Search for a Cold Dark Matter Candidate with the CMS Detector at the LHC

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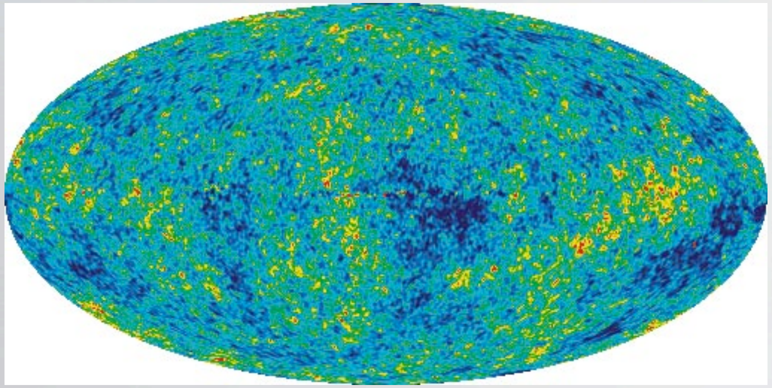
- Motivation and Evidence for Dark Matter
- Dark Matter at Colliders
- Missing Energy Signatures in Multi-Jet Events
    - robust analysis techniques
    - di-jets as a detailed example
    - data-driven background estimates
- Interpretation in the Context of SUSY
- Conclusions

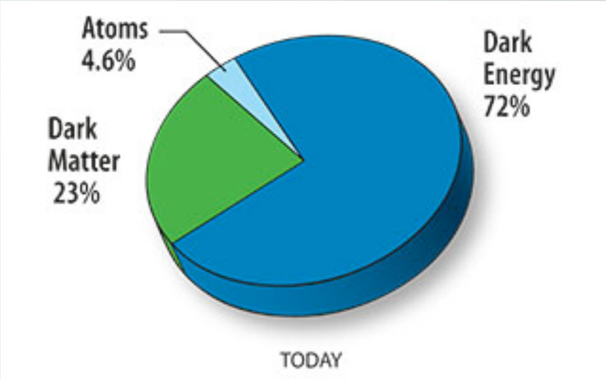
Seminar Strasbourg (March 10th, 2009)

A Look at the
Energy and Matter Content of the Universe

- Cosmic microwave background gives precise information about dark matter content of the universe

- WMAP 5 year result:





Credit: NASA/WMAP Science Team

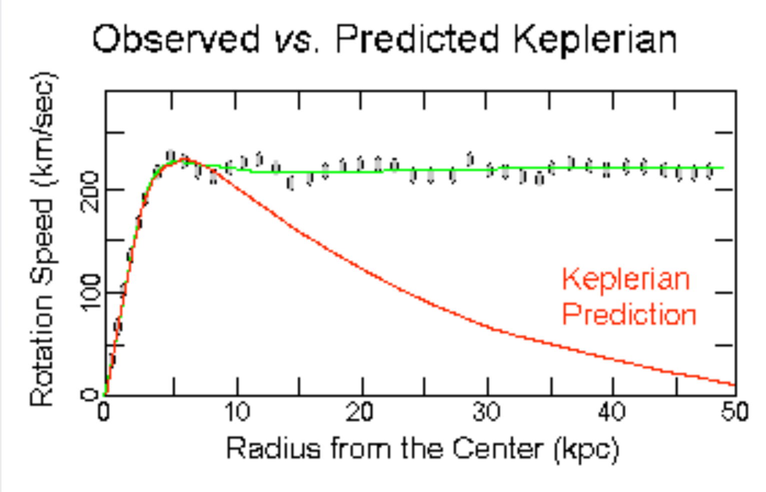
  - relic dark matter density of the universe
    $\Omega_{DM}h^2 = 0.110 \pm 0.006$

- Only 5% is made from baryonic matter, 23% from unknown "dark matter"

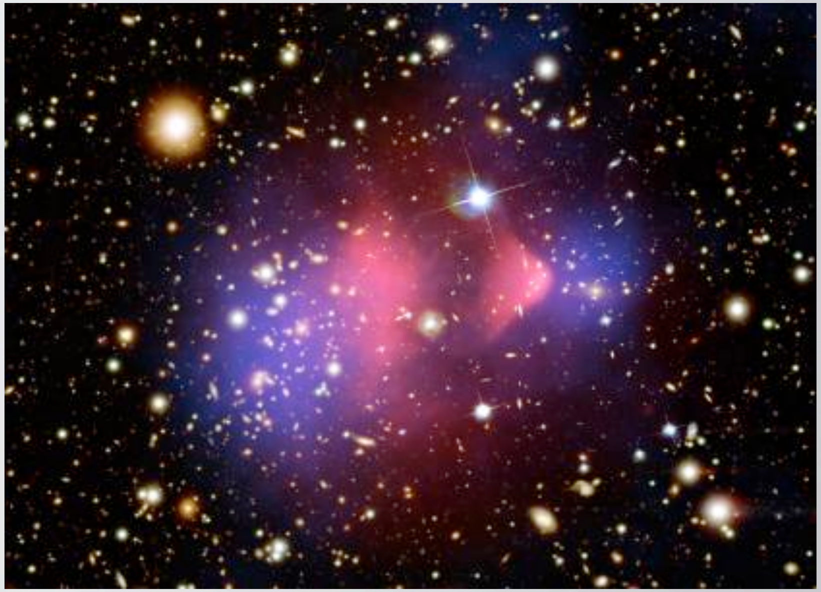
- Attractive explanation for Dark Matter:
  - new weakly interacting particle

Experimental Evidence for Dark Matter

- Zwicky1933
  - rotation frequencies of galaxies
  - high rotation speed at large radii suggests matter far from the center of the galaxy that is not emitting light
  - Dark matter within the galactic halo



- Bullet cluster
  - collision of two galaxy clusters
  - mass distribution shown in blue
    - determined with gravitational lensing
  - hot gas distribution in red
  - Most of the mass does not interact, only visible matter (gas) is slowed down



Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScl; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScl; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

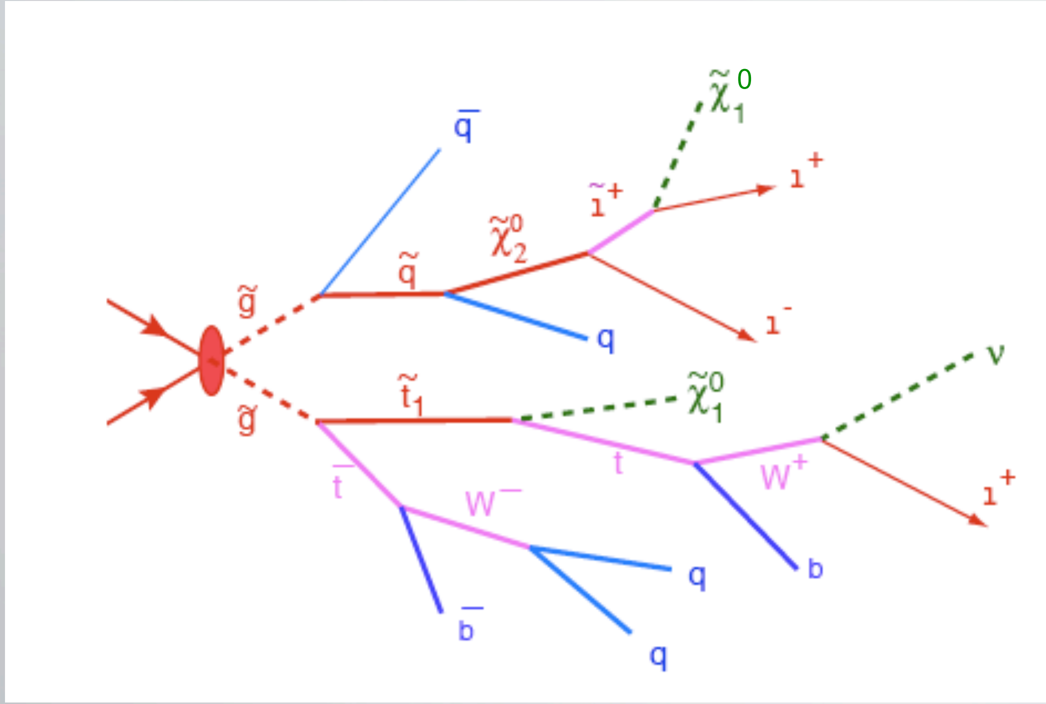
Can we produce Dark Matter particles at Colliders?

- Dark Matter candidate is a weakly interacting massive particle (WIMP)
- Many New Physics Models provide viable dark matter candidates, e.g.
  - R-parity conserving Supersymmetry
    - minimal super gravity mSugra → neutralino is WIMP
    - Gauge mediated SUSY → gravitino is WIMP (too light)
  - Universal Extra Dimensions
  - Warped Extra Dimensions
  - Little Higgs Models
  - Technicolor Models
- Production of WIMP's in cascade decays of heavy new particles
  - WIMP's escape the detector and remain undetected
  - Leads to a missing energy signature

An Example from SUSY

e.g. gluino pair-production

lots of missing energy, many jets, and possibly leptons in the final state



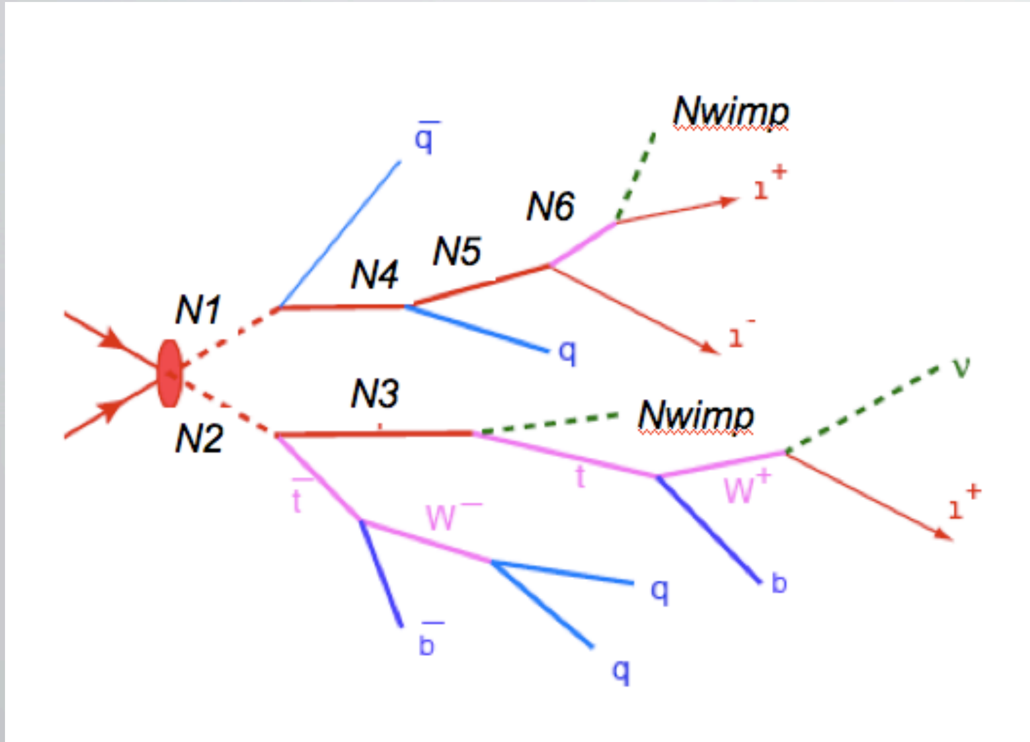
Missing Energy:
- from LSP

Multi-Jet:
- from cascade decay (gaugino)

