Search for SUSY in Same-Sign Di-Lepton Final States with the CMS Detector

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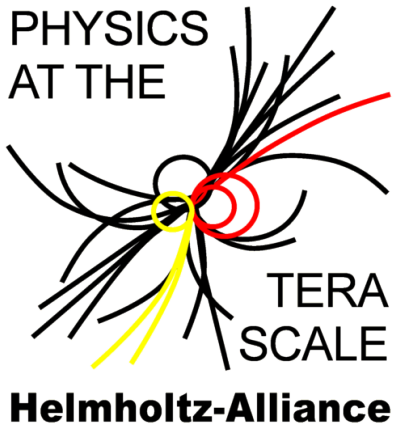

Overview

- Introduction/ Motivation
- Selection Cuts
- Event Yield
- $t\bar{t}$ Background Estimation
- Summary/ Outlook

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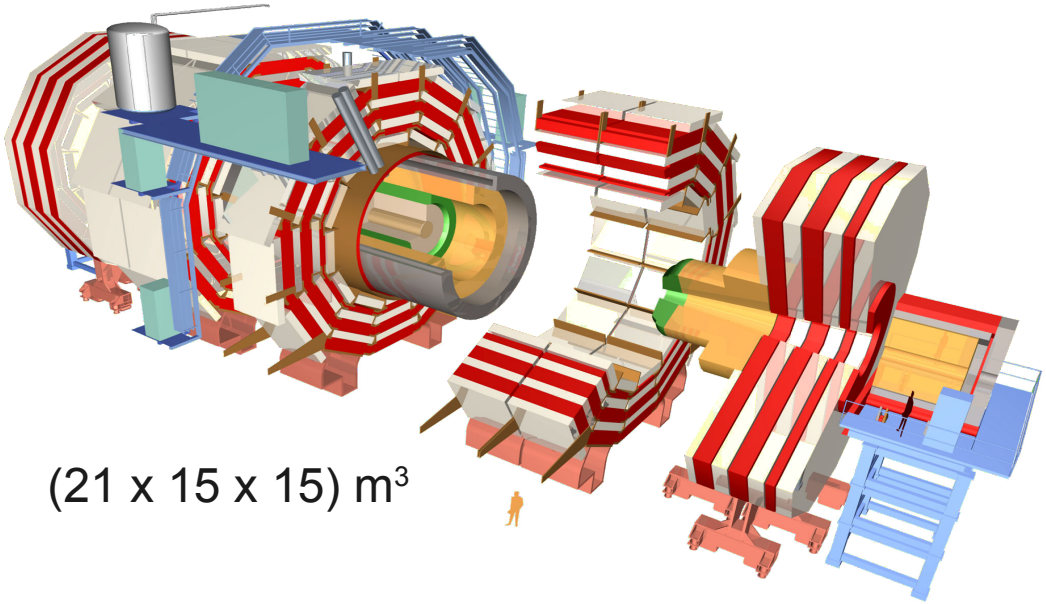
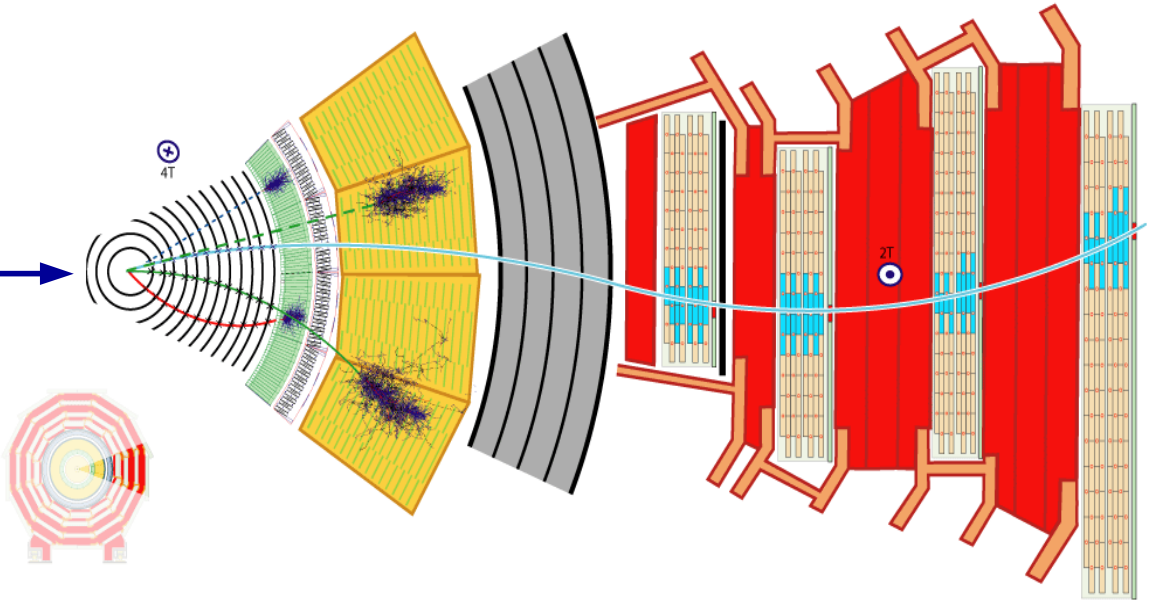
Introduction



