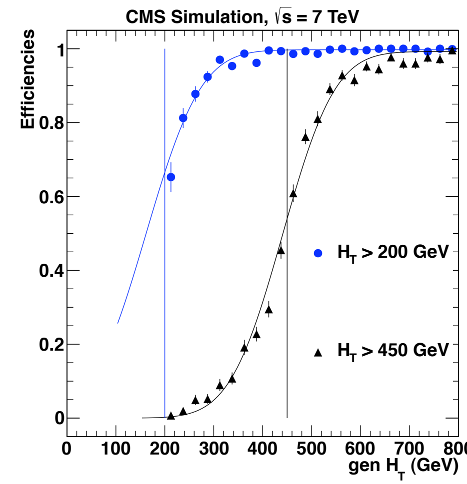
- Assume 100% BR to taus
- 50% BR to SS; 50% BR to OS
- Relevant for Higgsino-like chargino scenarios

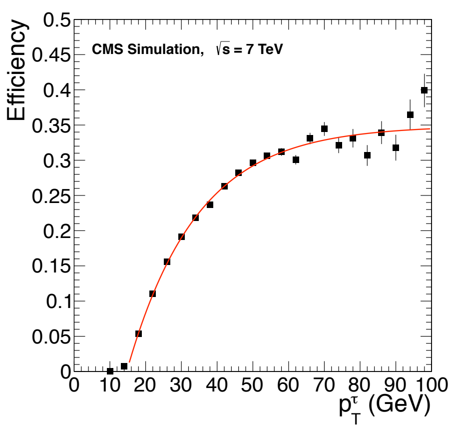
Acceptance Parameterization



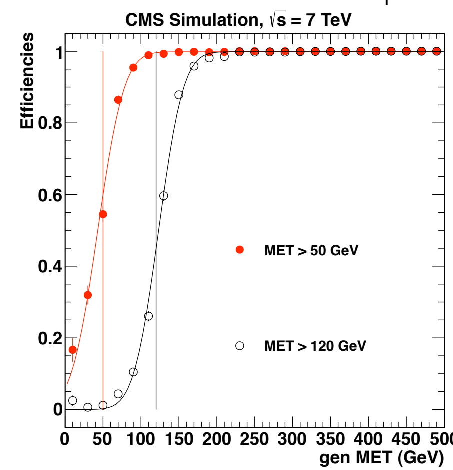
$$\epsilon = \epsilon_{\infty}\mathrm{erf}\left(\frac{p_T - C}{\sigma}\right) + \epsilon_C\left(1. - \mathrm{erf}\left(\frac{p_T - C}{\sigma}\right)\right)$$

Parameter	Electrons	Muons
C	10	5
ϵ_{∞}	0.721 ± 0.006	0.786 ± 0.005
ϵ_C	0.219 ± 0.017	0.412 ± 0.018
σ	22.5 ± 1.4	19.5 ± 1.4





Parameter	H_T		$\not{E}_T$	
	> 200 GeV	> 450 GeV	> 50 GeV	> 120 GeV
ϵ_{∞}	0.997 ± 0.001	0.992 ± 0.001	0.999 ± 0.001	0.999 ± 0.001
$x_{1/2}$	185.4 ± 4.0	440.6 ± 1.8	43.0 ± 1.1	123.3 ± 0.5
σ	99.2 ± 6.0	120.3 ± 3.4	38.9 ± 1.6	36.6 ± 0.9



Derived from representative mSUGRA benchmark point using the CMS Full Simulation. Gives agreement to within ~15%.

Summary

- A robust analysis strategy has been developed to search for new physics signal using the same-sign di-lepton topology with 4.7 fb^{-1}
- Multiple groups contributing and multiple cross-checks are performed
- Major backgrounds are successfully derived from data using thoroughly-validated and well-established methods
- No excesses above Standard Model predictions observed
- Competitive limits on the signal rate are presented for the *CMSSM* and *Simplified Models*
- A succinct and user-friendly parameterization of the signal acceptance is provided to guide model-builders

Backup
(Supporting Material)

$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

Fake Tau Prediction in Control Region

- Baseline region for taus already comes with aggressive cuts from the triggers, so to achieve a fake tau control region in data we go to MuHad/ElHad
  - Impose $H_T > 150$ GeV and invert MET < 50 GeV
  - Bgds from SS prompt-prompt leptons are negligible here

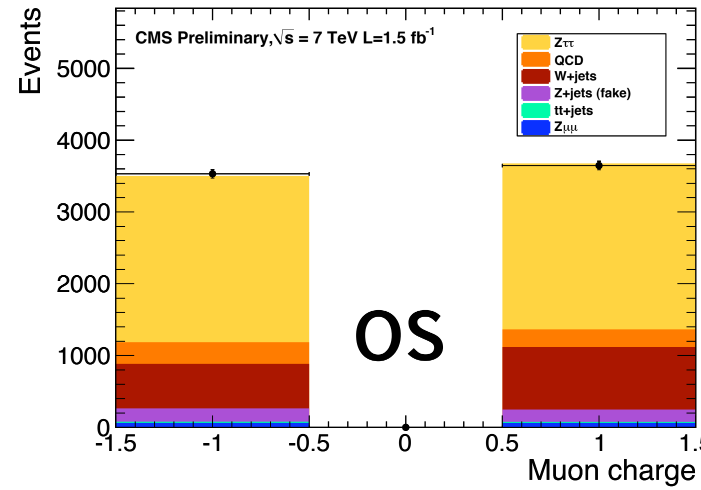
	$e\tau$	$\mu\tau$	$\tau\tau$
Predicted	221 ± 19	271 ± 24	61 ± 19
Observed	205	233	69

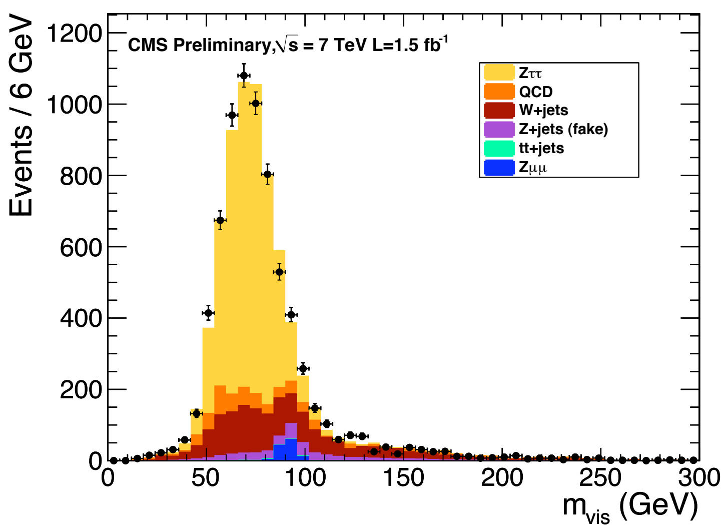
Good agreement observed

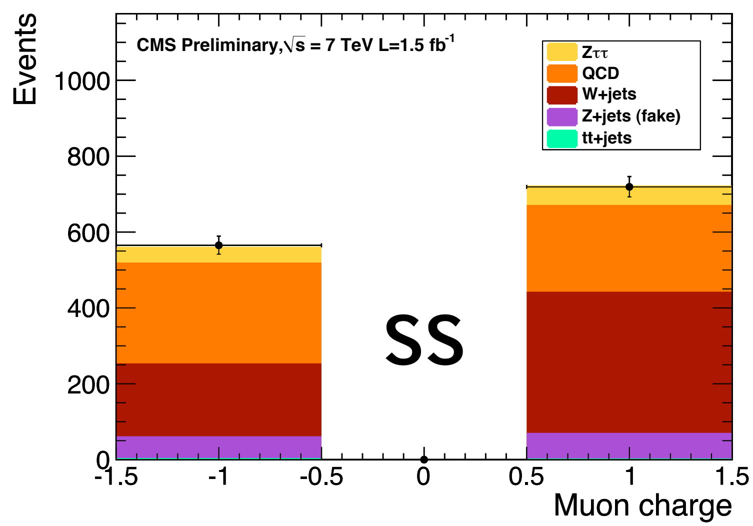
$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + \underline{N_{p-p}^{OS}} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