Multi-Leptons:
- from decay of charginos and neutralinos

...but signature is more general

- pair production of new heavy particles



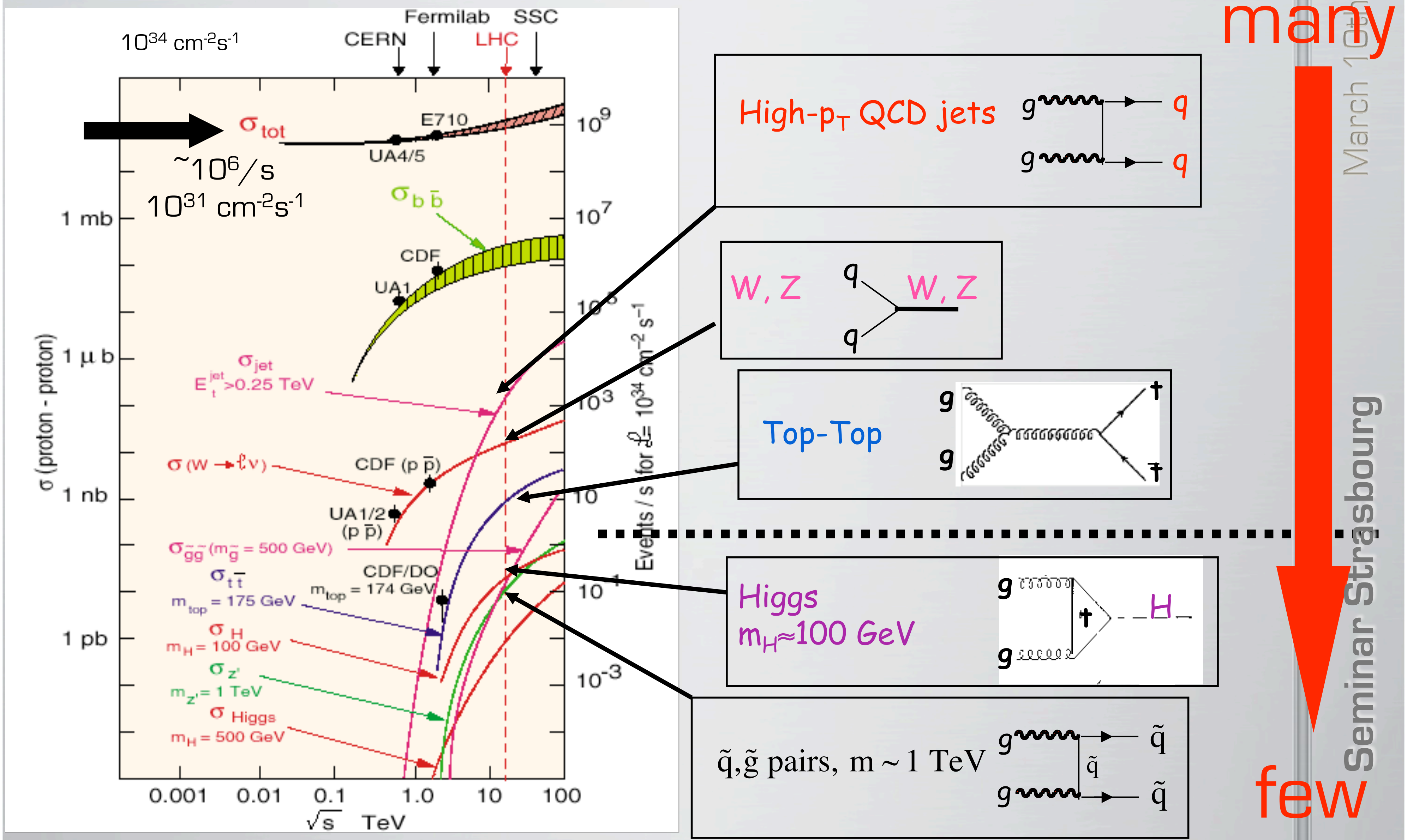
Missing Energy:
- Nwimp - end of the cascade

Multi-Jet:
- from decay of the Ns (possibly via heavy SM particles like top, W/Z)

Multi-Leptons:
- from decay of the N's

Model examples are Extra dimensions, Little Higgs, Technicolour, etc

What do we expect to see at LHC?



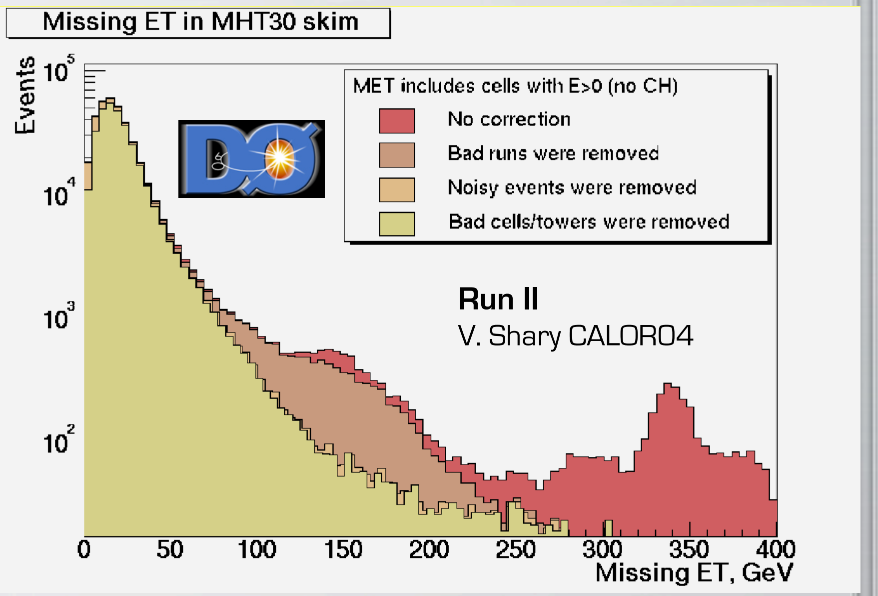
Sources for Missing Energy at LHC

- QCD multi-jet events
  - jet energy mis-measurements, calorimeter cracks etc.
- Neutrinos produced in W (mediated) decays
  - semi-leptonic decays of heavy quarks
    - tt events
    - bb + jets
  - W/Z + jets events
  - Diboson + jets production
- Unknown escaping particle

Missing Energy Measurement

- "Traditional" approach:
  - Calculate missing energy as negative vectorial sum of all calorimeter deposits
  - Susceptible to mis-measurements from, e.g.
    - Calorimetric noise (hot cells)
    - Cosmic rays
    - Beam-gas interactions
    - Beam-halo events
  - Difficult to understand in the early days of data taking
- Need for robust measurement techniques

Missing Energy from Tevatron during several cleanup stages:



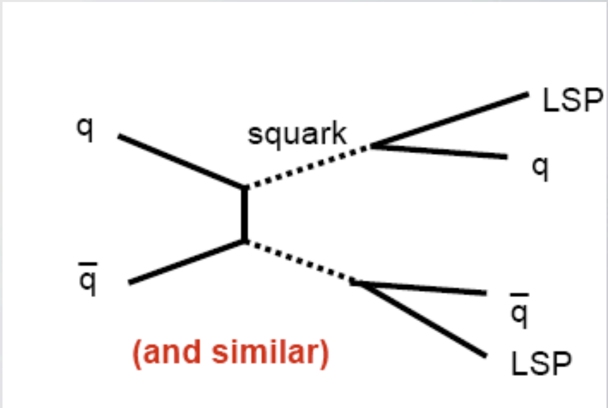
IDEA:
infer missing energy from well measured objects by applying transverse energy/momentum conservation

Missing Energy in Multi-Jet Events

Case study: di-jet events

Di-jet Analysis

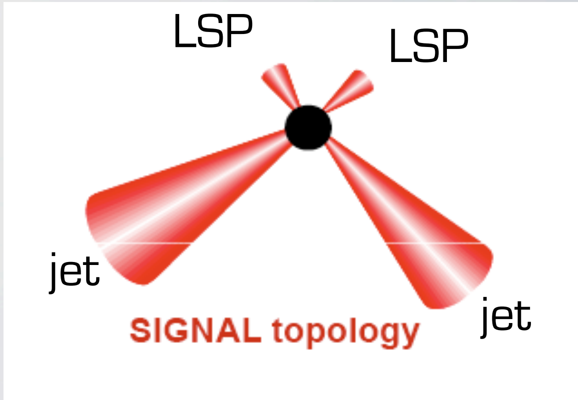
- New CMS study: PAS-SUS-08/005
  - CMS PTDR II focused on inclusive SUSY searches with ≥ 3 jets
- Motivated in addition by recent paper by
  - L. Randall, D.Tucker-Smith (Phys.Rev.Lett.101:221803,2008)
- Idea:
  - Squarks pair produced and directly decaying to quarks and neutralinos
    - Requires squarks lighter than gluino, so no cascade decays through gluinos
  - Possibility to constrain squark and neutralino masses with sufficient luminosity



- Event topology
  - Only two jets + missing energy
- Extendable to multi-jet events

Kinematics of signal and background events

- Exploit kinematics of the event
- Signal: 2 jets + 2 neutralinos (= missing E_T)
  - two jets, ~uncorrelated in ϕ and magnitude of E_T
- Background:
  - QCD dijet events
  - No real missing momentum,
  - transverse momentum conservation
    - jets back-to-back in Φ
    - E_T of jets equal in magnitude

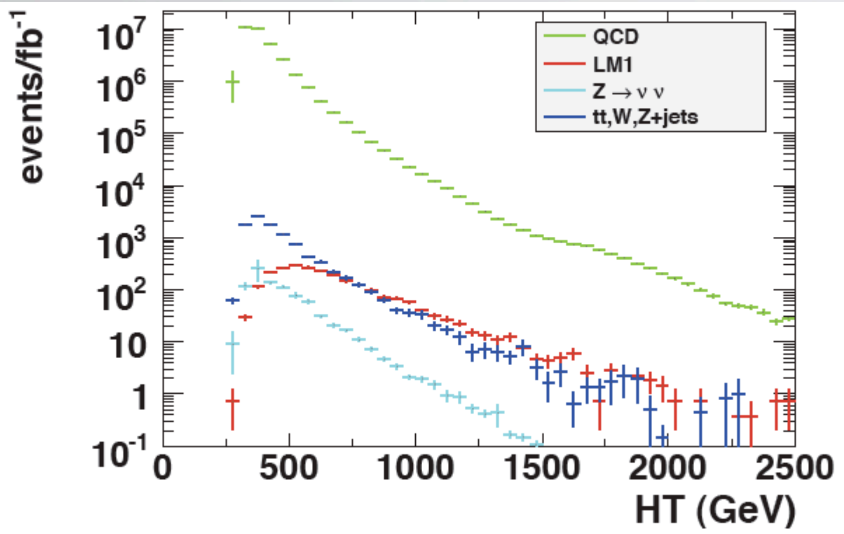


  - Z→νν + jets events
  - Irreducible background due to real missing E_T

  - W→lν + jets events
  - Leads to missing Et when lepton not reconstructed or out of acceptance

Event Selection

- Main variables of interest
  - Scalar sum of Jet p_T's:
    - $HT = p_T^{Jet1} + p_T^{Jet2}$
  - Jet based missing E_T
    - $MHT = -(\vec{p}_T^{Jet1} + \vec{p}_T^{Jet2})$
  - but also p_T of a possible 3rd jet
  - $\Delta\varphi$ between the jets
  - α (α_T) from 2 leading jets



- Trigger
  - di-jet trigger
    - two jets with pt > 150 GeV
- Preselection:
  - Jet Selection
    - 2 jets with pt > 50 GeV, $F_{em} < 0.9$
    - 3rd jet veto: pt < 50 GeV
    - $\Delta\varphi(MHT, jet_{1,2,3}) > 0.3$ rad
    - $|\eta_{j1}| < 2.5$
  - Lepton veto's:
    - no e, μ with pt >10 GeV
- Full Selection
  - HT > 500 GeV
  - α (α_T) > 0.55
  - ($\Delta\phi < 2\pi/3$)

Accounting for finite resolution (not optimised)

Discriminating Variables

- Exploit kinematics of the event
  - Define new variable α (Randall – Tucker-Smith):

$$\alpha = \frac{E_{T\ j2}}{M_{j1\,j2}} = \frac{E_{T\ j2}}{\sqrt{2E_1E_2(1-\cos\theta)}}$$

    - Can be at most 0.5 for QCD, $\alpha < 0.5$
    - $\alpha > 0.5$ implies missing momentum

  - And transverse α_T:

$$\alpha_T = \frac{E_{T\ j2}}{M_{T\ j1\,j2}} = \frac{\sqrt{E_{T\ j2}/E_{T\ j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

    - Exploits that for QCD jets need to be back-to-back and of equal magnitude
    - For QCD dijets $\alpha = 0.5$

Analysis does not rely on calorimetric MET, MHT inferred from 2 jets

⇒ well suited for early data

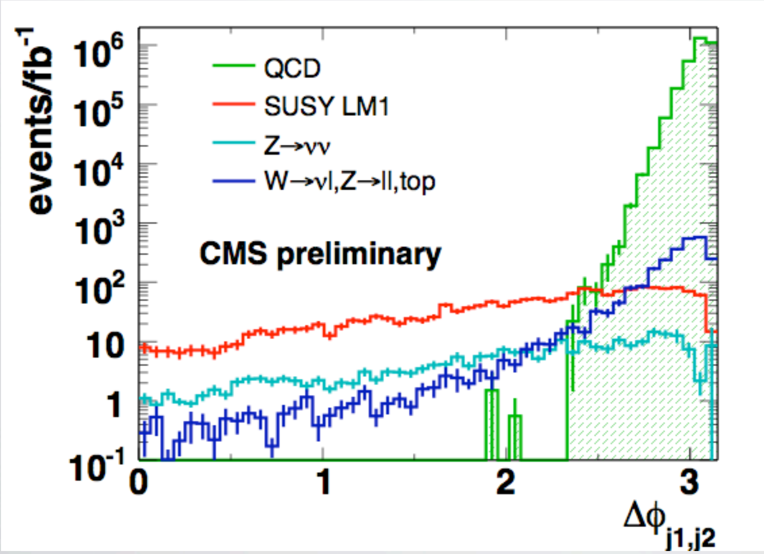
Discriminating Variables (II)