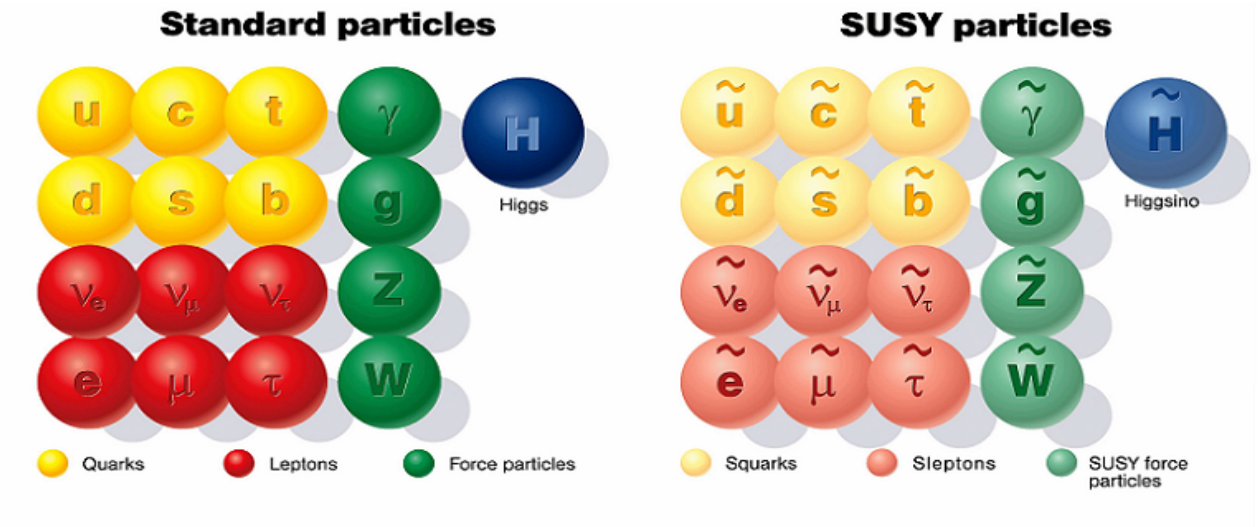
(21 x 15 x 15) m^3

- CMS = "**C**ompact **M**uon **S**olenoid"
  - One of two general purpose detectors
  - "4π-detector" (coverage $|\eta| < 5$)

- From inside out
  - Pixel (65 $\cdot 10^6$ channels)
  - Silicon Tracker
  - Crystal ECAL
  - HCAL (sampling calorimeter)
  - Solenoid magnet (4 Tesla)
  - Muon chambers (DT, CSC, RPC)



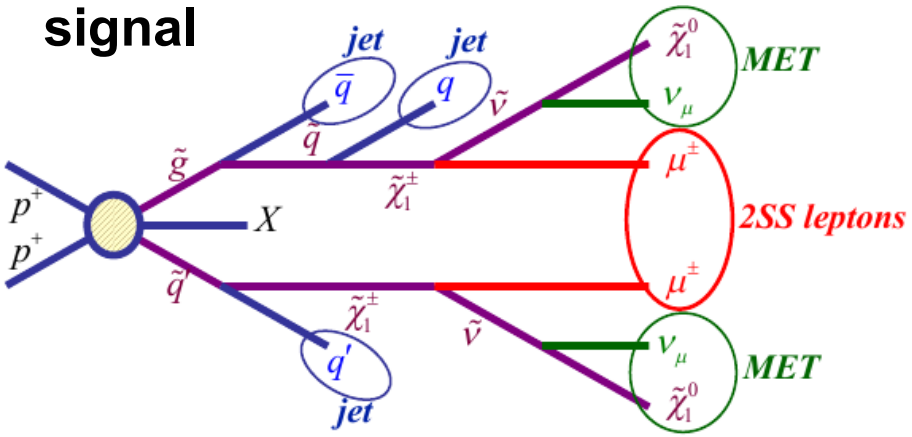
Motivation



- **Supersymmetry**
  - Solves hierarchy problem
  - Unification of gauge couplings
  - Natural DM candidates (if R-parity conserved)

- **mSUGRA (as an example!):**
  - Assumes symmetry breaking via gravitation
  - Reduces 105 parameters to 5 parameters: m_0, $m_{1/2}$, A_0, tanβ, sign μ = ± 1

- **Same-sign di-lepton signature**
  - Strongly suppressed SM background
  - Highly identifiable final state



SUSY Same-Sign Di-Lepton Selection

Aim:
- Reject SM
- Filter out SUSY same-sign di-lepton signature

Event

• H_T-Trigger*	(H_T > 150 GeV)
• 2 same-sign leptons	(ee, eμ, μμ)
• Number of Jets	≥ 2
• H_T	> 300 GeV
• MET (particle flow)	> 30 GeV

Jets (Anti-k_T, particle flow)

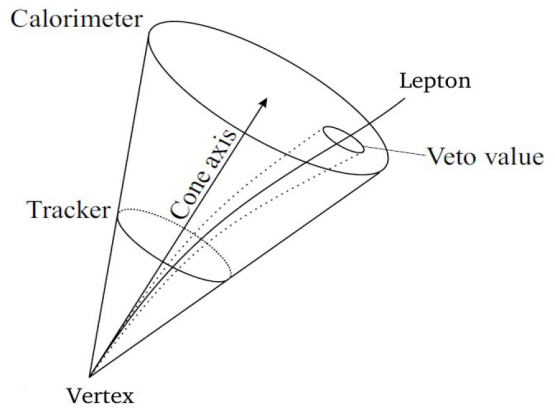
• p_T	> 30 GeV/c
• |η|	< 2.5
• ΔR to isolated leptons	> 0.4

Leptons

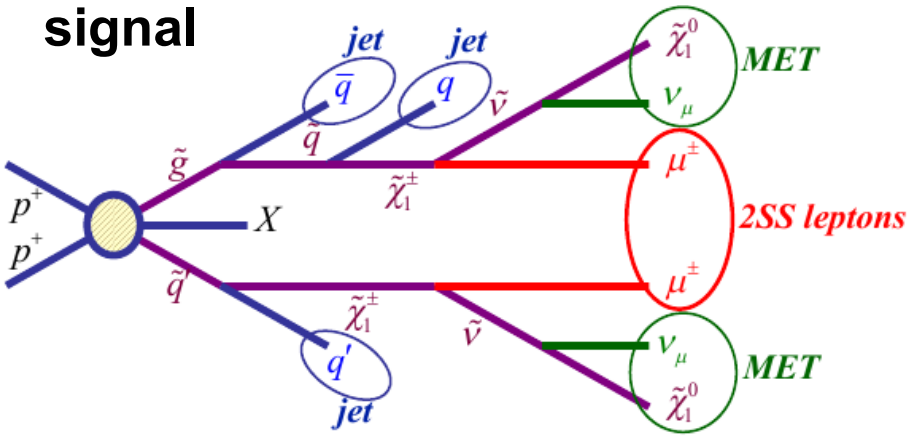
• p_T (e/μ)	> 10/5 GeV/c
• |η|	< 2.4
• Relative Isolation**	< 0.15 (R = 0.3)

$$RelIso = (TrackIso + EcalIso + HcalIso)/p_{T,l}$$

→ **low value = good isolation**
= well identified lepton



signal



*H_T: scalar sum of transverse momentum of jets

**Relative isolation = activity in a cone of radius R around the lepton (excluding the lepton itself), relative to the lepton p_T