Tau Charge Mis-ID

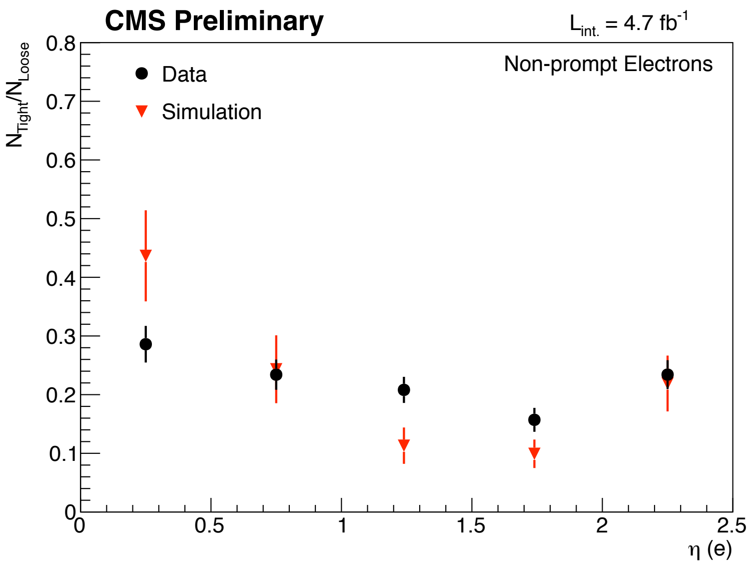
- Estimate the probability to mis-assign the charge for taus using $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$
- Large background contribution from W +jets/QCD in control region makes measurement challenging
- Simultaneous fits to visible mass(μ,t) spectrum and muon charge are used to extract the mis-ID rate: f=(0.9±2.4)%



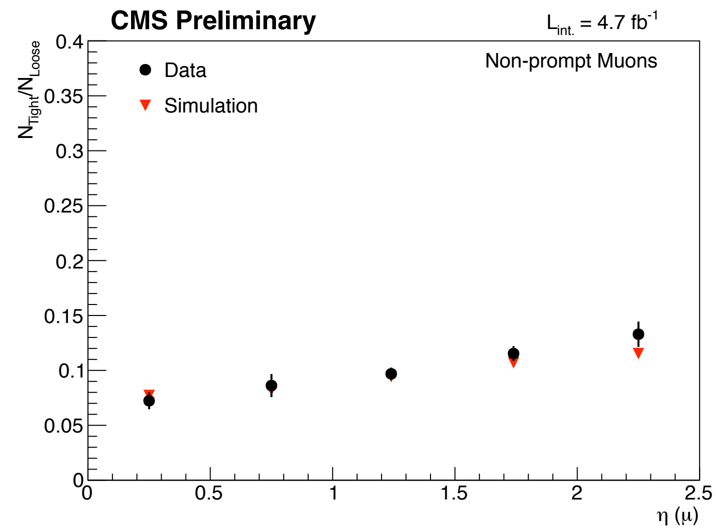




Plots



Electrons



Muons

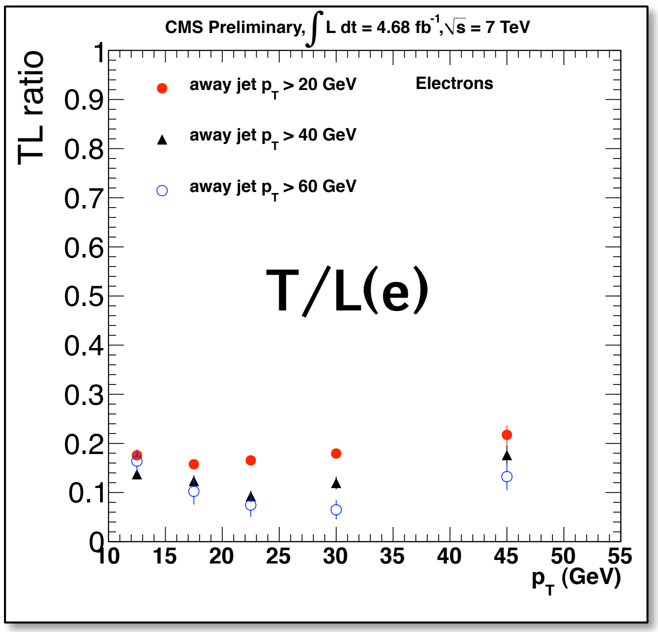
$$N^{\text{tot}}_{\text{bgd}} = N^{SS}_{p-p} + N^{OS}_{p-p} + N^{SS}_{f-f} + N^{SS}_{p-f}$$

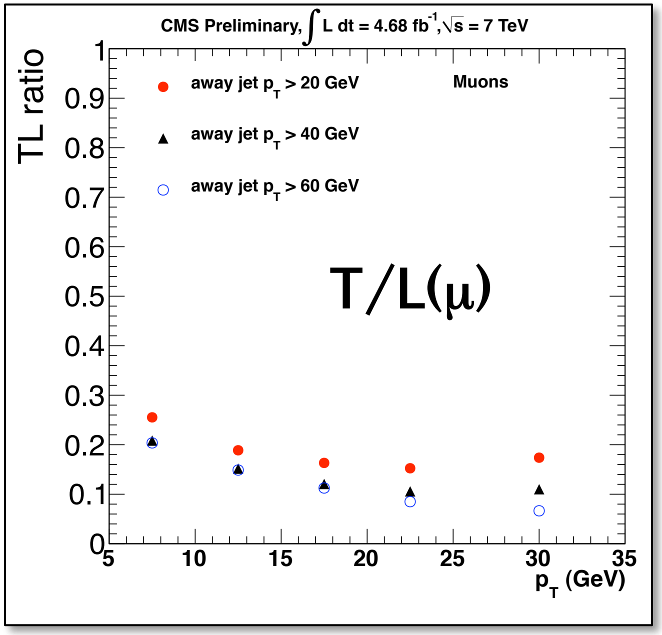
T/L Ratios from Data (e/μ)

UCSD/UCSB/FNAL

Notation : T/L Ratio = Probability for loose lepton to also pass tight selection

- Measure T/L ratio in a QCD control region

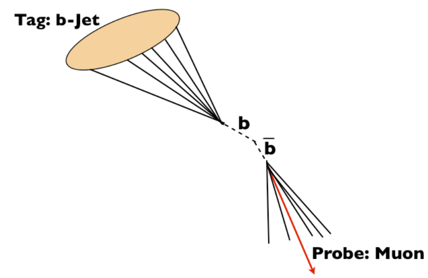




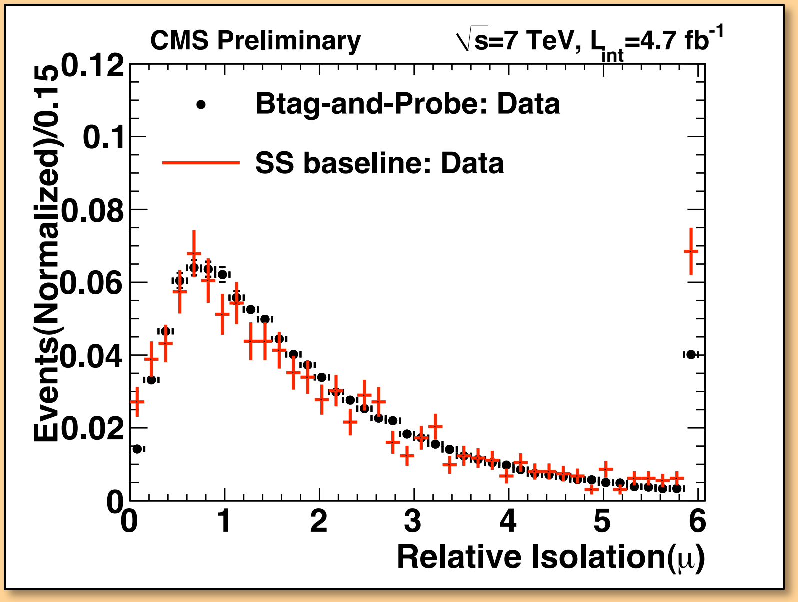
$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

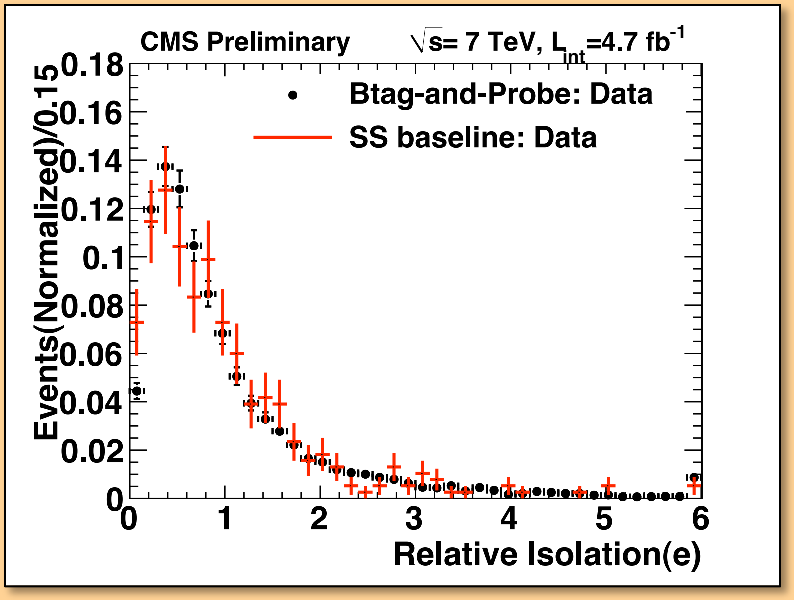
Single-Fake Control Regions *(Florida)*

" BTag-And-Probe "