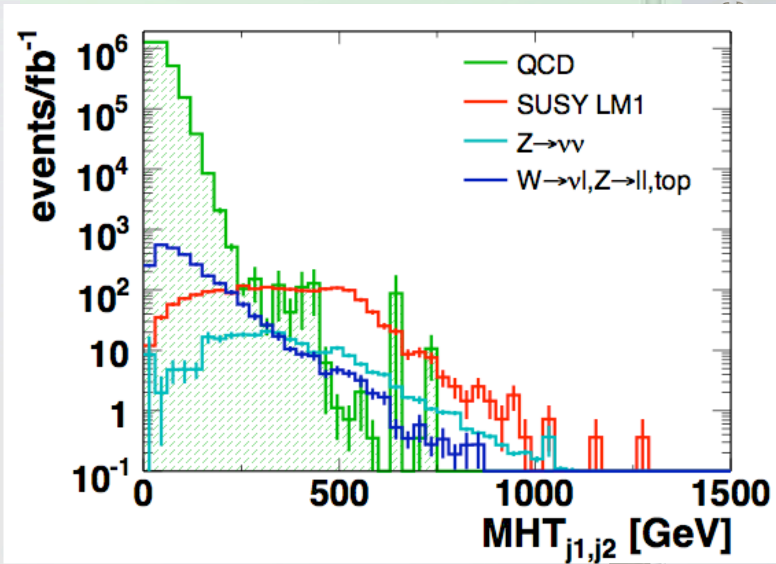
- Cuts applied:
  - Preselection & HT > 500 GeV

- $Z \to \nu\nu$ is main background
- W and other Z decays small

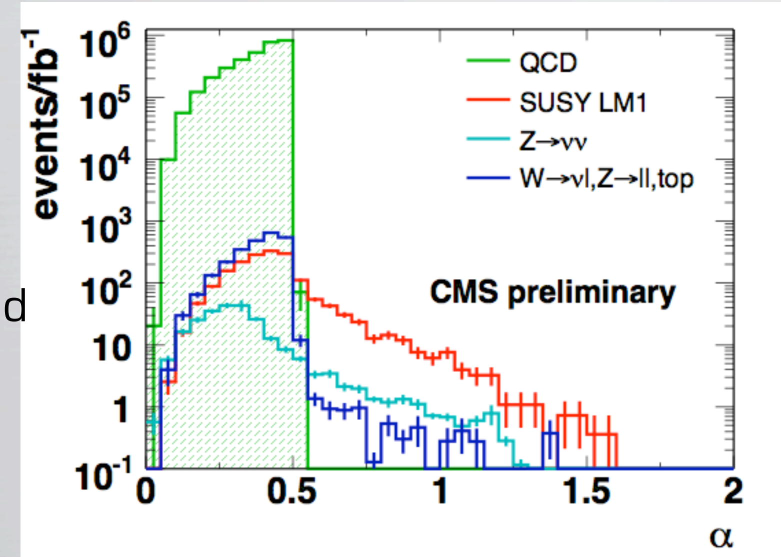
1 fb^{-1}

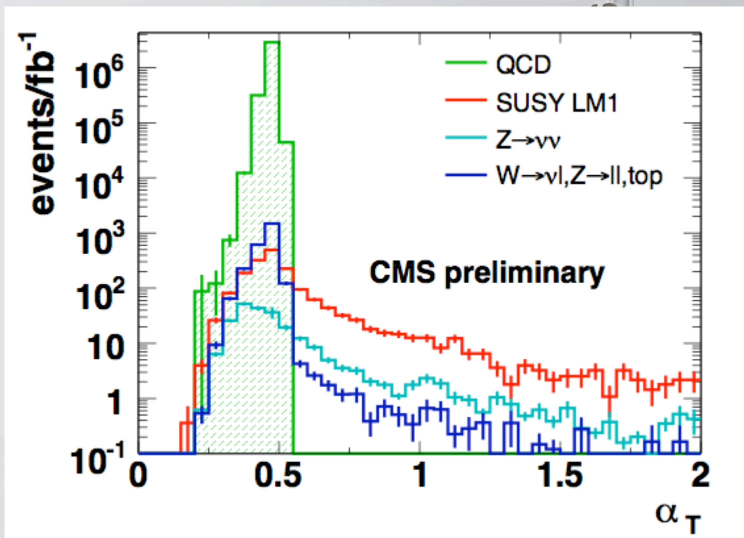
QCD peaking at $\Delta\phi = \pi$





Sharp drop of QCD background for α (αT) > 0.5





Signal & Background yields

- Expected event yields for 1fb^{-1}

Selection cut	QCD	$t\bar{t}$,W,Z	$Z \rightarrow \nu\bar{\nu}$	LM1
Trigger	1.1×10^8	147892	1807	25772
Preselection	3.4×10^7	9820	878	2408
HT > 500 GeV	3.2×10^6	2404	243	1784
$\alpha > 0.55$	0	7.2	19.7	227.6
$\alpha_T > 0.55$	0	19.9	58.2	439.6
$\Delta\phi_{j1,j2} < 2\pi/3$	0	18.7	57.2	432.4

=> Signal/Background = 5.6

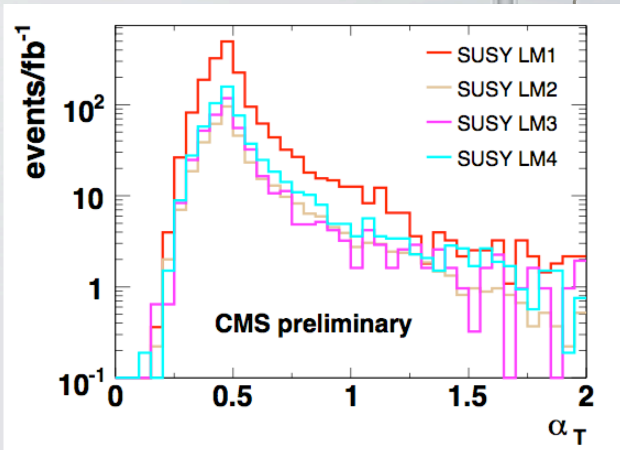
- Variation of jet energy scale and resolution
  - 10% gaussian smearing of jet p_T's and of 0.1 rad of φ measurement
  - Scaling of jet energy by ± 5%
  - Scaling of jet energy by ± 3% for endcap/forward (|η|>1.4)

- Smearing has only small influence (~3%)
- Scaling changes effective HT cut
- **Stable S/B for all variations!**

A closer look at SUSY yields

- CMS SUSY benchmark points

Sample	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0	$\tan\beta$	sign(μ)	σ NLO (pb)	(LO) (pb)	lightest $\tilde{q}$ (GeV)	$\tilde{\chi}_1^0$ (GeV)
LM1	60	250	0	10	+	54.86	(43.28)	410 ($\tilde{t}_1$)	97
LM2	185	350	0	35	+	9.41	(7.27)	582 ($\tilde{t}_1$)	141
LM3	330	240	0	20	+	45.47	(34.20)	446 ($\tilde{t}_1$)	94
LM4	210	285	0	10	+	25.11	(19.43)	483 ($\tilde{t}_1$)	112



- Reminder: desired topology is 2 squarks decaying to squarks and 2 neutralinos (LSPs)

Sample	Events	$\tilde{q}\,\tilde{q}$ (invisible)	$\tilde{q}\,\tilde{q}$ (other)	$\tilde{q}\,\tilde{g}$	$\tilde{g}\,\tilde{g}$	other
LM1	432	39%	22%	34%	3%	1%
LM2	132	46%	33%	18%	0%	2%
LM3	138	69%	17%	12%	0%	2%
LM4	195	49%	10%	36%	3%	1%

For comparison:
QCD: 0
$Z \to \nu\nu$: 57
W/Z: 19
Total: 76

- Dominated by squark-squark, but not only:
  - Squark - gluino contribution, where gluino decays to squark+quark
  - In LM1: small mass difference between gluino and squark => low p_T 3rd jet

Production process	$p_T^{j3} < 30\,\mathrm{GeV}$	$p_T^{j3} < 50\,\mathrm{GeV}$	$p_T^{j3} < 70\,\mathrm{GeV}$
$\tilde{q}\,\tilde{q}$	80%	61%	51%
$\tilde{q}\,\tilde{g}$	18%	34%	44%
$\tilde{g}\,\tilde{g}$	1%	3%	5%

  - Indeed observe increase in squark-gluino contribution when relaxing 3rd jet veto

Di-jet Analysis

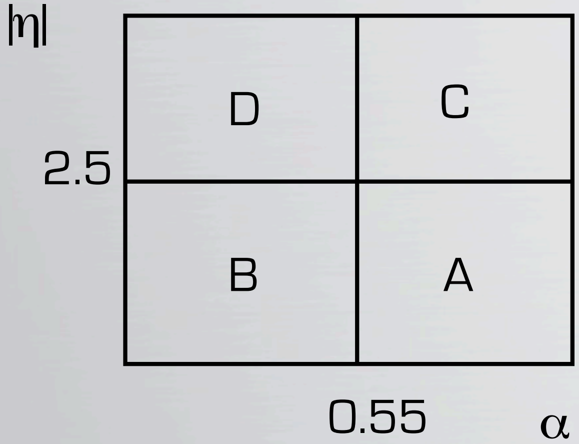
Data-driven background estimation

Background Studies

- LHC data in explores a new energy regime
  - Monte Carlo simulations should not be taken at face value
  - develop data-driven techniques
  - identify data control samples
- Two main sources of background:
- QCD
  - Seems to be under control but huge cross-section
  - MC uncertainties due to higher order QCD effects
- $Z \rightarrow \nu\nu$
  - represents an irreducible background
  - two jets + real missing E_T
  - Ideally study $Z \rightarrow \mu\mu$ events but not enough statistics in the early days
  - Other control samples:
  - W + Jets
  - Photon + Jets as shown in CMS-AN 36/2008

Central Production of Heavy Objects

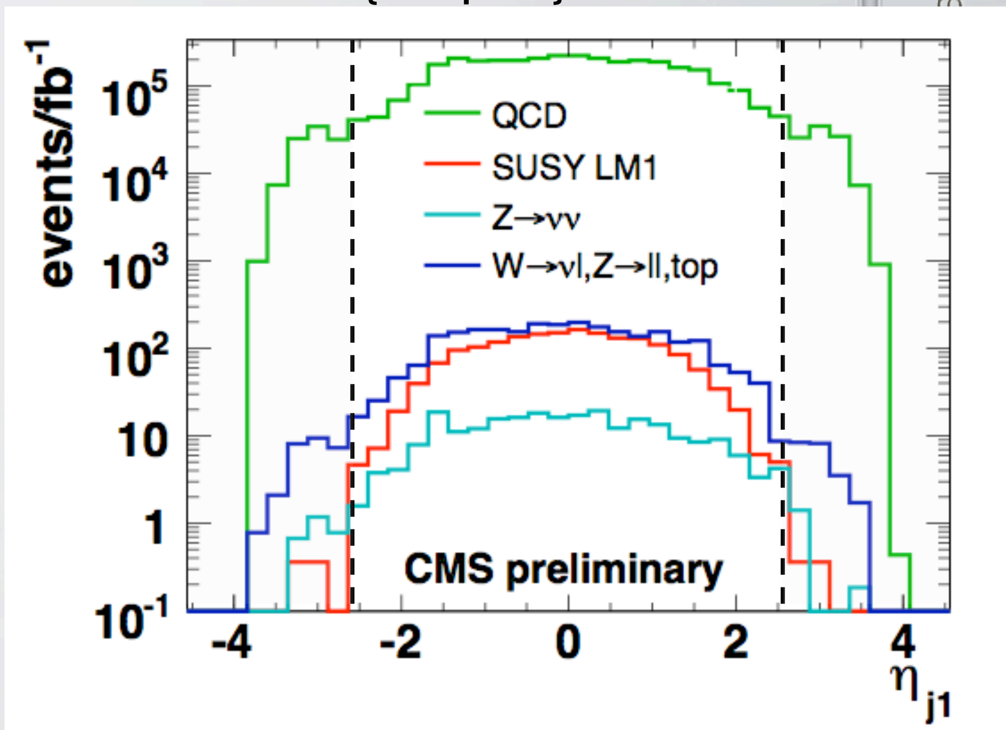
- Idea: define signal enriched and depleted regions by splitting data sample in events with first jet in barrel and forward region
  - SUSY jets are more central
  - Use ratio of events $R_a = \alpha_T > 0.55 / \alpha_T < 0.55$ in (signal depleted) forward η region to predict background in (signal enriched) barrel region.