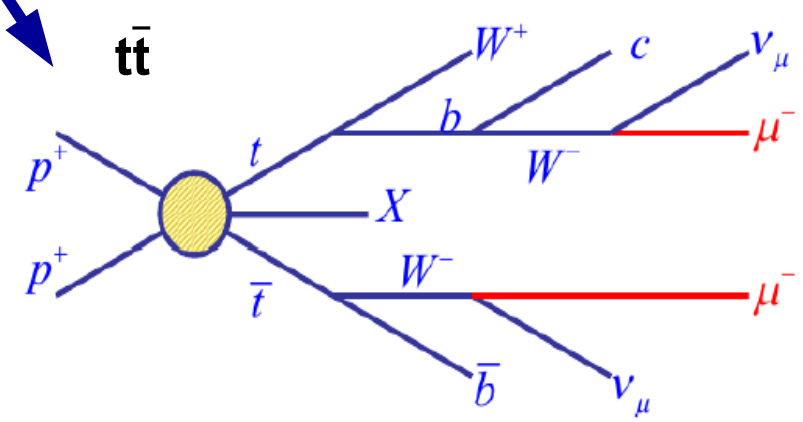
Event Yield

Normalized to L ≈ 35 pb^{-1}

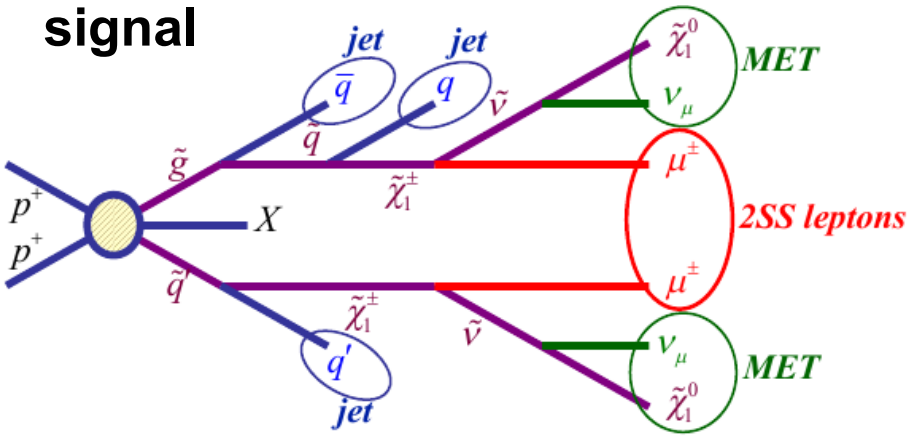
MC sample	event yield
ttbar	0.25
Single Top	0.03
WJets -> l+nu	0.06
ZJet -> mumu	≈ 0
W^+W^-	0
WZ	≈ 0
ZZ	0
QCD	0.04
Total background	**0.38**
Signal (LM0*)	**5.86**

$t\bar{t}$ is by far the dominant background
→ one lepton originates from the leptonic W-decay, the other (with the same sign!) **from a b-jet → bad isolated!**

$t\bar{t}$



signal



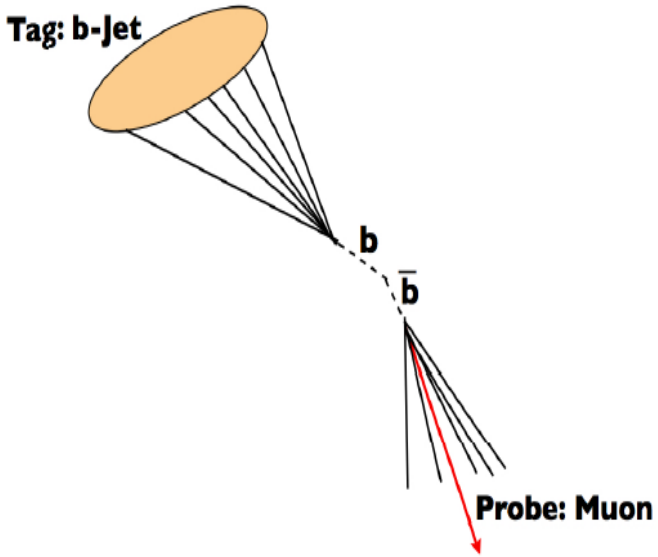
Selection yields good potential for SUSY discovery!