- Measure T/L ratio in B-enriched control sample (B-jet + away lepton)
- Suppress prompt leptons: $M_T < 15$ GeV, MET < 15 GeV
- ~50% systematic uncertainty from closure test precision and control region definition





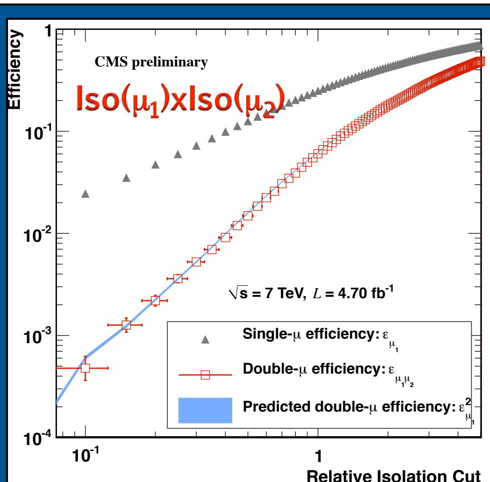
Re-weighted isolation templates for muons and electrons

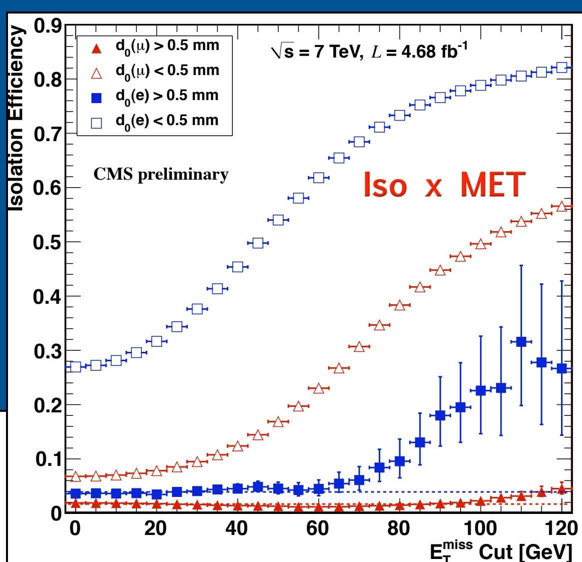
$$N^{\text{tot}}_{\text{bgd}} = N^{SS}_{p-p} + N^{OS}_{p-p} + \underline{N^{SS}_{f-f}} + N^{SS}_{p-f}$$

Double-Fake Control Regions *(Florida)*

" Factorization Method"

Data-Driven verification of Iso_1 x Iso_2 x MET factorization in QCD





Measure RelIso and MET Efficiencies in QCD-dominated subset of baseline region. Multiply together to obtain QCD predictions

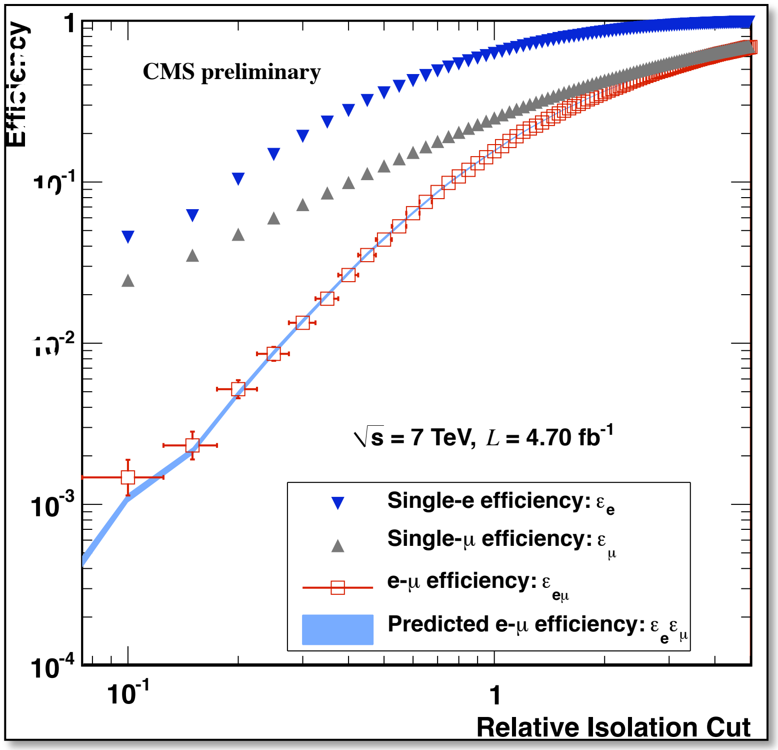
~65% systematics based on closure tests and estimates of prompt lepton contamination.

NOTE: All T/L methods assume that extrapolated observables factorize similarly

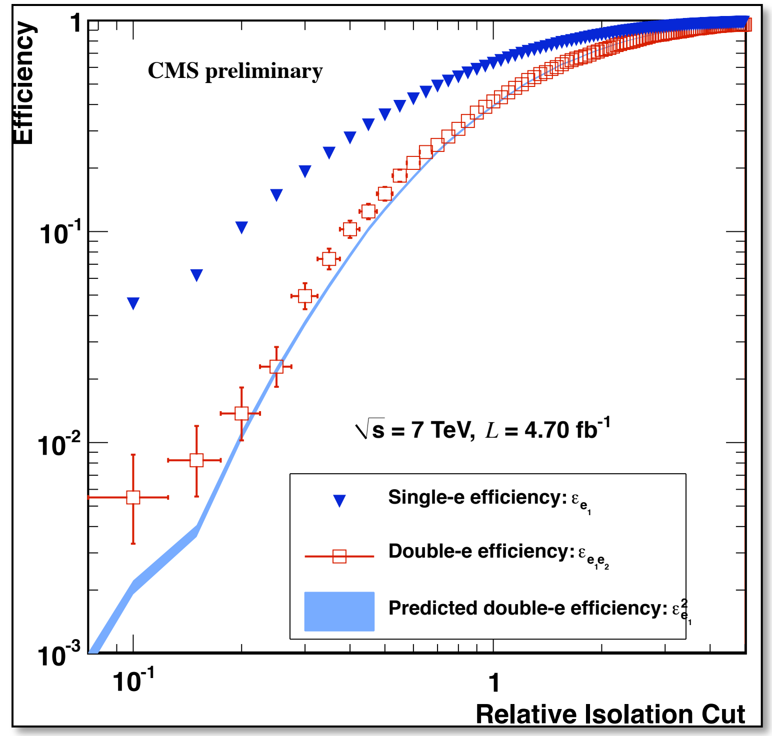
Double-Fake Control Regions *(Florida)*

"Factorization Method"