See also: Background Modeling in New Physics Searches Using Forward Events at LHC.

V. Pavlunin, D. Stuart, Phys.Rev.D78:035012,2008.

Pre-selection (no η cut) + HT > 500 GeV



R = C/D: assumed to be constant over η and nearly signal free

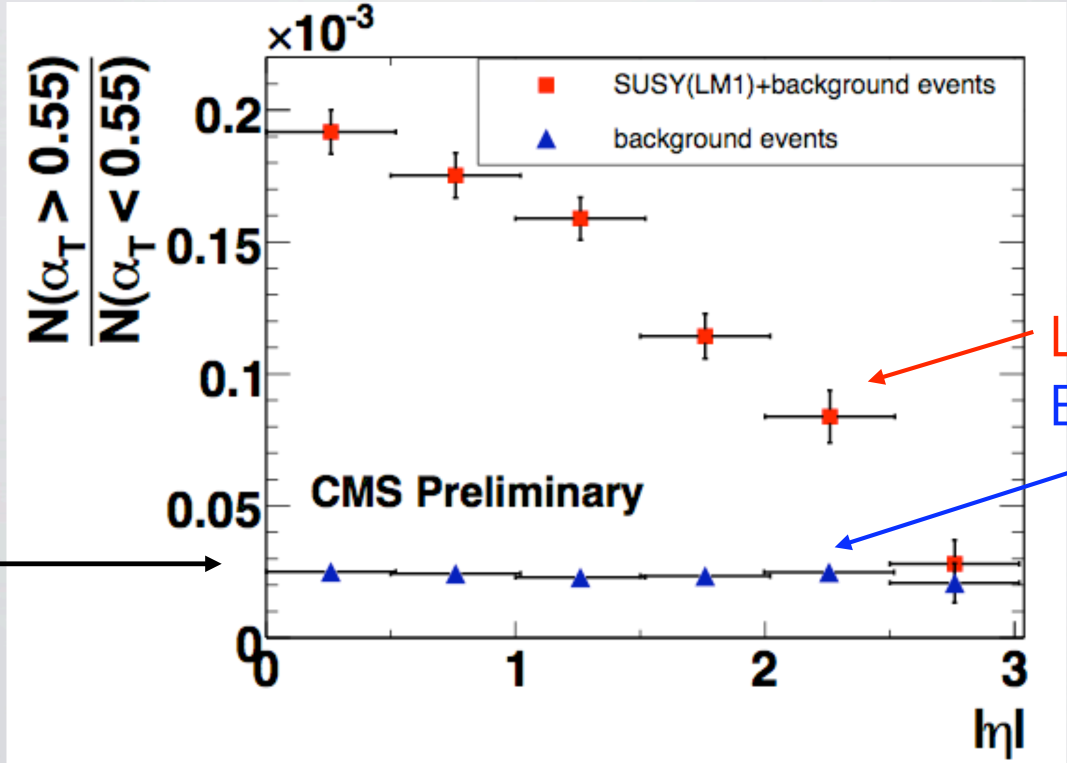
also: constant for all background contributions individually

Then, background in A can be obtained as:

A = B * R

η Dependence of Matrix Method

Pre-selection (no |η| cut) + HT > 500 GeV



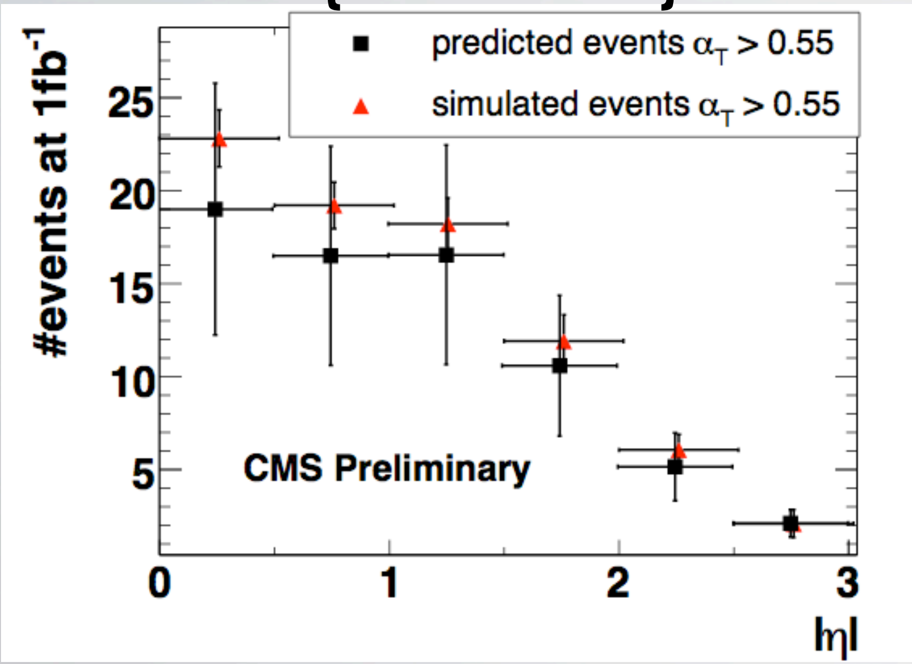
Verified that flat for all Bkgd contributions (see PAS SUS-08-005)

- R_a flat for background as function of $|\eta_{j1}|$
- α_T and $|\eta_{j1}|$ can be used for ABCD-matrix method

→ Measure $R\alpha_T$ in $2.5 < |\eta| < 3.0$ region.

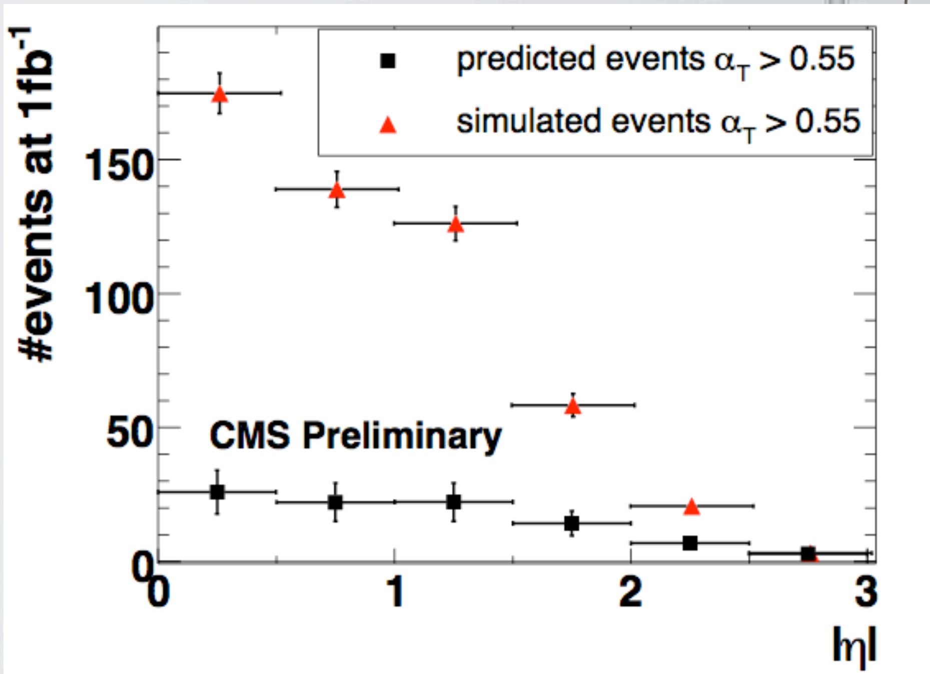
η Dependence of Matrix Method

without SUSY (closure test)



simulated: 77 ± 3 (8 @ 1fb^{-1})
predicted: 68 ±24 (42 @ 1fb^{-1})

with LM1 SUSY "contamination"



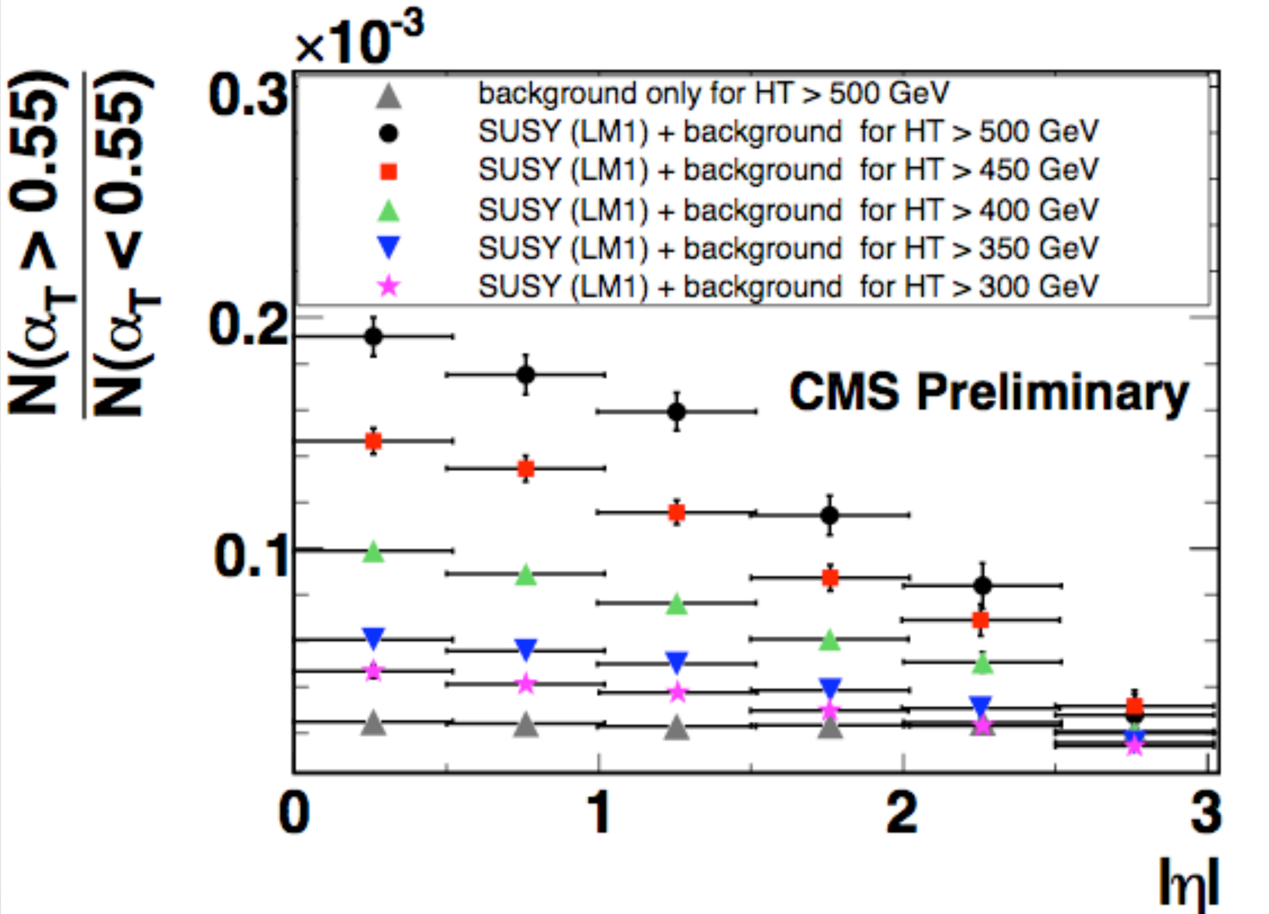
simulated: 517 ± 13 (22 @ 1 fb^{-1})
predicted: 91 ± 30 (51 @ 1 fb^{-1})

- Predicted BKGD agrees well with simulated BKGD
- SUSY LM1 leads to **significant** excess in signal region
- Method also verified with systematic variations

Test Background Estimation from Data

Variation of HT cut

Idea:
Increase background to check that $R\alpha_T$ is flat in $|\eta|_{j1}$ when signal sufficiently diluted



- Loosen HT cut to decrease signal to background ratio.