*LM0 = "**L**ow **M**ass" = A CMS-agreed benchmark-point in the m_0-$m_{1/2}$ mSUGRA parameter space
→ m_0 = 200 GeV/c^2; $m_{1/2}$ = 160 GeV/c^2; A_0 = -400; tanβ = 10; sign μ= 1

Tag & Probe

Aim:
- Enrich sample with $b\bar{b}$ events
- Investigate leptons originating from b-jets
- [not used to yield an efficiency]

→ Tag: very pure b-jet*
→ Probe: lepton



→ Investigate the relative isolation of leptons originating from b-jets

Cuts to enrich sample with $b\bar{b}$ events:

• No of good jets	≥ 2	
• No of good b-jets*	≥ 1 (Tag)	
• No of good leptons	= 1 (Probe)	
• ΔR(lep,b-jet)	≥ 1	
• H_T	> 100 GeV	
• MET (particle flow)	< 15 GeV	Only in Data
• M_T	< 15 GeV	

*very pure (99.9%) = strong b-jet identification criteria

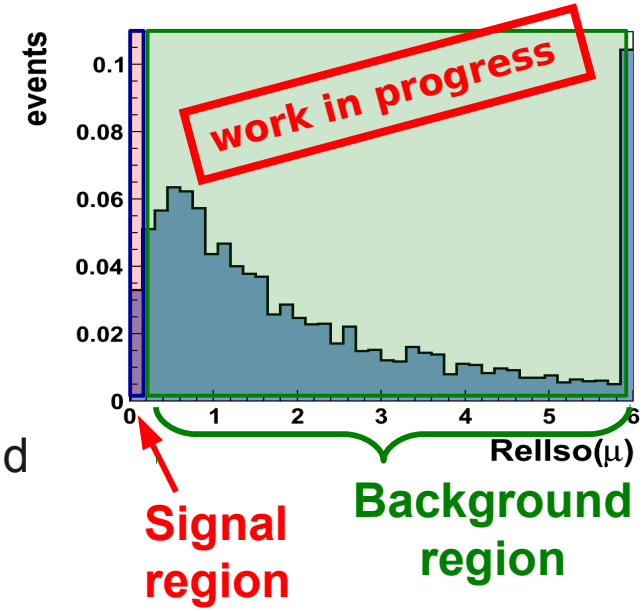
$t\bar{t}$ Background Estimation

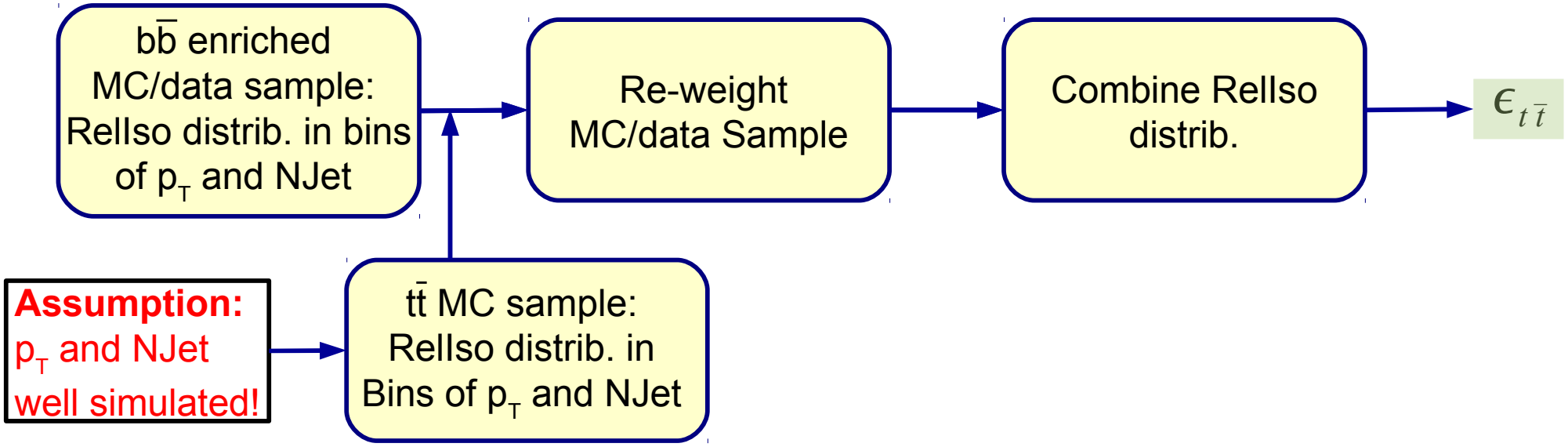
Motivation

- $t\bar{t}$ yields the largest background contribution
- Develop a data-driven method to estimate this background

Aim

- Use larger data sample to determine $t\bar{t}$ background
- Investigate leptons from $b\bar{b}$ enriched sample
- Do an extrapolation of the relative isolation from the background region (RelIso > 0.15) into the signal region (RelIso < 0.15)



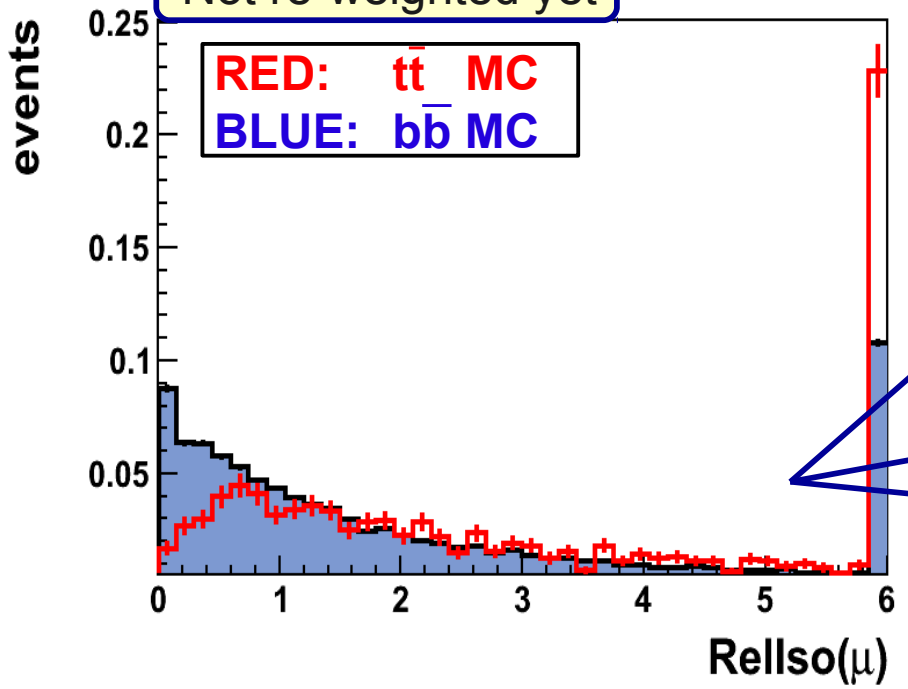


$\epsilon_{t\bar{t}}$:= probability ("efficiency") to find a $t\bar{t}$-event in the signal region, when an event is found in the background region in data