Data-Driven verification of Iso_1 x Iso_2 x MET factorization in QCD

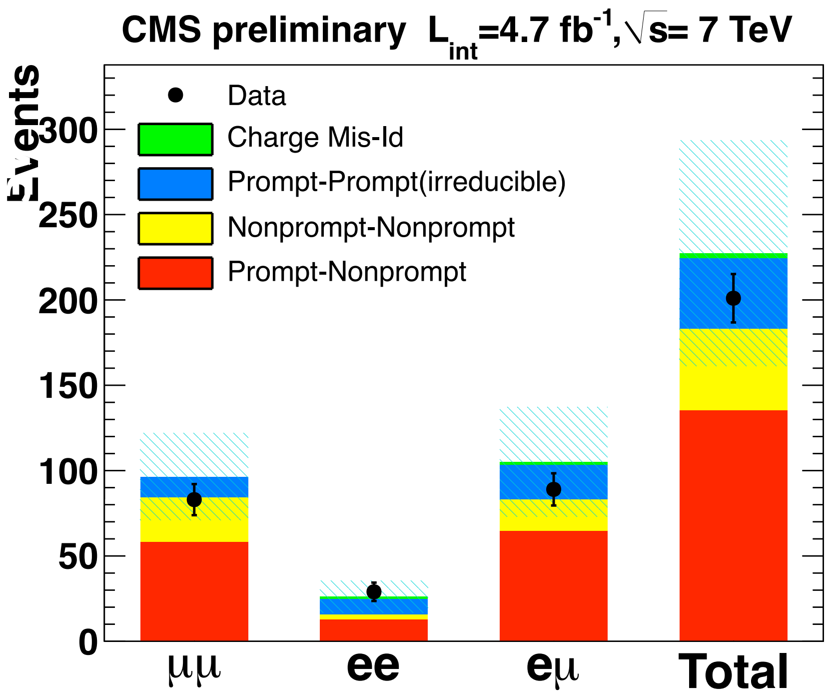


Electron-Muon RelIso Factorization

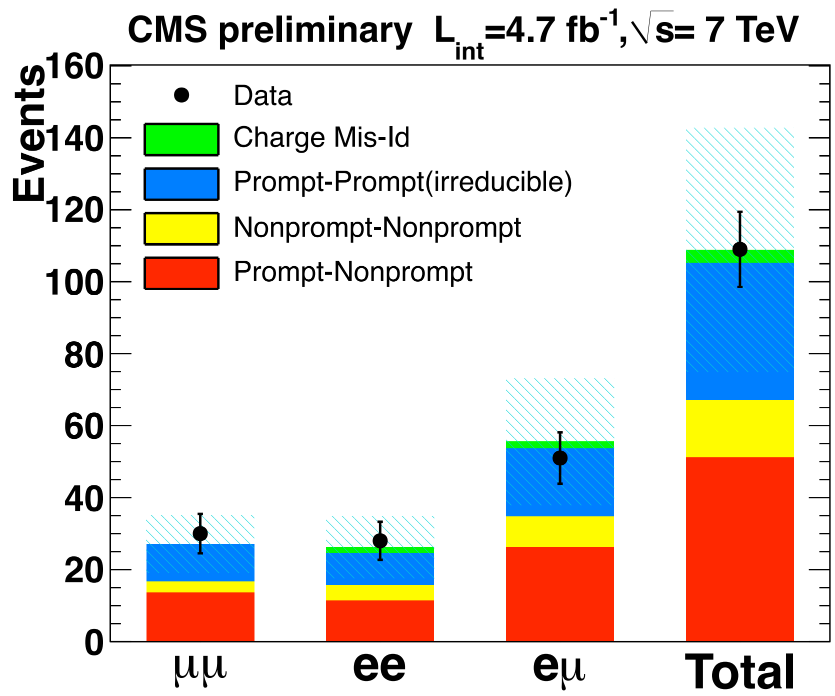


Di-Electron Factorization

Background Summary (Florida)

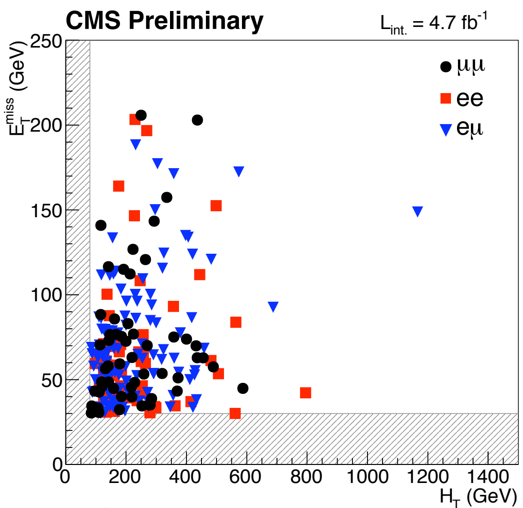


Low-pT : HT > 200 , MET > 30

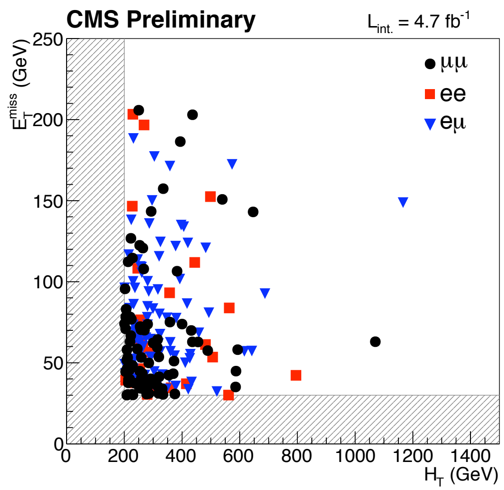


High-pT : HT > 200 , MET > 30

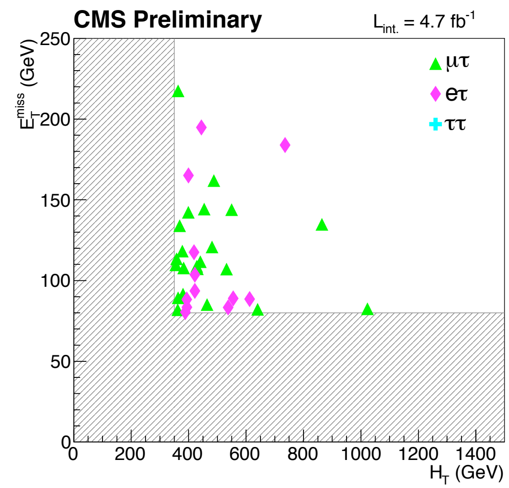
Baseline Yields



High pT



Low pT



Tau

Object Definitions

Muons

Observable	Value or Range
Id	Tracker and Global
p_T	> 5 GeV
$\|\eta\|$	< 2.4
χ^2/ndof	< 10
$\sigma(p_T)/p_T$	< 0.1
# Valid Si Hits	> 10
# Valid SA Hits	> 0
$\|d_{0,pv}\|$	< 0.02
Ecal/Hcal Non-MIP Veto	$< 4/6$ GeV
RelIso	< 0.15

Electrons

Observable	Value or Range
Missing pixel hits	0
$\|\Delta \cot\|$	> 0.02
$\|dist\|$	> 0.02
$\sigma_{i\eta i\eta}$ (B/E)	$< 0.01/0.03$
$\Delta\phi_{\text{In}}$ (B/E)	$< 0.06/0.03$
$\Delta\eta_{\text{In}}$ (B/E)	$< 0.004/0.007$
H/E (B)	< 0.04
Seed	Ecal-Driven
p_T	> 10 GeV
$\|\eta\|$	$< 2.4, \notin [1.4442, 1.566]$
$\|d_{0,pv}\|$	< 0.02
RelIso	< 0.15
$\Delta R(e,\mu)$	> 0.1
$fbrem > 0.15 \,\|\|\, (\|\eta_{SC}\| < 0.1 \&\& E/P_{In} > 0.95)$	
charge consistency among CTF, GSF and SuperCluster	

AK5 PFJets

Observable	Value or Range
p_T	> 40 GeV
$\|\eta\|$	< 2.5
Id	Loose
$\Delta R(\text{jet},\ell)$	> 0.4

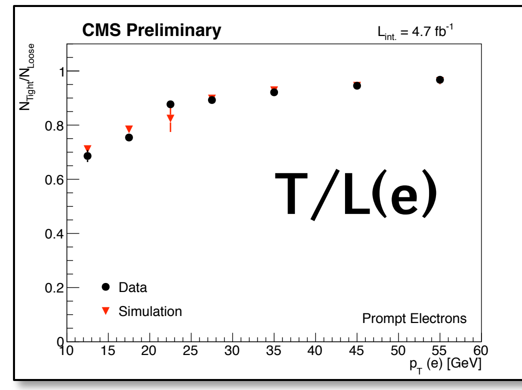
$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

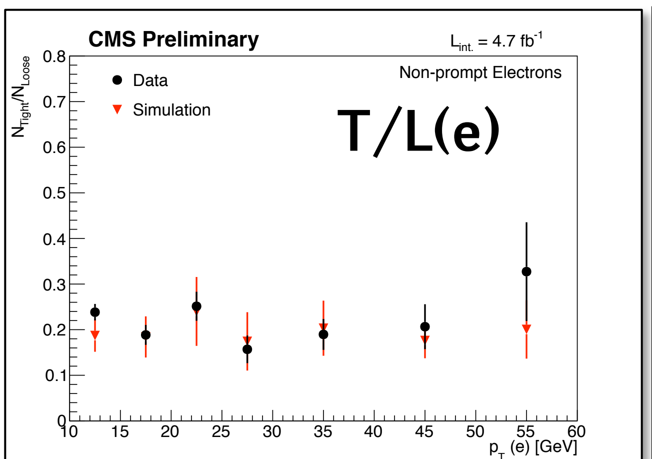
T/L Control Regions (e/μ)

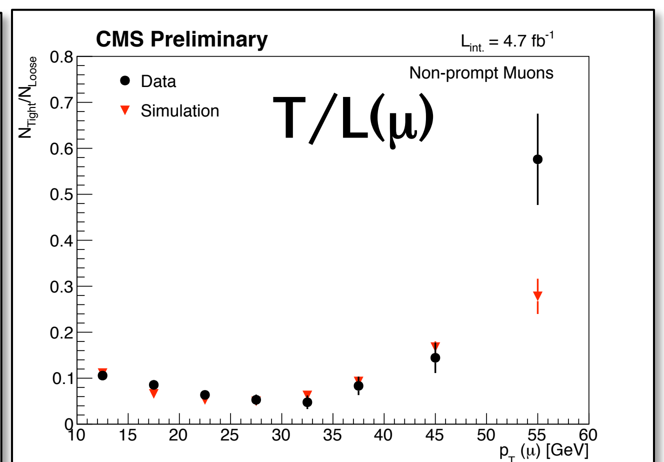
ETH et. al.