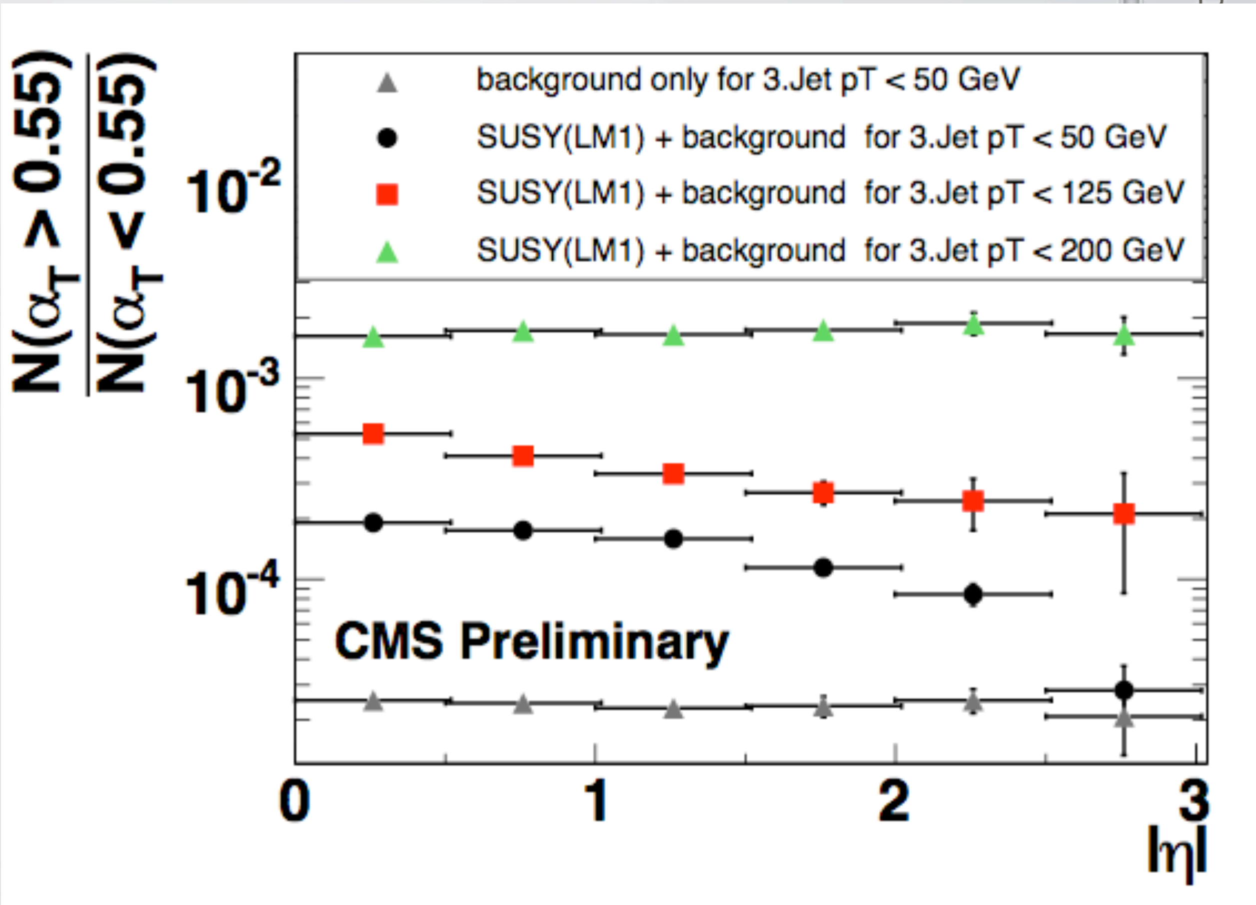
- As HT loosened $|\eta|_{j1}$ dependence gets flatter

=> Clear indication that at HT > 500 GeV signal is present

Background estimation from data (II)

Variation of 3rd jet p_T

Idea:
dilute signal by increasing background contribution
Loosen cut on 3rd jet p_T to create missing E_T
=> tail in $\alpha(\alpha_T)$



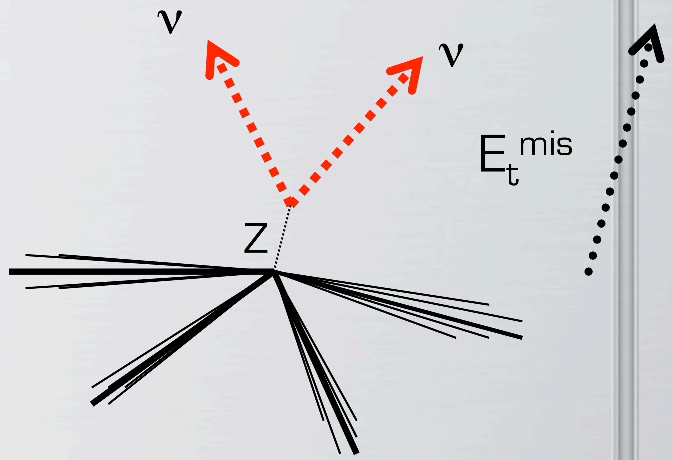
Test if $R\alpha_T$ is stable
Slope should be observed when signal contribution becomes sizable

⇒ Slope is observed for hard enough jet veto

Data Driven Background Estimation via Control samples

An illustrative example: $Z \rightarrow \nu\nu$+jets

Irreducible background for Jets+E_t^{mis} search



Data-driven strategy:

- define control samples and understand their strength and weaknesses:

Data Driven Background Estimations

An illustrative example: $Z \rightarrow \nu\nu$+jets

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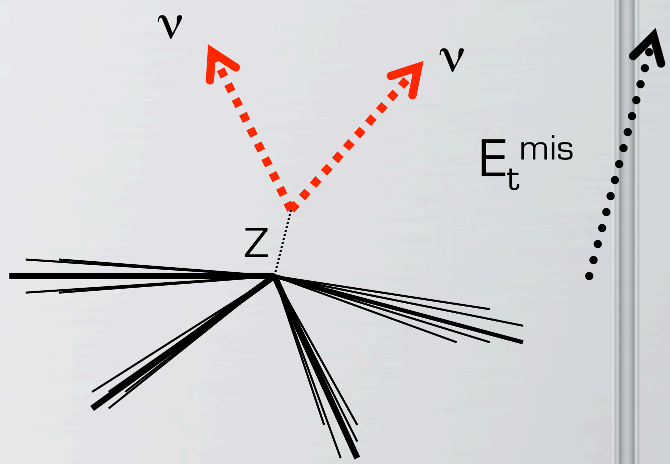

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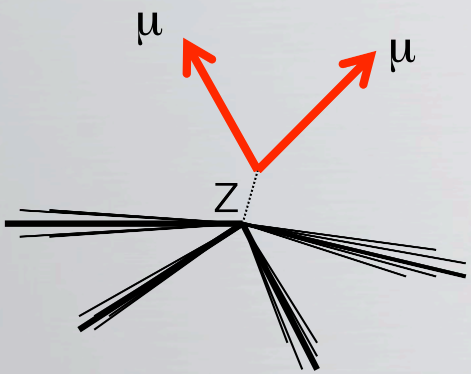

$Z \rightarrow \mu\mu$+jets

Strength:
- very clean, easy to select

Weakness:
- low statistic: factor 6 suppressed w.r.t. to $Z \rightarrow \nu\nu$

Data Driven Background Estimations

An illustrative example: $Z \to \nu\nu$+jets

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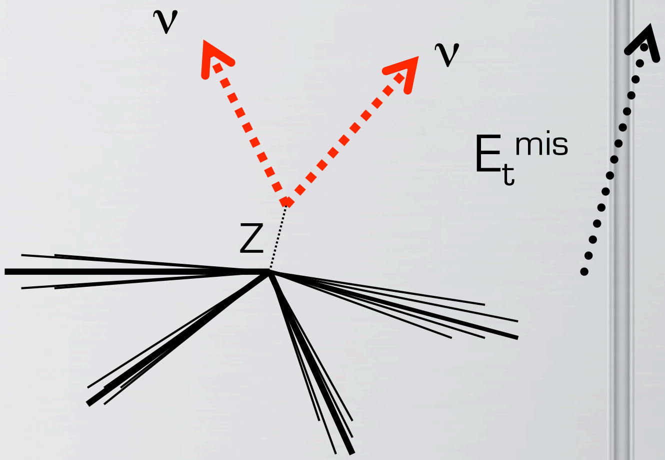

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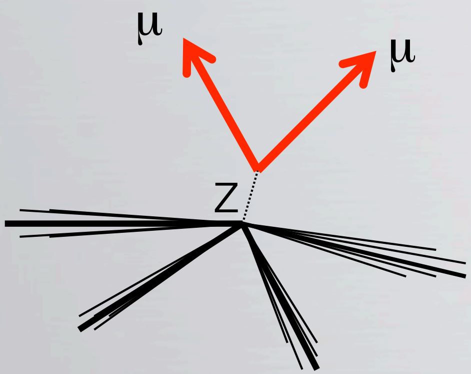

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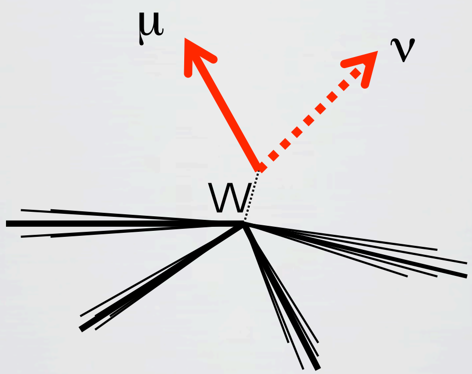


$W \to \mu\nu$+jets

Strength:
- larger statistic

Weakness:
- not so clean, SM and signal contamination

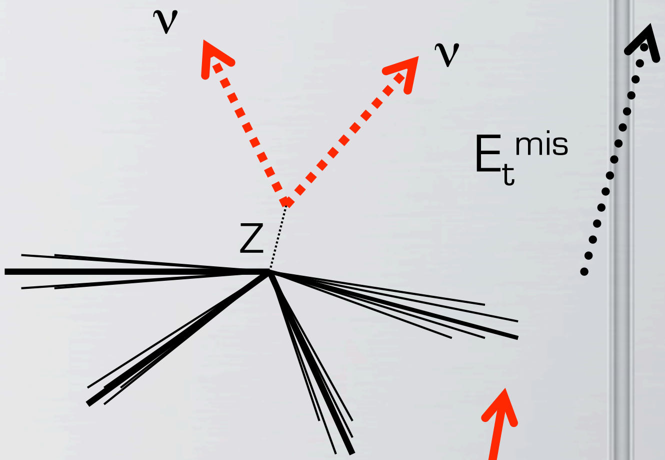
Data Driven Background Estimations

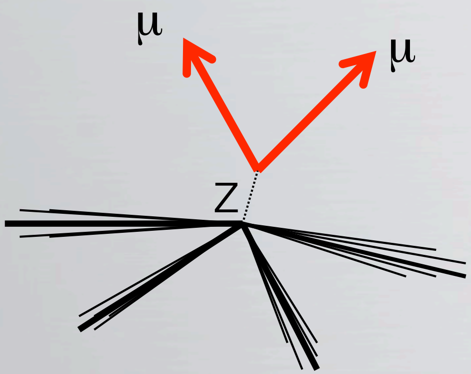
An illustrative example: $Z \rightarrow \nu\nu$+jets

Irreducible background for Jets+E_t^{mis} search

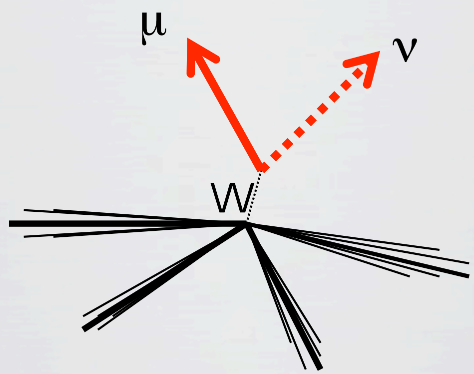
Data driven strategy:

• define control samples and understand their strength and weaknesses

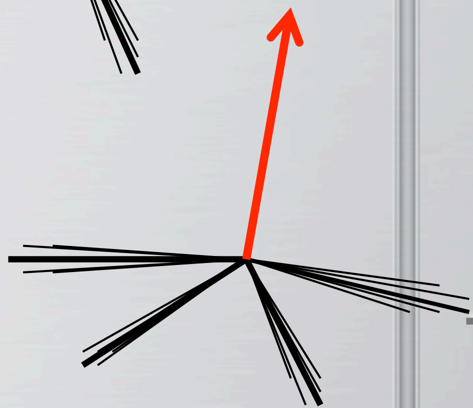




$Z \rightarrow ll$+jets



$W \rightarrow l\nu$+jets



γ+jets

Strength:
• very clean, easy to select

Weakness:
• low statistic: factor 6 suppressed wrt. to $Z \rightarrow \nu\nu$

Strength:
• larger statistic

Weakness:
• not so clean, SM and signal contamination

Strength:
• large stat, clean for high E_γ

Weakness:
• not clean for E_γ<100 GeV,
• possible theo. issues for normalization (u. investigation)

γ+jets: Estimate Z to invisible

γ+jets selection & properties:

- E_γ>150 GeV

→ clean sample: S/B>20

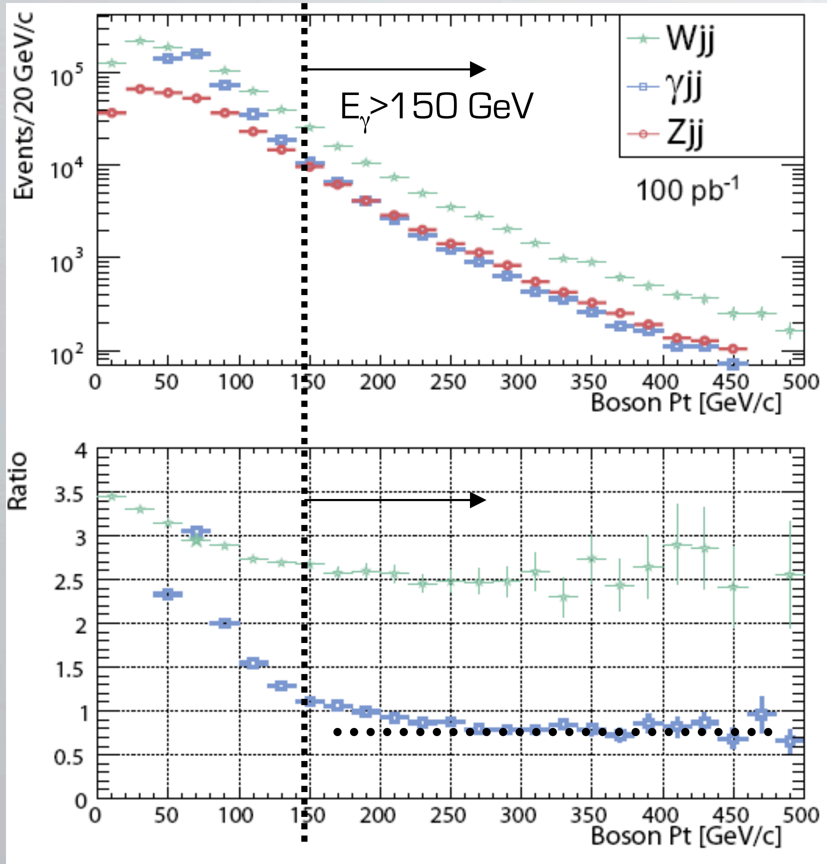
→ ratio σ(Z+jet)/σ(γ+jet) constant

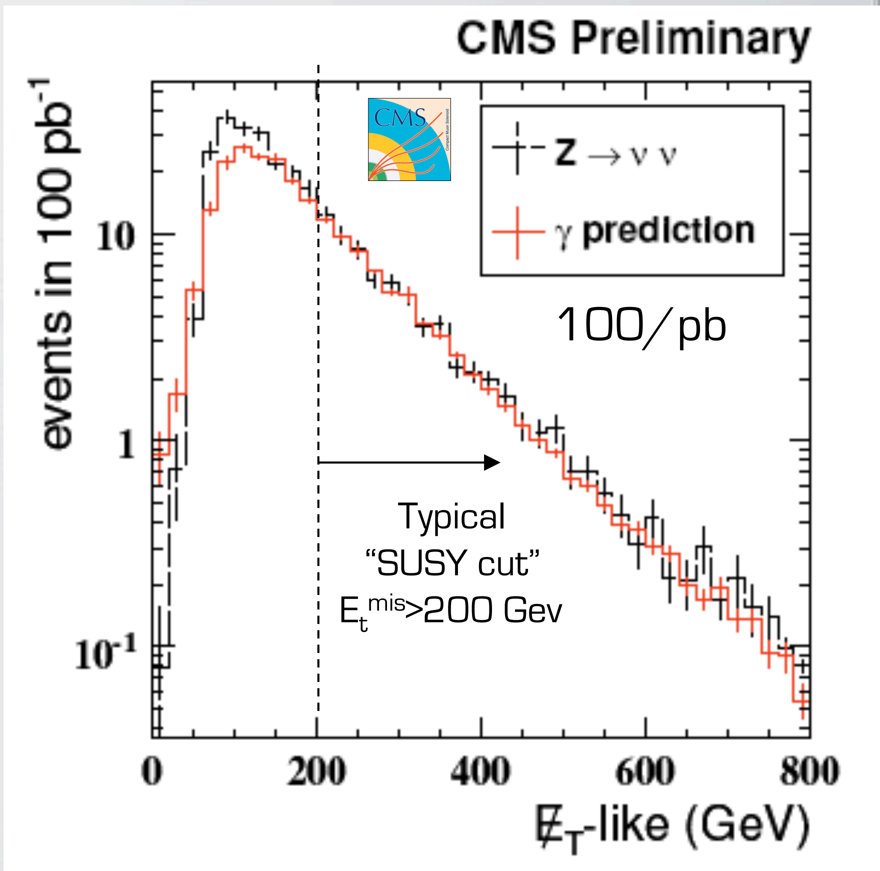
γ+jets: Strategy:

- remove γ from the event:

  → γ becomes E_T^{mis}

- take σ(Z+jet)/σ(γ+jet) for E_γ>200 GeV from MC or measure in data





Missing Energy in Multi-Jet Events

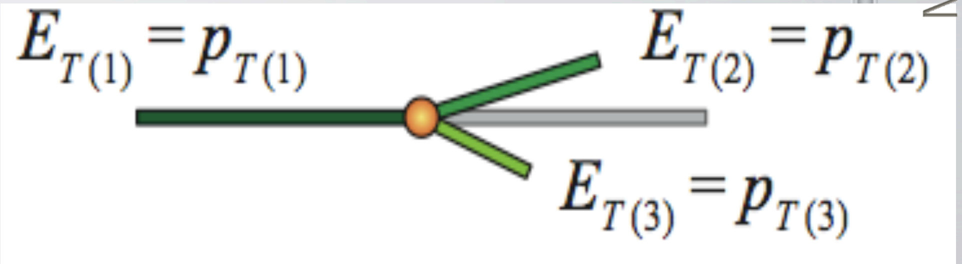
From di-jet to n-jet events

Extending the search to n-jets

Extend the search to signal events like:

$$pp \rightarrow \tilde{g}\tilde{q} \rightarrow \tilde{q}q\tilde{N}q \rightarrow q\tilde{N}q\tilde{N}q$$

The approach we have taken:
combine n-jets into a pseudo-dijet system
and apply $\Delta\Phi$, α_T, etc.



Conserved QCD-like three jet event

<u>Questions:</u>

- How should one choose **which jets to combine**?

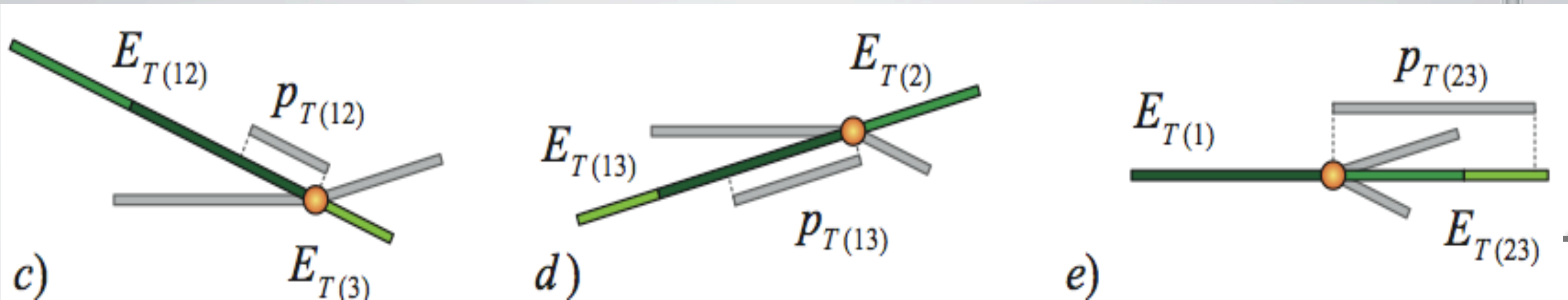
  i.e. for n=4, {X,XXX} or {XX,XX}? {1,234} or {14,23}?

- How should we **merge the jets** into a pseudo-jet

  (bearing in mind that QCD is still back-to-back and balanced)

Extending the search to n-jets

- Choose following approach:
- Maximise p_T balance of pseudo-jets (minimise ΔE_T)
  - trying to recreate original di-jet
- Only consider transverse components of jets



$$E_{t(kl)} = E_{t(k)} + E_{t(l)};\ p_{x(kl)} = p_{x(k)} + p_{x(l)};\ p_{y(kl)} = p_{y(k)} + p_{y(l)}$$

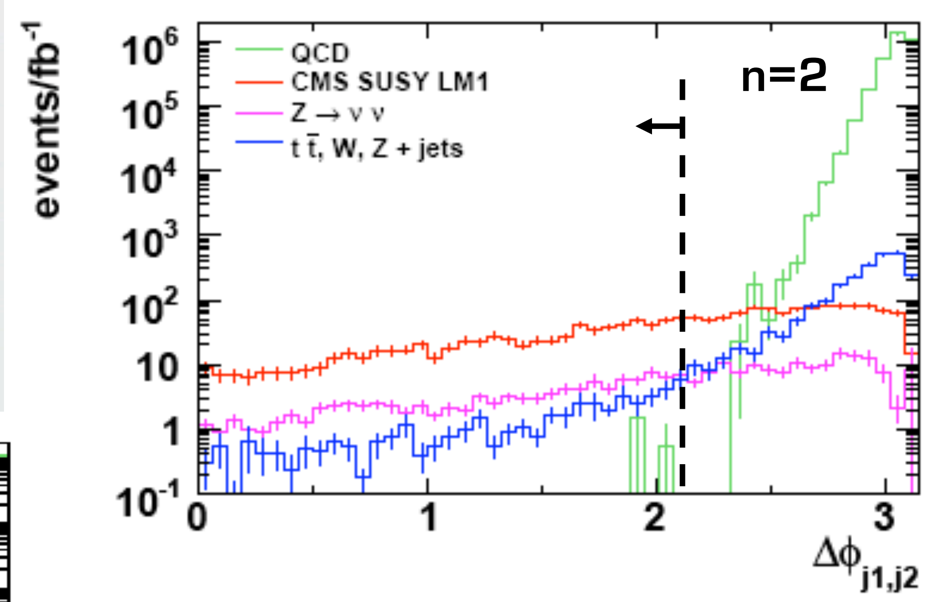
Selection method purely based on E_T measurements, and not **angular information** or **event shape**

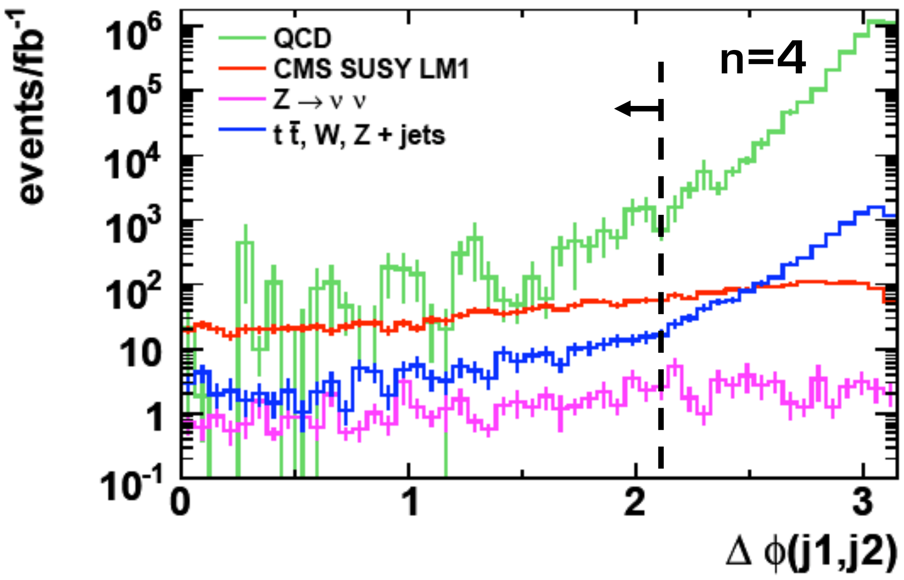
Alternative methods possible – to be studied

Robustness: Acoplanarity with n-jets

Analysis Note: CMS AN-08/114

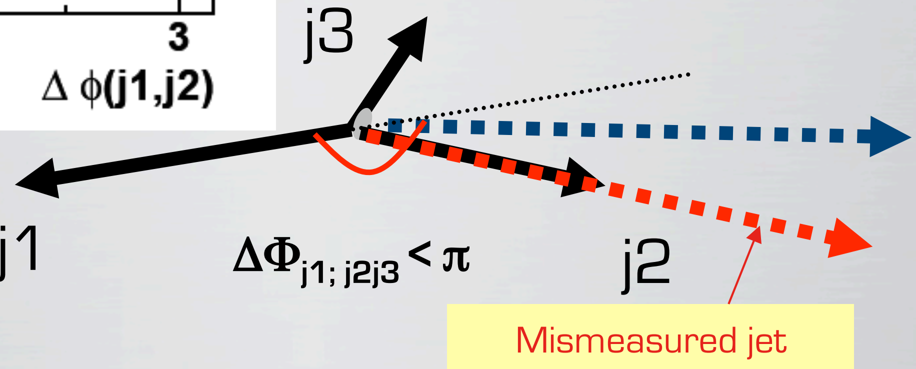
$\Delta\phi$ between jets works for di-jets
small influence of energy
mis-measurements