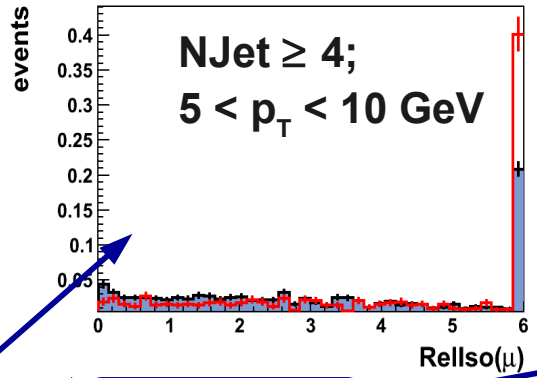
Exemplary Distributions for Muons

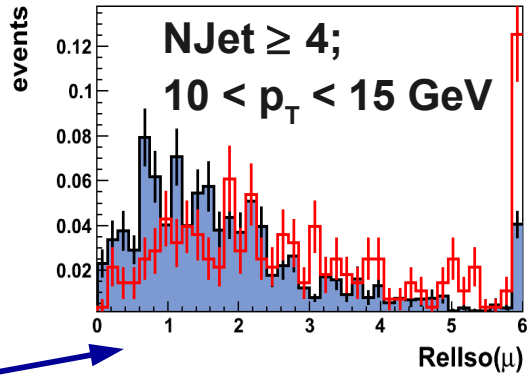
work in progress

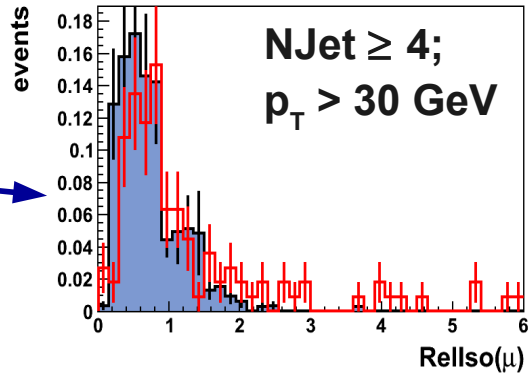
Not re-weighted yet



Split distrib. into kine-matic bins*







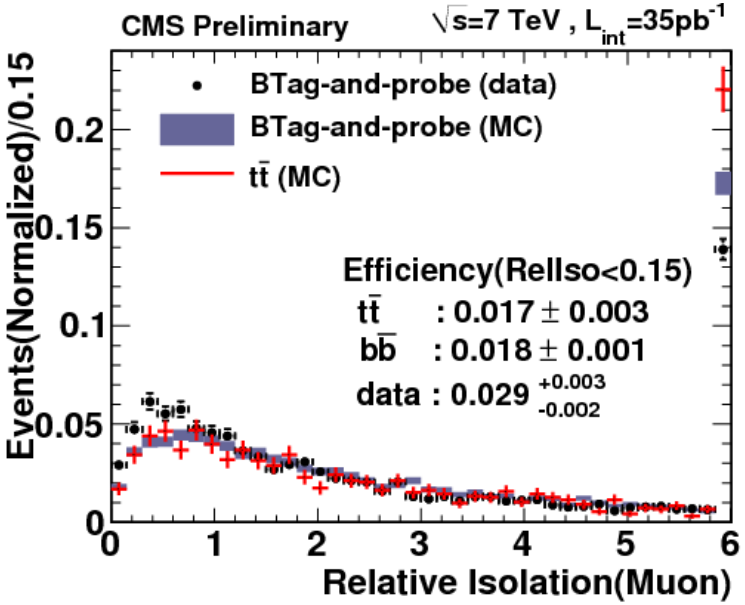
- Closure test: The red and blue distributions **look similar** in the single kinematic bins
- **Re-weight** the blue distribution according to the number of entries of the red distribution

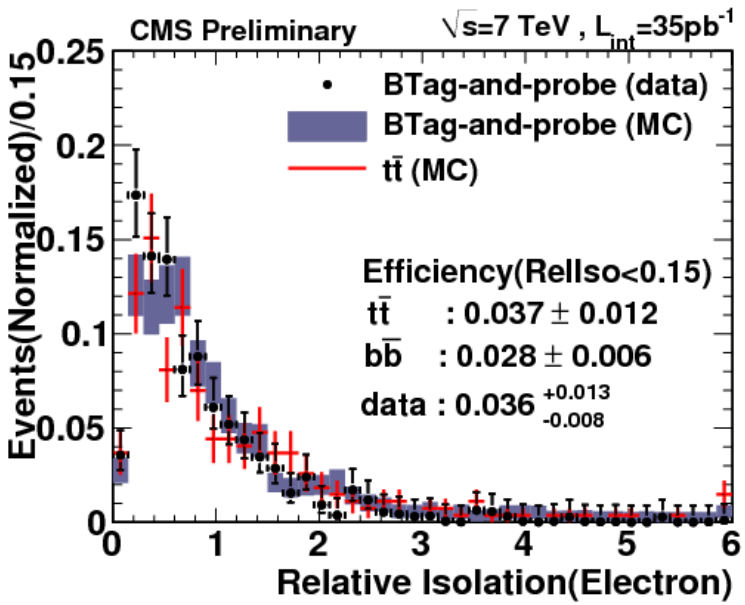
$$\omega(p_T, NJet) = \frac{N_{t\bar{t}}(p_T, NJet)}{\sum_{p_T, NJet} N_{t\bar{t}}(p_T, NJet)}$$

*kinematic bins: electrons: p_T > 10, 15, 20, 25, 35 GeV; NJet =2, =3, ≥4
muons: p_T > 5, 10, 15, 20, 30 GeV; NJet =2, =3, ≥4

Results

Results taken from SUS-10-004-PAS*





Relative Isolation after re-weighting for muons (left) and electrons (right). Efficiencies for RelIso > 0.15 (first bin) are explicitly quoted. Distributions normalized to unity.