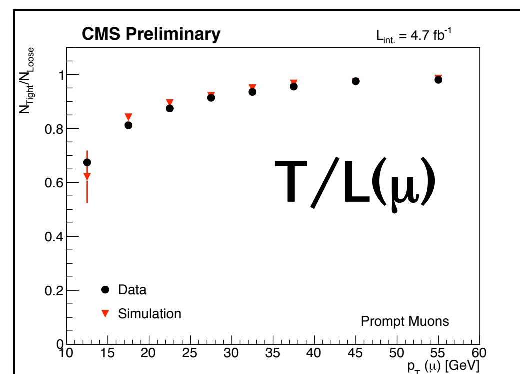
Notation : T/L Ratio = Probability for loose lepton to also pass tight selection

- Measure Fake T/L ratio in a QCD control region (jet + away lepton)
- Prompt leptons are suppressed by inverting M_T < 20 GeV, MET < 20 GeV
  - Avg: T/L(e) = 9.8%, T/L(μ) = 20.8%
- Measure Prompt T/L ratio in Z-events
- 50% systematic error from closure tests









$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

Details on Each Approach

Notation : T/L Ratio = Probability for loose lepton to also pass tight selection

- **UCSD/USCB/FNAL [short sideband]**
  - Relax RelIso, d_0, and χ^2/ndof (for μ)
  - T/L Ratios range from 20-40% [p_T/η - dependent]
- **ETH, et. al. [med sideband]**
  - Relax RelIso for muons, RelIso & ID for electrons
  - T/L Ratios ~10%(μ), ~20%(e)
  - Also employ T/L-ratios for prompt leptons: ~90%
- **Florida [long sideband]**
  - Completely invert RelIso cut
  - Ratios vary between 1%-5% and are derived in unique control samples for single-fake (ttbar) and double-fake (QCD) backgrounds
  - Apply the BTag-And-Probe Method (ttbar) and Factorization Method (QCD)
- **Imperial, et. al [taus]**
  - Relax HPS tau discriminators (Iso, decay-mode reconstruction)
  - T/L Ratios between 1% and 20% [p_T-η dependent]

T/L Details : ETH

- Loose μ (tight in parenthesis):
- RelIso < 1.0 (0.15)
- Loose e (tight in parenthesis):
- RelIso < 0.6 (0.15)
- $EcalRecHitSumE_T/p_T$ < 0.2, $HcalTowerSumE_T/p_T$ < 0.2, $TrackSumP_T/p_T$ < 0.2
- $\sigma_{ietaieta}$ < 0.011 (0.01) in barrel, < 0.031 (0.03) in endcap
- $|\Delta\Phi|$ < 0.15 (0.06) in barrel, < 0.10 (0.03) in endcap
- $|\Delta\eta|$ < 0.007 (0.004) in barrel, < 0.009 (0.007) in endcap
- H/E < 0.10 (0.04) in barrel only
- No cut on f_{brem}, $|\eta_{SC}|$ or E/P_{in}, was:
  - f_{brem} > 0.15 OR ($|\eta_{SC}|$ < 0.1 AND E/P_{in} > 0.95)
- Control region:
- ME_T < 20 GeV, m_T < 20 GeV (m_T between lepton and ME_T)
- Additional lepton veto
- At least one jet with pT > 50 GeV

T/L Details : UCSD/UCSB/FNAL

- Loose μ (tight in parenthesis):
  - Chi^2/N_{Dof} (global fit) < 50 (10)
  - $|d_0|$ < 0.2 cm (0.02 cm)
  - RelIso < 0.4 (0.15)
- Loose e (tight in parenthesis):
  - No d_0 cut (0.02 cm)
  - RelIso < 0.6 (0.15)

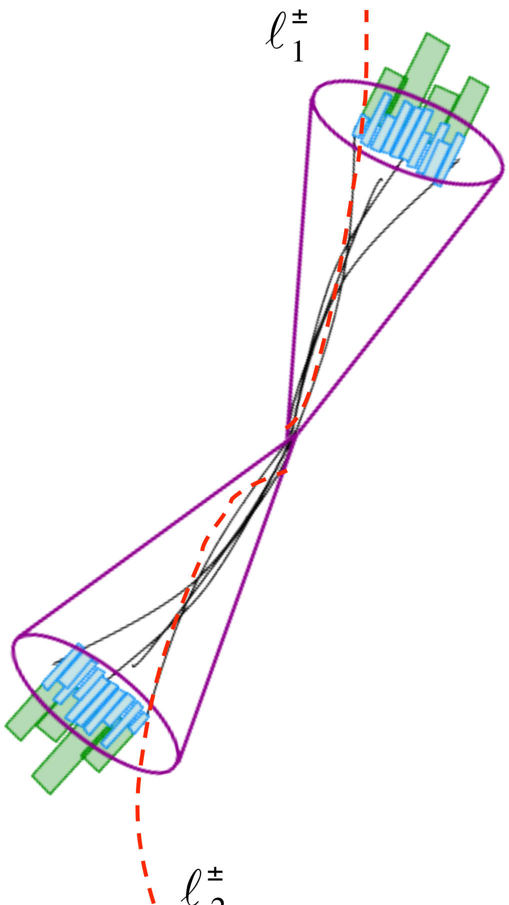
- Control region:
  - ME_T < 20 GeV
  - m_T < 25 GeV (m_T between lepton and ME_T)
  - Z veto: m_{ll} not in (71 - 111 GeV), only if both p_Ts > 20 GeV
  - Opposite side jet with p_T > 40 GeV, ΔR(l, jet) > 1.0

- Electron fake-ratios measured separately for different trigger level cuts

$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$

Fake-Fake Same-Sign Di-Leptons:

(aka "the QCD background")



- The background from QCD events can be estimated by exploiting the fact that the 3 variables used in the final selection are **uncorrelated**

$$\text{(i)}\,\text{RelIso}(\ell_1^{\pm}) < 0.15$$

$$\text{(ii)}\,\text{RelIso}(\ell_2^{\pm}) < 0.15$$

$$\text{(iii)}\,E_T^{miss} < 50\text{ GeV (120 GeV)}$$

- Qualitatively, for QCD events we expect
  - The two fake leptons to come from different jets
    - RelIso calculations should involve different tracks and calorimeter deposits
  - The missing energy (if any) should come from jet mis-measurement and not from neutrino activity
- The 3 selection efficiencies should factorize:

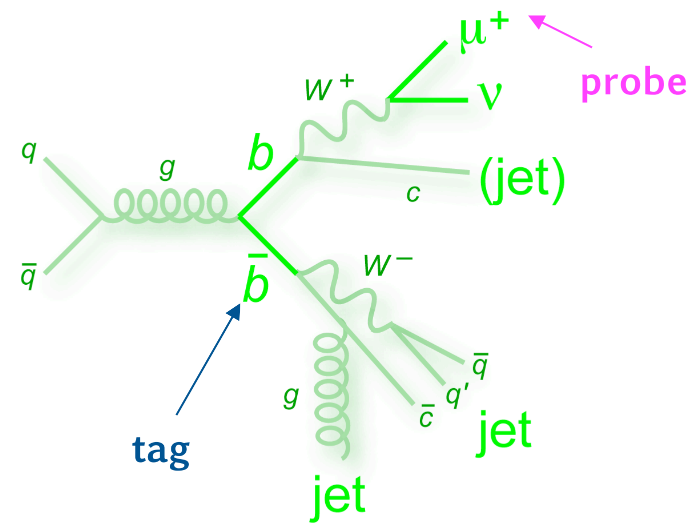
$$\varepsilon_{total}(\ell_1, \ell_2, E_T^{miss}) = \varepsilon(\ell_1) \cdot \varepsilon(\ell_2) \cdot \varepsilon(E_T^{miss})$$

- This background estimation method is aptly named: *"The Factorization Method"*

$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$

Fake-Prompt Same-Sign Di-Leptons:

- **Deriving the Prediction via Tag-And-Probe**
  - Select a **bb control** sample using a high-purity b-jet tagging algorithm
    - **Tag = b-tagged jet**
    - **Probe = lepton on opposite side of the event**
  - Parameterize the isolation of probe-leptons as a function of lepton-p_T and jet multiplicity (N_{jets})
  - Use simulated top-quark events to re-weight the templates
    - **Simulation should model p_T and N_{jets}**
  - Obtain the probability for fake leptons in top events to survive the isolation cut using these re-weighted templates
  - Multiply probability by the number of events in the ***sideband region***



sideband region : all final selection requirements imposed except for RelIso on the least isolated lepton

Interpretation of Results

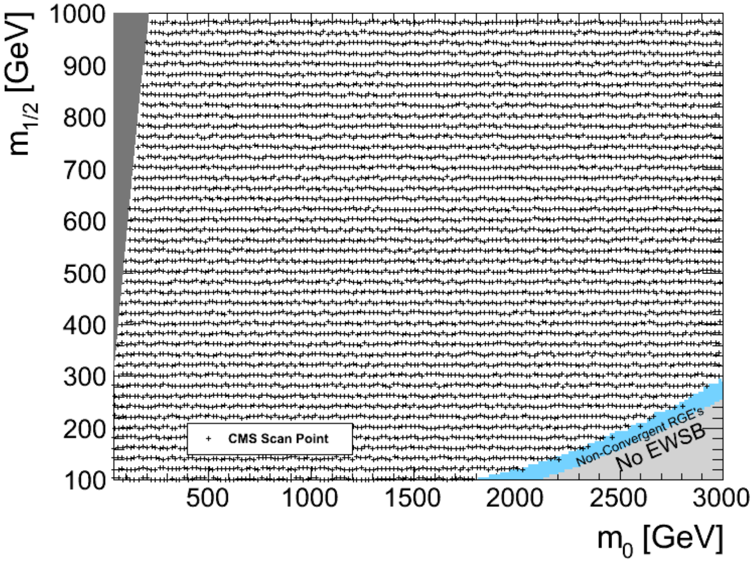
		HT80 MET120	HT200 MET120	HT450 MET50	HT450 MET120
High-p_T	Pred.	33.2	22.1	12.5	4.6
	ΔPred	12.0	9.8	4.7	2.0
	Obs.	24	21	11	4
	N_{Sig} <	14.0	16.3	9.9	6.1
Low-p_T	Pred.		34.3	18.2	6.4
	ΔPred		13.2	6.9	2.6
	Obs.		28	18	6
	N_{Sig} <		17.4	14.3	7.4
Tau	Pred.				7.1
	ΔPred				2.8
	Obs.				6
	N_{Sig} <				7.1

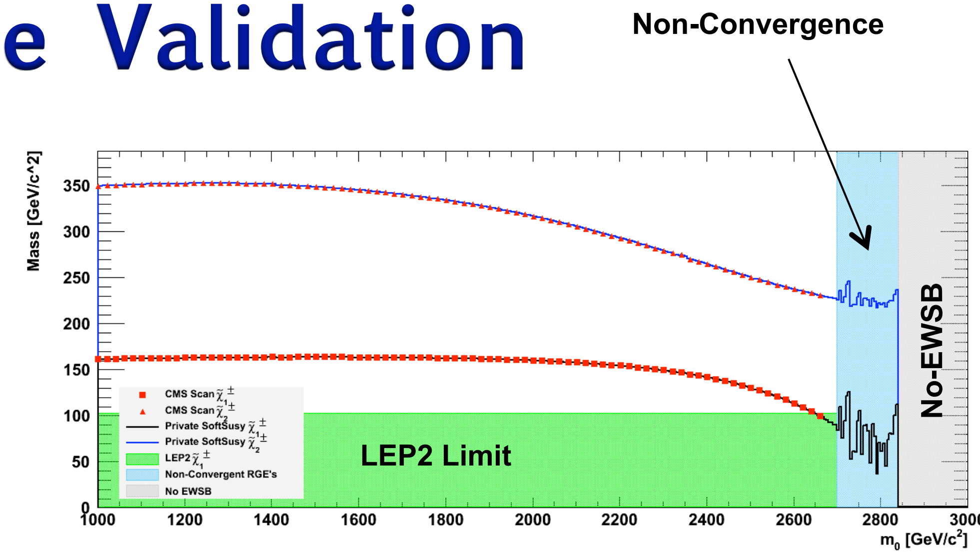
For the reported limits we assume a flat 20% uncertainty on signal acceptance

- Signal acceptance and uncertainties are model dependent
- Based on LM6 uncertainties range from 14%-20%

Systematics	
e/μ selection (trigger, id, iso)	6-10%
Tau selection (trigger, id, iso)	10%
Isolation dependence on H_T	10%
Jet energy scale (7.5%)	3-30%
PDF (Acceptance)	2%
Luminosity	4.5%

CMSSM Template Validation





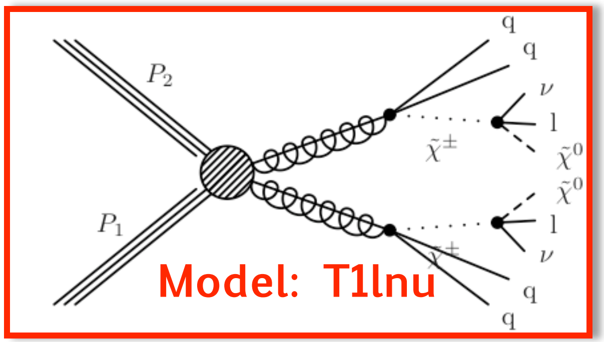
From SoftSusy Manual: Hep-ph/0104145

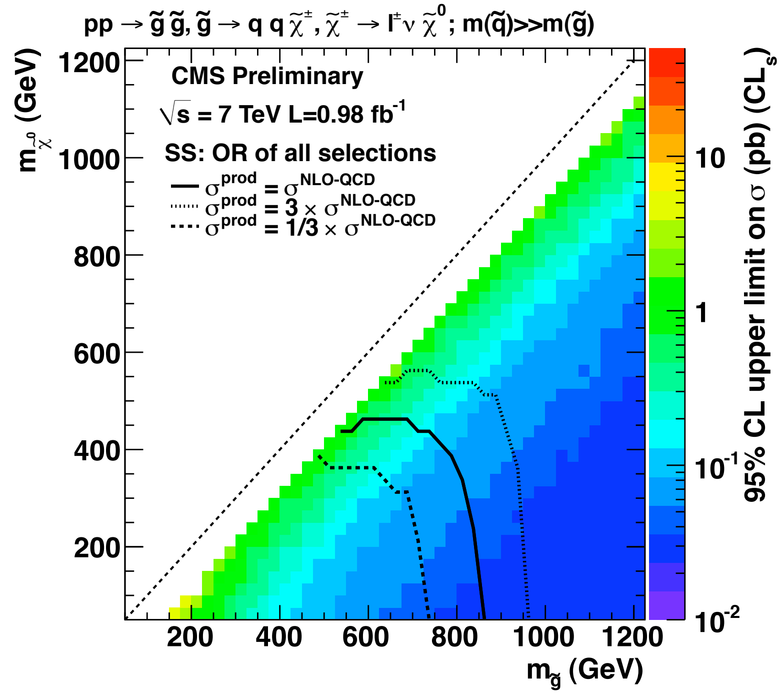
If `No convergence` appears, then `SOFTSUSY` is indicating that it didn't achieve the accuracy of `TOLERANCE` within less than 40 iterations. The output of the code is therefore to be considered unreliable and it is not clear from the output whether the point is allowed or disallowed, despite the presence or absence of other warning messages. This error flag often appears near the boundary of electroweak symmetry breaking, (where $\mu(M_{SUSY}) = 0$)), where the iterative algorithm is not stable. To calculate the position of the electroweak symmetry boundary, one should interpolate between regions a small distance away from it.