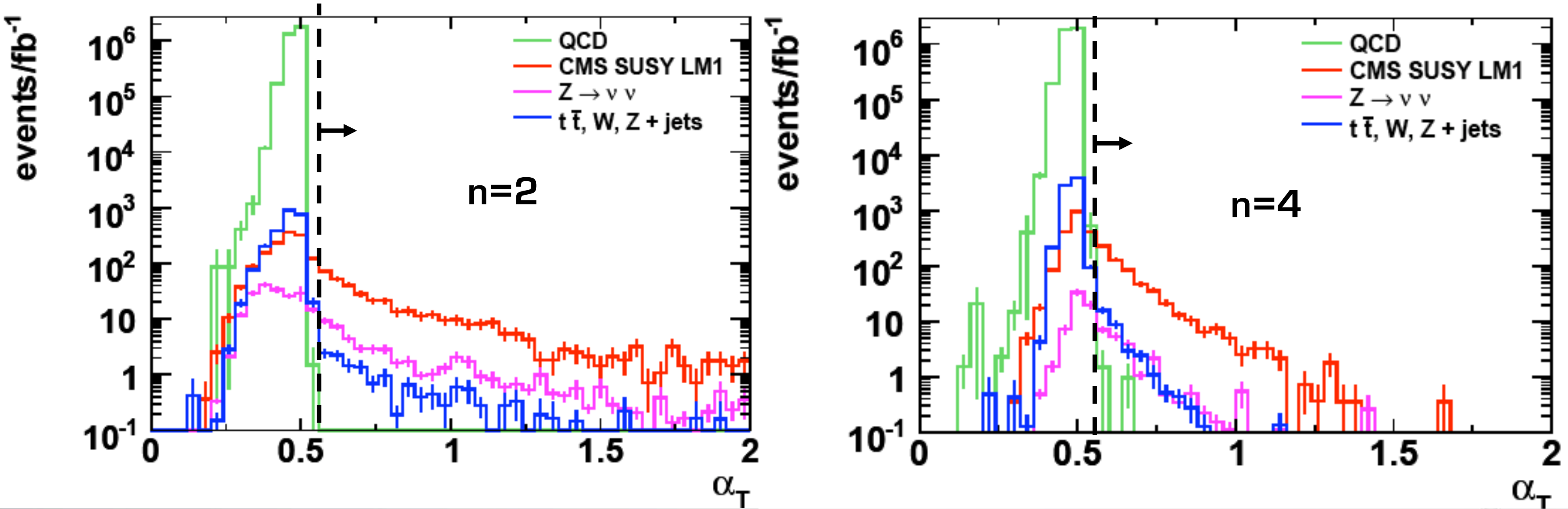
Works not so well for pseudo-jets
mis-measurements, missed jets, etc.

Will lead to non-back-to-back pseudo-jet for n > 2



Robustness: α_T with n-jets

α_T gives promising results. Even for n > 2 a reasonable edge at α_T=0.5 is maintained, but as n increases the signal (and real MET) slopes get steeper.



α_T appears to provides a **robust observable** for rejecting QCD events while maintaining a **good signal yield**.

Important to note that ΔH_T method places no contraint on the event shape – purely clusters jets on E_T

α_T with n-jets: results

Important note:

No optimizations for the N-jet topologies. Apply (blindly) the di-jet cuts for all topologies.

Certainly (much) room for improvement.

These results are meant for illustrative purpose only but an S/B ~7 is very promising.

CMS preliminary

1 fb^{-1}

n	Cut	QCD	$t\bar{t}$, W, Z	$Z \rightarrow \nu\bar{\nu}$	LM1
2	H_T	3.3×10^6	245	2414	1770
	α_T	0	58.8	20.4	440.0
	$\Delta\phi$	0	57.7	19.2	432.7
3	H_T	6.8×10^6	213	5669	3071
	α_T	24.0	64.4	49.9	852.5
	$\Delta\phi$	24.0	63.9	45.9	837.7
4	H_T	4.0×10^6	86.0	7078	2510
	α_T	2.5	24.5	41.8	676.5
	$\Delta\phi$	2.5	24.0	41.4	668.2
5	H_T	1.0×10^6	19.2	4710	1350
	α_T	21.5	5.8	16.4	295.3
	$\Delta\phi$	21.5	5.8	16.1	290.3
6	H_T	1.8×10^5	2.6	2105	552.5
	α_T	0.4	0.8	8.4	103.1
	$\Delta\phi$	0.4	0.8	8.2	101.0
Total	α_T	48.4	154.3	136.9	2367.4
	$\Delta\phi$	48.4	152.2	130.8	2329.9

After preselection

After cut in α_T

After additional cut in $\Delta\Phi$ - no gain as expected!

$S/B \approx 7$

Further robustness studies: α_T

Compare the relative S/B performance of α_T analysis to the more traditional "TDR style jet+MET" analysis.

Apply additional smearing to jet energy and momenta to probe robustness

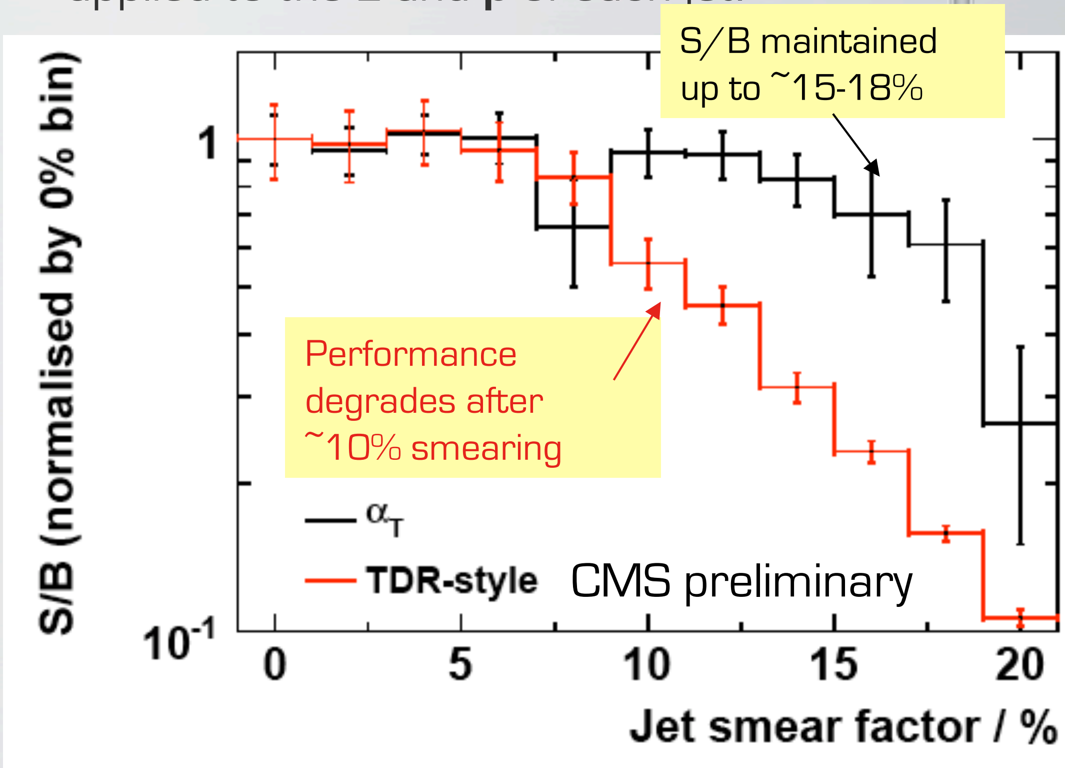
---

"**TDR style**" analysis cuts inspired by MET +jet SUSY search:

- `HLT2JET` trigger;
- 10 GeV lepton veto;
- 3-6 "good" jets (inclusive);
- H_T > 500 GeV, MH_T > 250 GeV
- $\Delta\Phi(Mh_T, ji)$>0.3, i=1,2,3
- R1, R2 > 0.5

Jet smearing:

Gaussian smearing (σ is the "smear factor") applied to the E and **p** of each jet.



Samples used: S = LM1, B = QCD, Z ($\rightarrow\nu\nu$) + jets, and tt, W, Z + jets.

Generalising the α_T approach

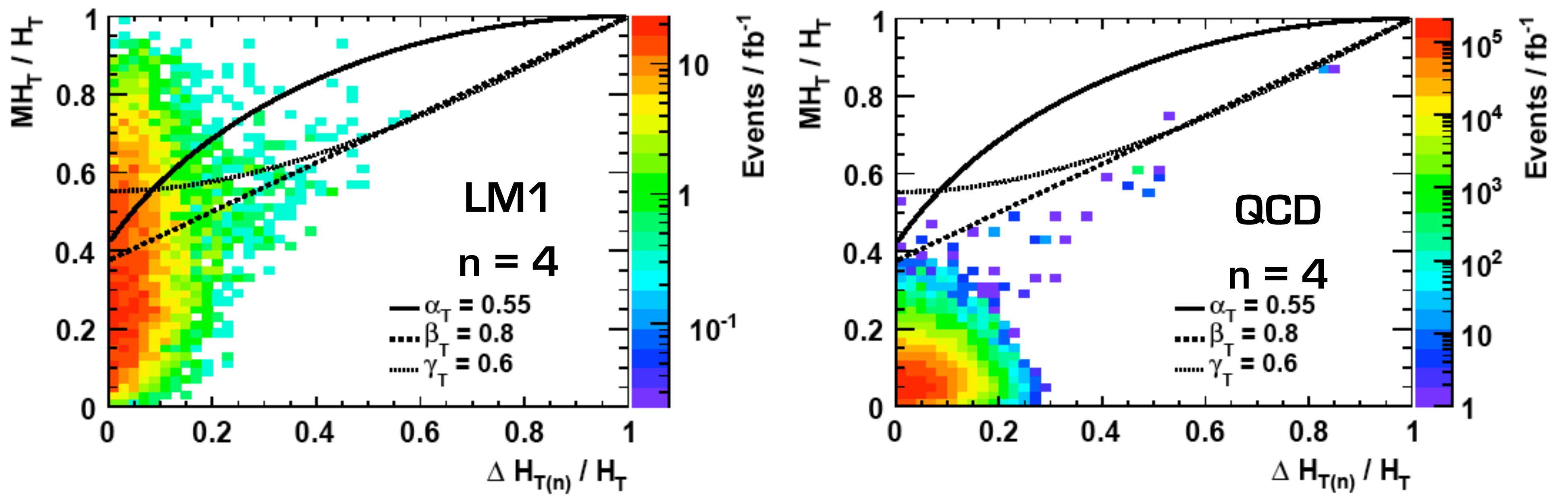
With better understanding of α_T, we can design alternative "self-correcting" observables by tuning the form of the numerator and denominator to adjust the rate of correction:

$\Delta HT = E_T^{j1} - E_T^{j2}$

$$\alpha_T = \frac{\frac{1}{2}\left(H_T - \Delta H_{T(n)}\right)}{\sqrt{H_T^2 - |\not{H}_T|^2}}$$

$$\beta_T = \frac{\frac{1}{2}\left(H_T - \Delta H_{T(n)}\right)}{H_T - |\not{H}_T|}$$

$$\gamma_T = \frac{\frac{1}{2}\sqrt{H_T^2 - \Delta H_{T(n)}^2}}{\sqrt{H_T^2 - |\not{H}_T|^2}}$$



Study effect of cuts in ΔHT/HT vs. MHT/HT plane.