- After re-weighting the relative Isolation distributions **agree well**
- From the first bin follows

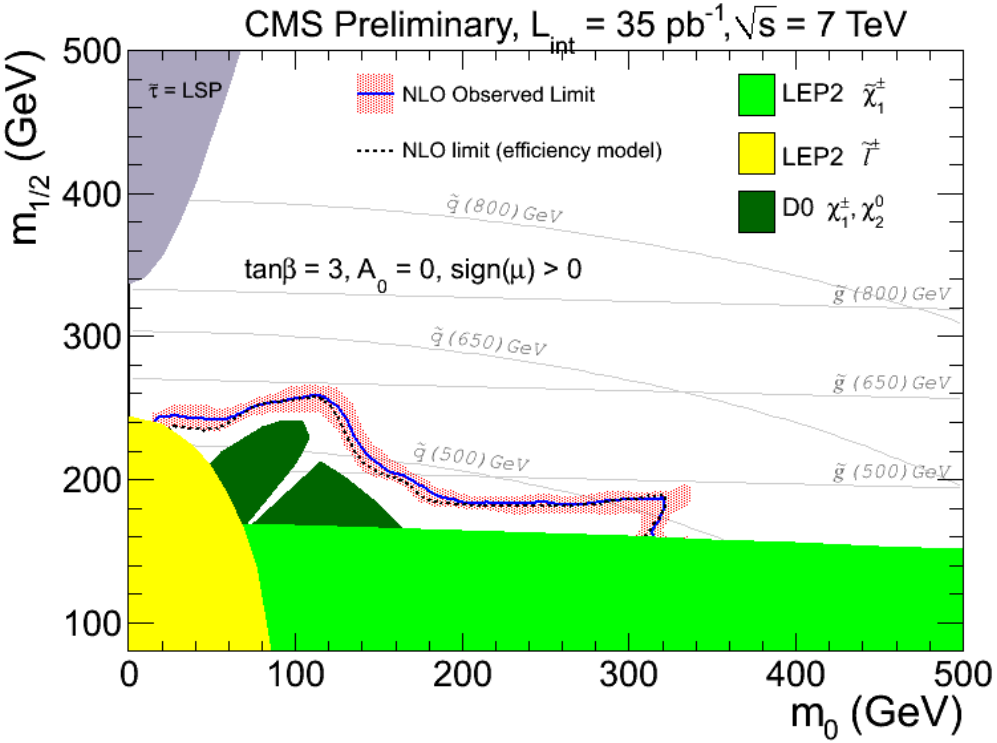
$$\epsilon^{e}_{t\bar{t}} = 0.029^{+0.002}_{-0.003}$$
$$\epsilon^{\mu}_{t\bar{t}} = 0.036^{+0.013}_{-0.008}$$

→ Now: Use this “efficiency” to get a tt̄ background prediction in data

*https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS10004

Results taken from SUS-10-004-PAS*

Search region	ee	μμ	eμ	total
bkg prediction	0.10 ± 0.07	0.30 ± 0.13	0.40 ± 0.18	0.80 ± 0.31
observed	1	0	0	1



Exclusion contour in the m_0 -$m_{1/2}$ plane.
Red shaded band: theoretical uncertainty.

- Observation in agreement with standard model
- Therefore: Set exclusion limits

*https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS10004

Summary/ Outlook

Summary

- A SUSY same-sign di-lepton cut-flow has been established
- $t\bar{t}$ is the dominant background
- A data driven method to estimate the $t\bar{t}$ background has been developed and shown to work on 2010 data

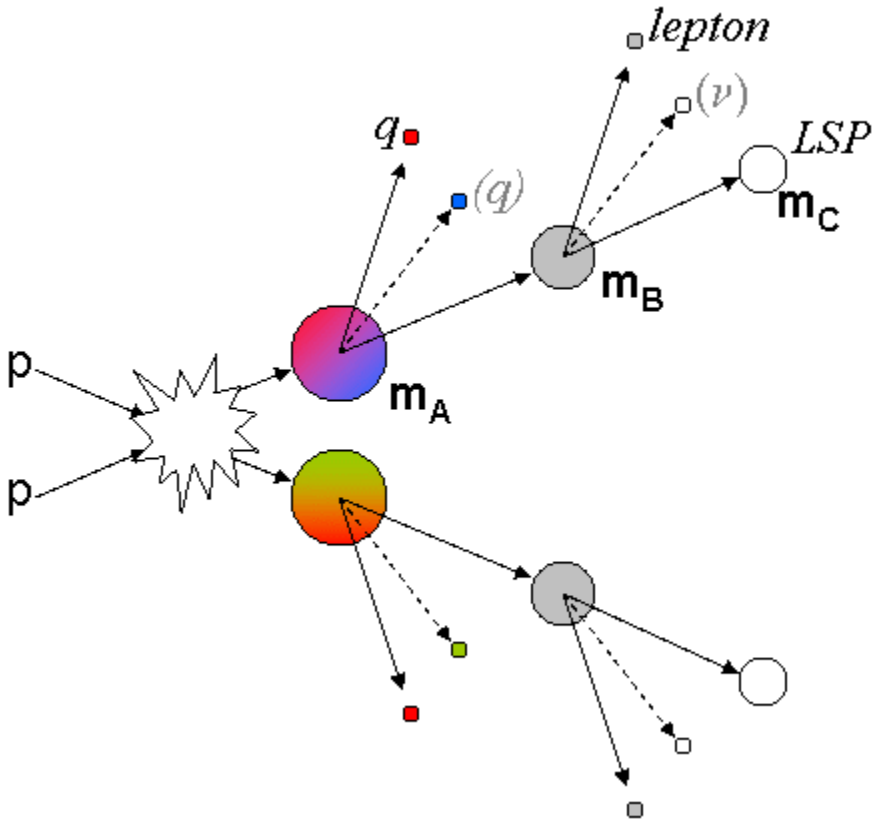
Outlook

- Use more sophisticated reconstruction methods for leptons (particle flow)
- Adapt to the 2011 conditions (pile up!)
- Apply the method to 2011 data

Backup

Search Regions

- **high p_T Selection** (ee, eμ, μμ; lepton $p_T \geq$ 20/10): this allows to search for events with lower H_T and MET (i.e. **smaller Δm_{AB} mass split**)
- **low p_T Selection** (ee, eμ, μμ): best suited for the case with **smaller Δm_{BC} mass split**)
- **tau-enhanced** final states (eτ, μτ, ττ): target high tanβ scenarios that may lead to predominant yield of τ-leptons."