Simplified Model Interpretation

$$M(\tilde{\chi}_1^{\pm}) = \frac{M(\tilde{g}) + M(\tilde{\chi}_1^0)}{2}$$

$$pp \to \tilde{g}\tilde{g} \to qqqq\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm} \to qqqq\ell^{\pm}\ell^{\pm}\upsilon\upsilon\tilde{\chi}_1^0\tilde{\chi}_1^0$$

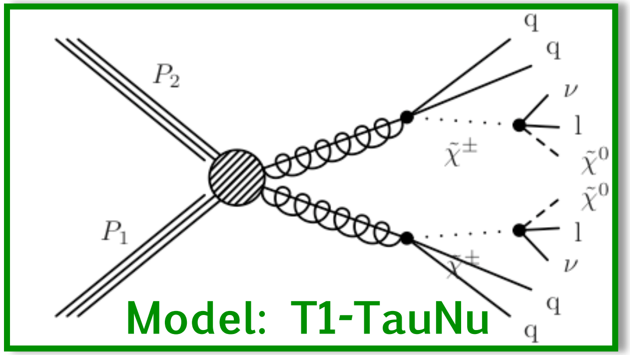


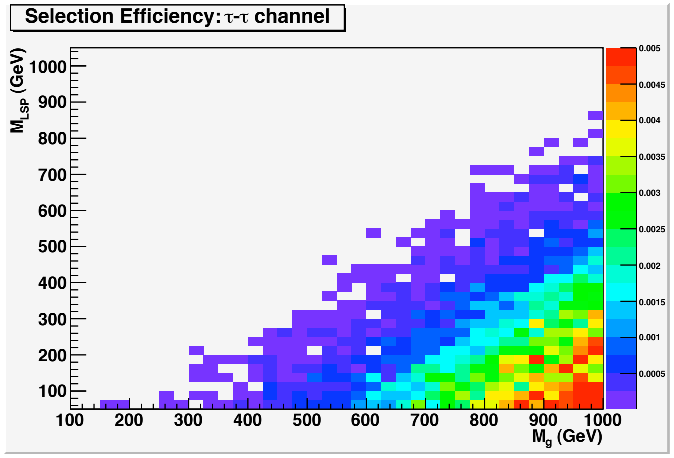


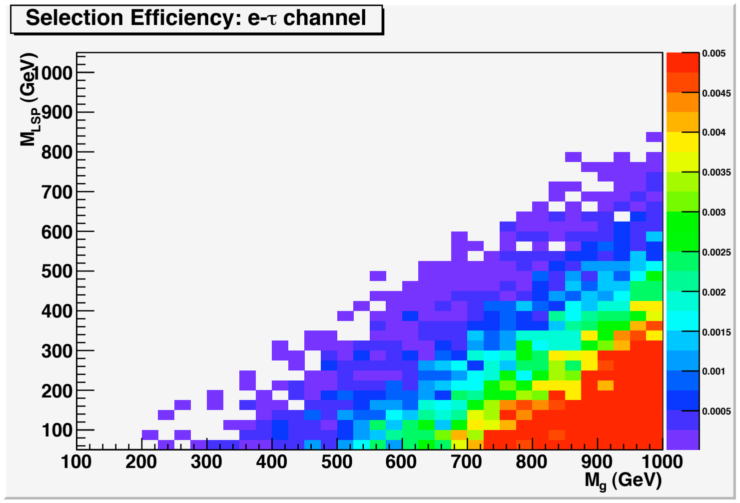
- Update version for 4.7 fb-1 in progress

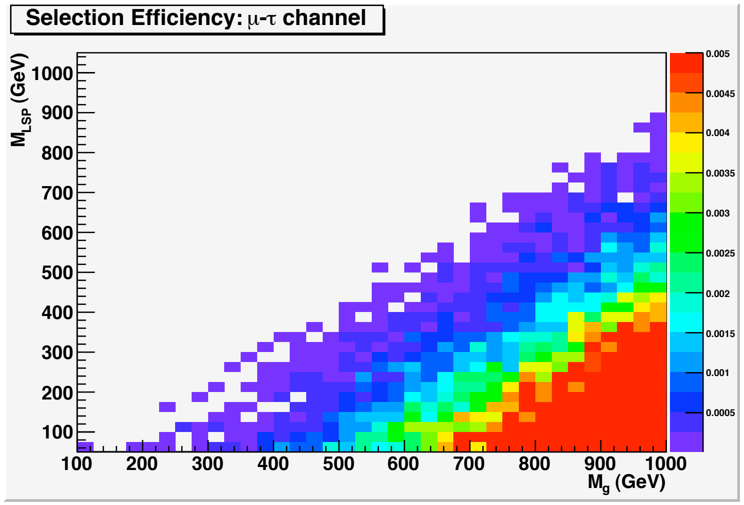
Simplified Model Interpretation

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow qqqq\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm} \rightarrow qqqq\tau^{\pm}\tau^{\pm}\upsilon\upsilon\tilde{\chi}_1^0\tilde{\chi}_1^0$$



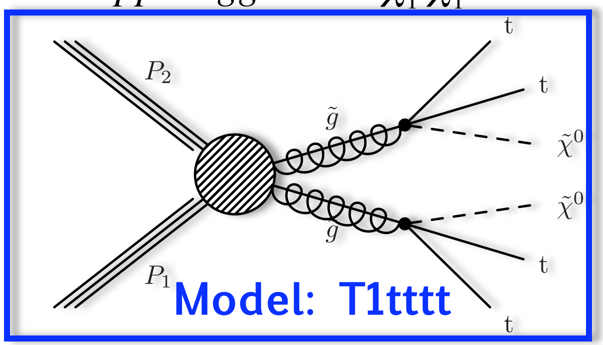




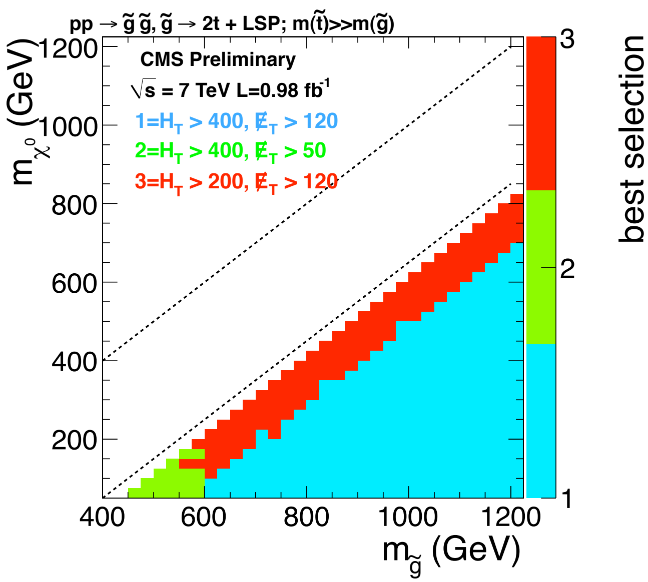


Simplified Model Interpretation

$pp \rightarrow \tilde{g}\tilde{g} \rightarrow tt\bar{t}\bar{t}\,\tilde{\chi}_1^0\tilde{\chi}_1^0$



- Updated version for 4.7 fb-1 in progress



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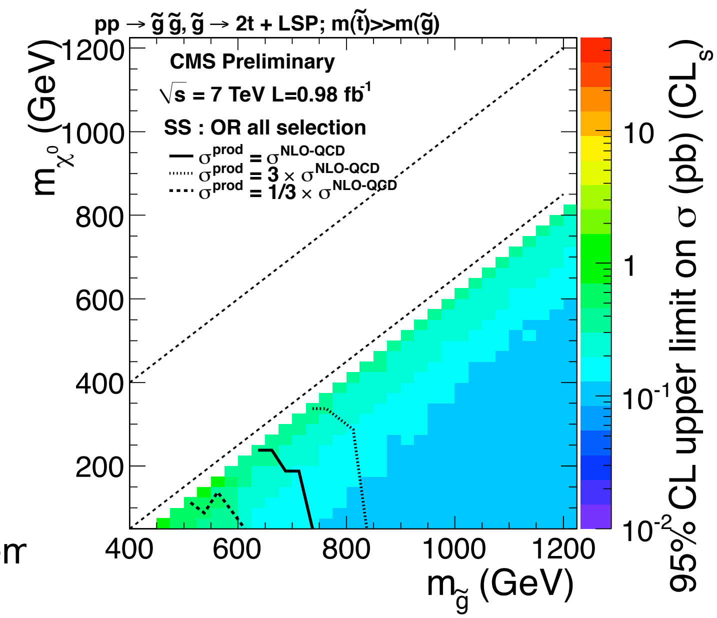


The Large Hadron Collider

A proton-proton collider

Parameter	Design	Achieved in 2011
$\sqrt{s}$	14 TeV	7 TeV
Luminosity (L)	10^{34} cm^{-2} s^{-1}	3.5×10^{33} cm^{-2}s^{-1}
Bunches per beam	2808	1380