Event selection

- Trigger: HLT_HT100U, HLT_HT120U, HLT_HT140U, HLT_HT150U
- Cleaning cuts
  - No of good vertex > 0
  - HBHE noise filter
  - Pure tracks
- No of good leptons > 1 (ee, eμ, μμ)
- No of good leptons = 2 (ee, eμ, μμ)
- Is same-sign (ee, eμ, μμ)
- M_{inv}(SS ll) > 5 GeV
- SSPrimary vertex Z < 1 cm
- $|M_{inv}(OS\ ll) - M_Z|$ > 15 GeV
- # Jets > 1
- H_T (particle flow) > 300 GeV
- MET (particle flow) > 30 GeV
- RelIso1 < 0.15
- RelIso2 < 0.15

Vertex

- IsNotFake
- |DistZ| < 15/ 24 (MC/ Data)
- |DistRho| < 2
- Ndof > 3

Pure Tracks: if # of all Tracks > 10, check: (# high pure tracks / # of all Tracks) > 0.25

Electron selection

- p_T > 10 GeV
- $|\eta|$ < 2.4
- Exclude η-gap (1.47 < $|\eta|$ < 1.57)
- VBTF_IDc 80 == 5 || 7
  - $\sigma_{i\eta i\eta}$ < 0.01/ 0.03 (barrel/ endcap)
  - $d\phi_{in}$ < 0.06/ 0.03 (barrel/ endcap)
  - $d\eta_{in}$ < 0.004/ 0.007 (barrel/ endcap)
  - Hoe < 0.04/ 0.025 (barrel/ endcap)
- |d0_corr| < 0.02 (z-distance with respect to beam spot)
- No μ within ΔR < 0.1
- Conversion rejection
  - # Expected Hits in the inner layers > 0
  - $\Delta\cot(\theta)$ < 0.02
  - Dist < 0.02
- ECAL driven seed
- Charge(GSF) = Charge(CTF) = Charge(ScPix)
- RelIso < 0.15 (cone R = 0.3)
- No double-counting of events (Priority: $\mu\mu$, eμ, ee)

$$RelIso = (TrackIso + max[0., (EcalIso - 1)] + HcalIso) / max(p_T, 20) \quad (Barrel)$$

$$RelIso = (TrackIso + EcalIso + HcalIso) / max(p_T, 20) \quad (Endcap)$$

$\Delta\cot(\theta)$ / dist := angle/ distance between the electron candidate's GSF track and the closest, oppositely charged CTF Track in a cone of R < 0.3 that does not belong to the electron itself in the single electron gun

Muon selection

- p_T > 5 GeV
- $|\eta|$ < 2.4
- Reduced χ^2 < 10
- Is Global and Tracker muon
- NoOfTrackerHits > 10
- # valid silicon Hits > 10
- |d0_corr| < 0.02 (z-distance with respect to beam spot)
- Valid Stand Alone Hits > 0
- ecalvetoDep < 4 GeV*
- hcalvetoDep < 6 GeV
- Relative Isolation < 0.15 (cone R = 0.3)

$$RelIso = (TrackIso + max[0., (EcalIso - 1)] + HcalIso)/p_T \quad (Barrel)$$
$$RelIso = (TrackIso + EcalIso + HcalIso)/p_T \quad (Endcap)$$

*Require that muon is minimum ionizing. Cut is on energy of the "veto cone".

Jet/b-jet Selection

Jets

- p_T > 30 GeV
- $|\eta|$ < 2.5
- Ak5Jets: loose ID (L2 & L3; PF)
- ΔR to electrons > 0.4
- ΔR to muons > 0.4

BJets

- Same as Jets
- ak5JetPF2PATTrkCountingHighPurBJetTagsPat > 3.4

PF Jet ID	Loose (Recommended)	Medium	Tight
Neutral Hadron Fraction	<0.99	<0.95	< 0.90
Neutral EM Fraction	<0.99	<0.95	< 0.90
Number of Constituents	>1	>1	> 1
And for η<2.4 , η>-2.4 in addition apply			
Charged Hadron Fraction	>0	>0	>0
Charged Multiplicity	>0	>0	>0
Charged EM Fraction	<0.99	<0.99	<0.99

Bb Samples for Tag & Probe Method

label	sample	cross section [pb]
BJets_HT100To250	/BJets_HT-100To250_TuneD6T_7TeV-madgraph/Fall10-START38_V12-v1/AODSIM	197000
BJets_HT250To500	/BJets_HT-250To500_TuneD6T_7TeV-madgraph/Fall10-START38_V12-v1/AODSIM	6213
BJets_HT500To1000	/BJets_HT-500To1000_TuneD6T_7TeV-madgraph/Fall10-START38_V12v1/AODSIM	161.7
BJets_HT1000ToInf	/BJets_HT-1000_TuneD6T_7TeV-madgraph/Fall10-START38_V12-v1/AODSIM	2.281
label	**sample**	**Luminosuty [pb^{-1}]**
EG_Run2010A	/EG/Run2010A-Nov4ReReco_v1/AOD	3.13
El_Run2010B	/Electron/Run2010B-Nov4ReReco_v1/AOD	32.96
Mu_Run2010A	/Mu/Run2010A-Nov4ReReco_v1/AOD	3.13
Mu_Run2010B	/Mu/Run2010B-Nov4ReReco_v1/AOD	32.96

Used Monte Carlo Samples for SUSY Selection

label	sample	cross section [pb]
ttbar	/TTJets_TuneZ2_7TeV-madgraph-tauola/Fall10-START38_V12-v3/AODSIM	121
Single Top t-channel (tbq)	/TToBLNu_TuneZ2_t-channel_7TeV-madgraph/Fall10-START38_V12-v2/AODSIM/	63/3
Single Top s-channel (tb)	/TToBLNu_TuneZ2_s-channel_7TeV-madgraph/Fall10-START38_V12-v1/AODSIM/	0.99
Single Top tW	/TToBLNu_TuneZ2_tW-channel_7TeV-madgraph/Fall10-START38_V12-v2/AODSIM/	10.56
WJetsToLNu	/Fall10-START38_V12-v1/WJetsToLNu_TuneZ2_7TeV-madgraph-tauola	24640
ZJetToMuMu15to3000Flat	/Fall10-START38_V12-v1/ZJetToMuMu_Pt_15to3000_TuneZ2_Flat_7TeV_pythia6/	494200
W^+W^-	/WWtoAnything_TuneZ2_7TeV-pythia6-tauola/Fall10-START38_V12-v1/AODSIM/	27.79
WZ	/WZtoAnything_TuneZ2_7TeV-pythia6-tauola/Fall10-START38_V12-v1/AODSIM/	10.4
ZZ	/ZZtoAnything_TuneZ2_7TeV-pythia6-tauola/Fall10-START38_V12-v1/AODSIM/	4.297
QCD	/Fall10-START38_V12-v1/QCD_Pt_15to3000_TuneZ2_Flat_7TeV_pythia6	22130000000
LM0	/LM0_SUSY_sftsht_7TeV-pythia6/Fall10-START38_V12-v1/GEN-SIM-RECO	38.93

Detailed Event Yield

MC sample	μμ	ee	eμ
ttbar	0.099	0.0432	0.109
Single Top t-channel (tbq)	0.014	0.002	0.008
Single Top s-channel (tb)	0	0	0
Single Top tW	0.004	0	0.004
WJets -> l+nu	0	0	0.057
ZJet -> mumu	0.001		
W^+W^-	0	0	0
WZ	0	0.001	0.002
ZZ	0	0	0
QCD	0	0	0.037
Sum of channels	**0.11**	**0.05**	**0.22**
Total background		**0.38**	
Signal (LM0*)	**1.96**	**1.16**	**2.74**
Total		**5.86**	

Weighting Factors in Formulas

$$\epsilon_{b\bar{b}}(i,j;l) = \frac{N_{b\bar{b}}^{RelIso<0.15}(i,j;l)}{N_{b\bar{b}}^{RelIso>0.15}(i,j;l)}$$

$$\omega_{t\bar{t}}(i,j;l) = \frac{N_{t\bar{t}}(i,j;l)}{N_{t\bar{t}}(l)}$$

$$N_{t\bar{t}}^{predicted}(ll) = N_{b\bar{b}}^{RelIso>0.15}(ll)\cdot\sum_{i,j}\epsilon_{b\bar{b}}(i,j;l)\cdot\omega_{t\bar{t}}(i,j;l)$$

$\epsilon :=$ efficiency/ prob. to have an entry in the signal region (RelIso<0.15)

$\omega(i,j) :=$ weight = prob. of a b-Jet in $t\bar{t}$ to be in a certain ij bin

$N_{t\bar{t}}(l) :=$ # of all $t\bar{t}$ events with a lepton from a b-Jet $= \sum_{i,j} N_{t\bar{t}}(i,j;l)$

$N_{t\bar{t}}(i,j;l) :=$ # events in a certain bin of $t\bar{t}$

$i :=$ p_T -bin

$j :=$ N_{Jet} -bin

$l := e, \mu$

$ll := ee, \mu\mu, e\mu, \mu e$

Situation

- Measure N events with N_{SS} and N_{OS} signature
- **Assumption**: All N events are coming from Z decay

$$N = \underbrace{N_{oo} + N_{xx}}_{N_{OS}} + \underbrace{N_{xo}}_{N_{SS}}$$

measured

$N := no.\ of\ Events \rightarrow measured$

$N_{xo} := no.\ of\ Events\ with\ one\ flip \rightarrow N_{SS}$

$N_{SS} := no.\ of\ SS\ Events \rightarrow measured$

$N_{OS} := no.\ of\ OS\ Events \rightarrow measured$

unmeasured

$N_{oo} := no.\ of\ Events\ with\ no\ flip \rightarrow ?$

$N_{xx} := no.\ of\ Events\ with\ two\ flips \rightarrow ?$

$\varepsilon := flip\ rate \rightarrow ?$

$x := no.\ of\ all\ fliped\ leptons \rightarrow ?$

→ **Goal:** **determine ε**

→ **Solution:** **find 4 constraints to solve for ε**

$$(1)\ N = N_{SS} + N_{OS}$$
$$(2)\ N_{xx} = \varepsilon^2 \cdot N$$
$$(3)\ x = N_{SS} + 2 \cdot N_{xx}$$
$$(4)\ x = 2 \cdot \varepsilon \cdot N$$

$$(2) \rightarrow (3):\quad x = N_{SS} + 2\varepsilon^2 N$$
$$+(4):\quad 2\varepsilon N = N_{SS} + 2\varepsilon^2 N$$
$$+(1):\quad 2\varepsilon (N_{SS} + N_{OS}) = N_{SS} + 2\varepsilon^2 (N_{SS} + N_{OS})$$

$$\varepsilon^2 - \varepsilon + \frac{N_{SS}}{2 \cdot (N_{SS} + N_{OS})} = 0$$

$$\varepsilon_{1,2} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{N_{SS}}{2 \cdot N}}$$