9 km

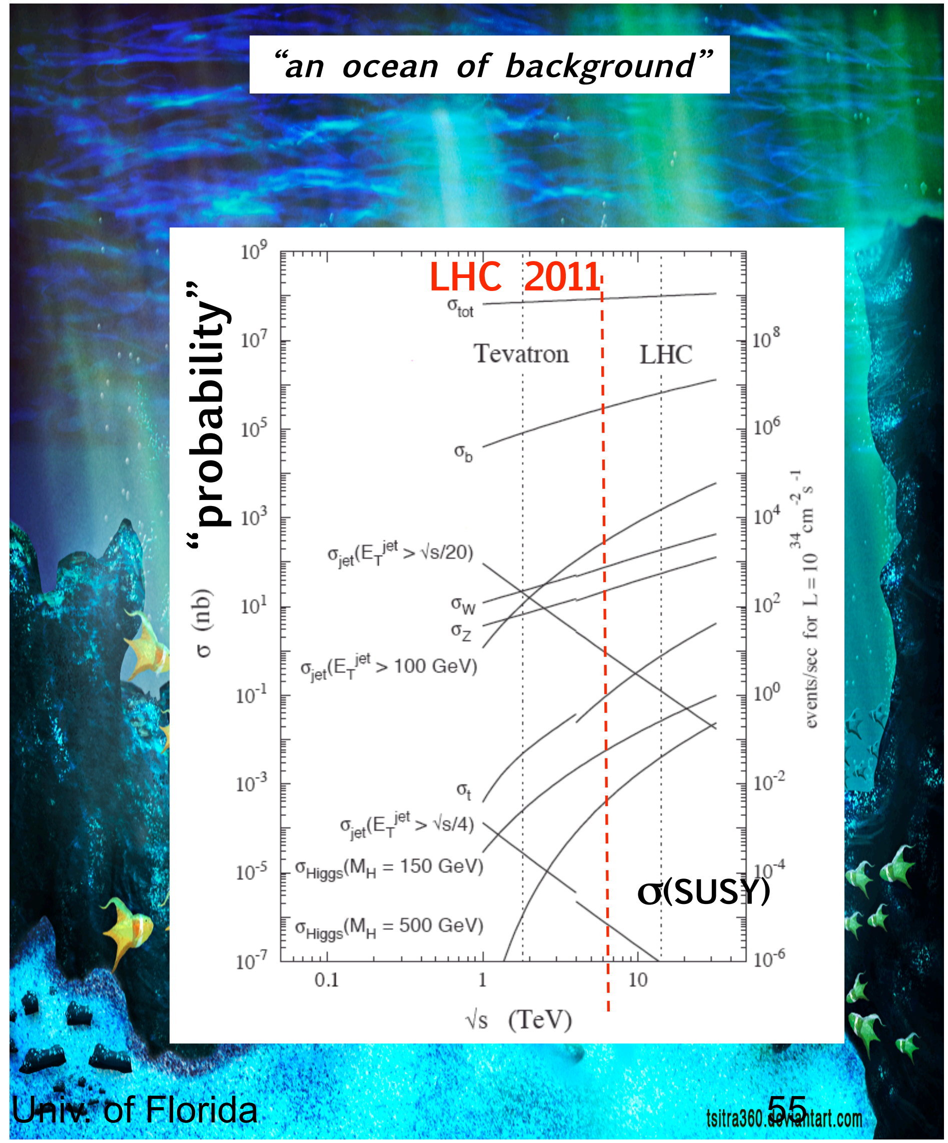
My old place in Thoiry, FR

The design $\sqrt{s}$ is 7x higher than the Tevatron collider, while the design L is ~70x greater. The LHC is performing wonderfully but has still yet to reach its full potential.

Importance of High Luminosity

- **All particles in the SM are able to be produced, but their production is not equiprobable.**
  - determined by their cross-sections (σ)
- **Small cross-sections correspond to rare processes:**

  - Heavy particles (e.g., top quark, SUSY)
  - Particles blind to the strong force (Z/W/higgs)
- **In order to produce these particles you need a machine that can "roll the dice" very rapidly**
  - This means "high-luminosity"
- **The LHC rolls the dice (by design) at a rate of 40 million hz.**



Integrated Luminosity

- **The total amount of data produced by a collider is measured by the time-integrated luminosity:**

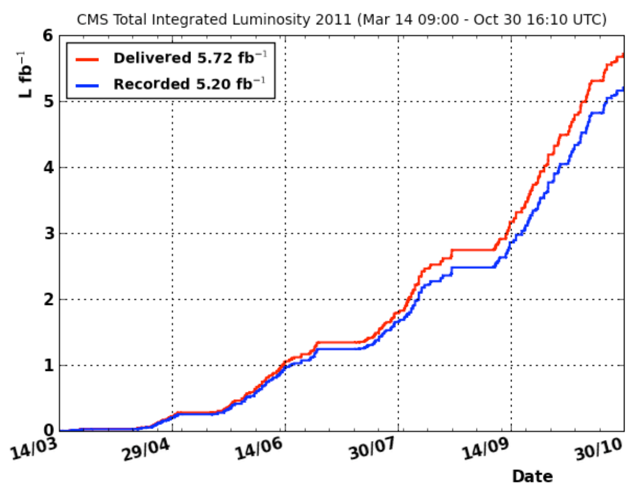
$$\int L \cdot dt$$

- **The total expected events produced for process *X* in the data:**

$$N^{events} = \sigma(pp \rightarrow X) \cdot \int L \cdot dt$$ = *probability × trials*

- **In 2011 the CMS Detector recorded 5.2 fb^{-1} of good data**

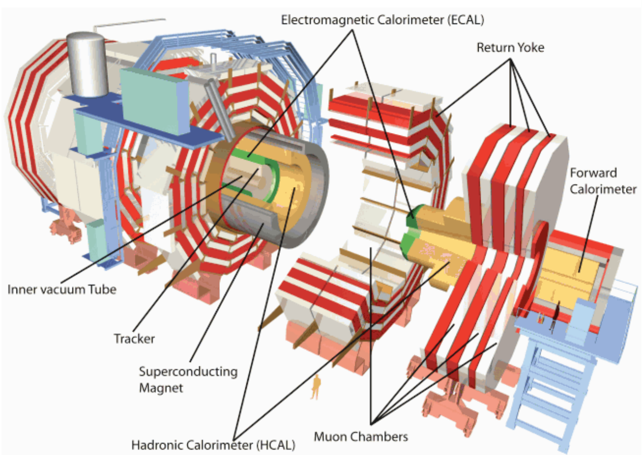
Process	σ (pb)	$\langle N^{events} \rangle$
light quarks	> 8e+10	> 4.2e+16
bottom quarks	> 8e+9	> 4.2e+13
top quarks	157.5	820,000
W	~9.2e+4	~4.8e+8
Z	~2.7e+4	~1.4e+8
ZZ	~4.3	22,000
Higgs (m~120)	~5-20	26,000-100,000
SUSY	Model dependent	Discussed Later!

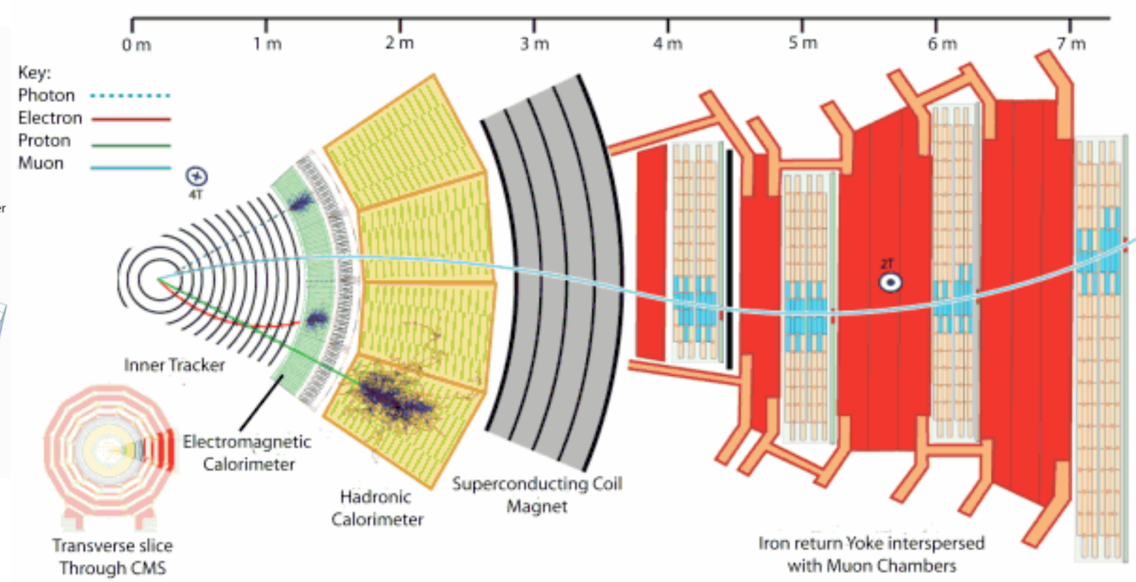


The Compact Muon Solenoid

(CMS)

A general purpose particle detector capable of directly detecting all species of stable particles known to exist, except for the weakly interacting neutrino





- 14,000 tons
- 15 meters in diameter
- 21 meters long
- 3.8 Tesla B-Field
- 100 meters underground
- 3,600 collaborators
- 180 institutions
- 38 countries

Most common particles that live long enough to directly interact with the CMS detector: $\mu^{\pm}$, $e^{\pm}$, γ, n, $p^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K^0