Generalising the α_T approach

$$\alpha_T = \frac{\frac{1}{2}\left(H_T - \Delta H_{T(n)}\right)}{\sqrt{H_T^2 - |\not{H}_T|^2}}$$

$$\beta_T = \frac{\frac{1}{2}\left(H_T - \Delta H_{T(n)}\right)}{H_T - |\not{H}_T|}$$

$$\gamma_T = \frac{\frac{1}{2}\sqrt{H_T^2 - \Delta H_{T(n)}^2}}{\sqrt{H_T^2 - |\not{H}_T|^2}}$$

		$\beta_T > 0.8$				$\gamma_T > 0.6$			
n	Cut	QCD	$Z \to \nu\bar{\nu}$	$t\bar{t}$, W, Z	LM1	QCD	$Z \to \nu\bar{\nu}$	$t\bar{t}$, W, Z	LM1
2	β_T/γ_T	2.1	101.8	52.1	754.1	1.5	80.8	30.4	600.4
	$\Delta\phi$	2.1	92.4	37.8	672.6	1.5	80.8	30.4	600.4
3	β_T/γ_T	29.0	105.4	122.3	1339.3	6.0	69.8	47.9	916.3
	$\Delta\phi$	27.5	88.4	82.4	1174.9	6.0	69.8	47.7	914.9
4	β_T/γ_T	13.7	44.2	91.4	1068.5	2.5	21.1	26.9	556.4
	$\Delta\phi$	7.7	37.0	76.6	940.5	1.0	21.1	26.9	555.0
5	β_T/γ_T	24.0	7.9	38.0	462.7	21.5	4.0	7.9	176.0
	$\Delta\phi$	22.0	7.5	28.9	408.6	21.0	4.0	7.9	176.0
6	β_T/γ_T	2.5	0.9	16.2	151.5	0.4	0.3	2.8	46.5
	$\Delta\phi$	2.5	0.9	13.6	138.1	0.4	0.3	2.8	46.5
Total	β_T/γ_T	71.3	260.2	320.0	3776.1	31.9	176.0	115.9	2295.6
	$\Delta\phi$	61.8	226.2	239.3	3334.7	29.9	176.0	115.7	2292.8

1 fb^{-1}: S/B = 5.8, S/√B = 148 S/B = 7.1, S/√B = 128

Clear signal very early on for favourable low mass SUSY points!

Dark Matter Search in Context of SUSY

Bounds from precision measurements: electroweak, flavour and cosmological data

Constrain parameter space of MSSM

- How can we best exploit the available experimental data to constrain New Physics models?
  - Combine as much experimental information as possible
  - Famous example:
    - Standard Model fit to electroweak precision data

- Extend it to include New Physics models
  - Here: Minimal SuperSymmetic Standard Model (MSSM)

- Necessary tools:
  - calculations for experimental observables in that model

  and

  - a common framework that interfaces between the different calculations and combines the obtained information

- Objectives/Outcome:
  - Fit model parameters in some MSSM scenarios
  - Explore sensitivity of different observables to parameter space

General Idea

- What observables can be used to constrain the model?
  - Low energy (precision) data
    - Flavour physics (many constraints from B physics)
    - Other low energy observables, e.g. g-2
  - High energy (precision) data
    - Precision electroweak observables, e.g. M_W, m_{top}, asymmetries
  - Cosmology and Astroparticle data
    - e.g. relic density
- How to exploit this information?
  - State of the art theoretical predictions (tools)
  - Development of a framework for combination of these tools
- Collaboration between experiment and theory

Buchmüller, Oliver (CERN) – Exp.
De Roeck, Albert (CERN & Uni. Antwerpen) – Exp.
Flächer, Henning (CERN) – Exp.
Isidori, Gino (INFN Frascati) – Theo.
Paradisi, Paride (Tech. Uni. München) – Theo.
Weiglein, Georg (Durham) – Theo.
Cavanaugh, Richard (Uni. of Florida) – Exp.
Ellis, John (CERN) – Theo.
Heinemeyer, Sven (Santander) – Theo.
Olive, Keith (Uni. of Minnesota) – Theo.
Ronga, Frédéric (CERN) – Exp.

See O. Buchmüller et al., PLB 657/1-3 pp.87-94

List of implemented Observables

Low energy observables

$R(b \to s\gamma)$	Isidori & Paradisi	micrOMEGAs
$R(B \to \tau\nu)$	Isidori & Paradisi	
$BR(K \to \mu \nu)$	Isidori & Paradisi	
$R(B \to X_s \ell\ell)$	Isidori & Paradisi	
$R(K \to \pi\nu\bar{\nu})$	Isidori & Paradisi	
$BR(B_s \to \ell\ell)$	Isidori & Paradisi	micrOMEGAs
$BR(B_d \to \ell\ell)$	Isidori & Paradisi	
$R(\Delta m_s)$	Isidori & Paradisi	
$R(\Delta m_s)/R(\Delta m_d)$	Isidori & Paradisi	
$R(\Delta m_K)$	Isidori & Paradisi	
$R(\Delta_0(K^*\gamma))$	SuperIso	
$\Delta(g-2)$	FeynHiggs	

Higgs sector observables

m_h^{light}	FeynHiggs	

Cosmology observables

Ωh^2	micrOMEGAs	DarkSUSY
σ_p^{SI}	DarkSUSY	

Electroweak observables

$\Delta\alpha^{(5)}_{\text{had}}(m_Z^2)$	SUSY-Pope
m_Z	SUSY-Pope
Γ_Z	SUSY-Pope
σ^0_{had}	SUSY-Pope
R_l	SUSY-Pope
$A_{\text{fb}}(\ell)$	SUSY-Pope
$A_\ell(P_\tau)$	SUSY-Pope
R_b	SUSY-Pope
R_c	SUSY-Pope
$A_{\text{fb}}(b)$	SUSY-Pope
$A_{\text{fb}}(c)$	SUSY-Pope
A_b	SUSY-Pope
A_c	SUSY-Pope
$A_\ell(\text{SLD})$	SUSY-Pope
$\sin^2\theta^\ell_w(Q_{\text{fb}})$	SUSY-Pope
m_W	SUSY-Pope
m_t	SUSY-Pope

Example Application

- Constraining the parameter space of the CMSSM
  - multi-parameter χ^2 "fit"

See O. Buchmüller et al. PLB 657/1-3 pp.87-94

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_j^M \frac{(f_{\mathrm{SM}_j}^{\mathrm{obs}} - f_{\mathrm{SM}_j}^{\mathrm{fit}})^2}{\sigma(f_{\mathrm{SM}_j})^2}$$

C_i: experimental constraint
P_i: predicted value for a given CMSSM parameter set

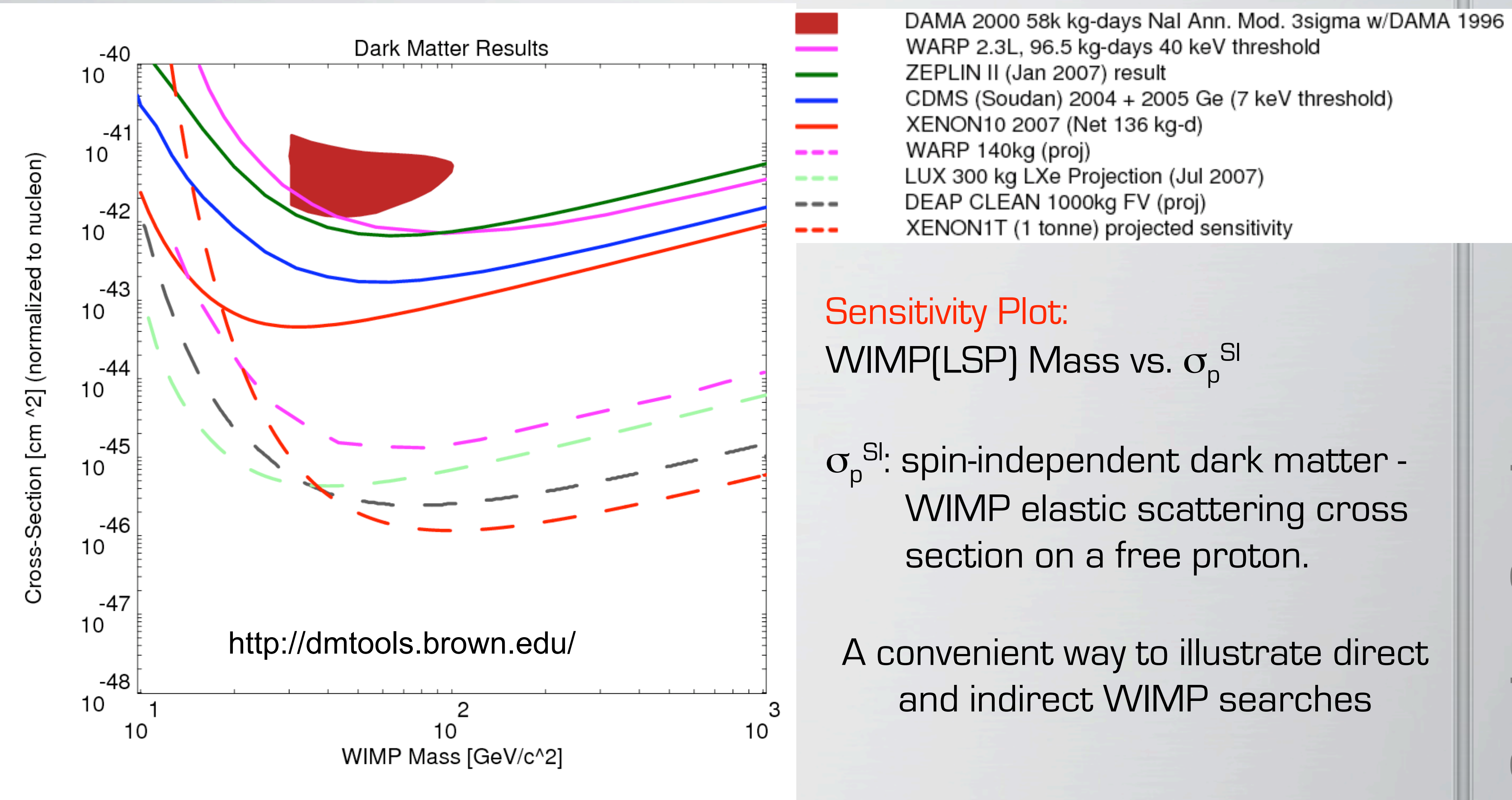
- fitting for all CMSSM (aka mSUGRA) parameters:
  - M_0 – common scalar mass (at GUT scale)
  - $M_{1/2}$ – common gaugino mass (at GUT scale)
  - A_0 – tri-linear mass parameter (at GUT scale)
  - $\tan\beta$ – ratio of Higgs vacuum expectation values
  - sign(μ) – sign of Higgs mixing parameter (fixed)
- including relevant SM uncertainties (m_{top}, m_Z, $\Delta\alpha_{\mathrm{had}}^{(5)}$)

  - Sampling of parameter space with Markov-Chain Monte Carlo type technique

Example: Constrain the Neutralino (WIMP) mass

Direct Dark Matter Searches

Direct detection of WIMP (LSP) Dark Matter



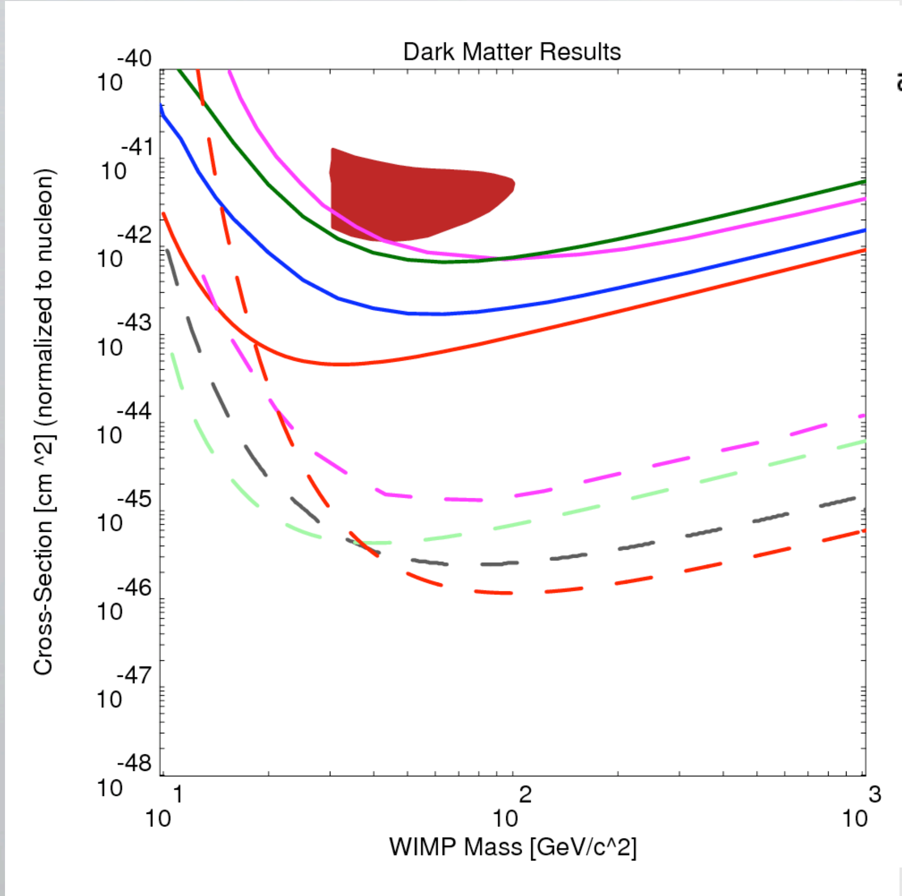
Sensitivity Plot:

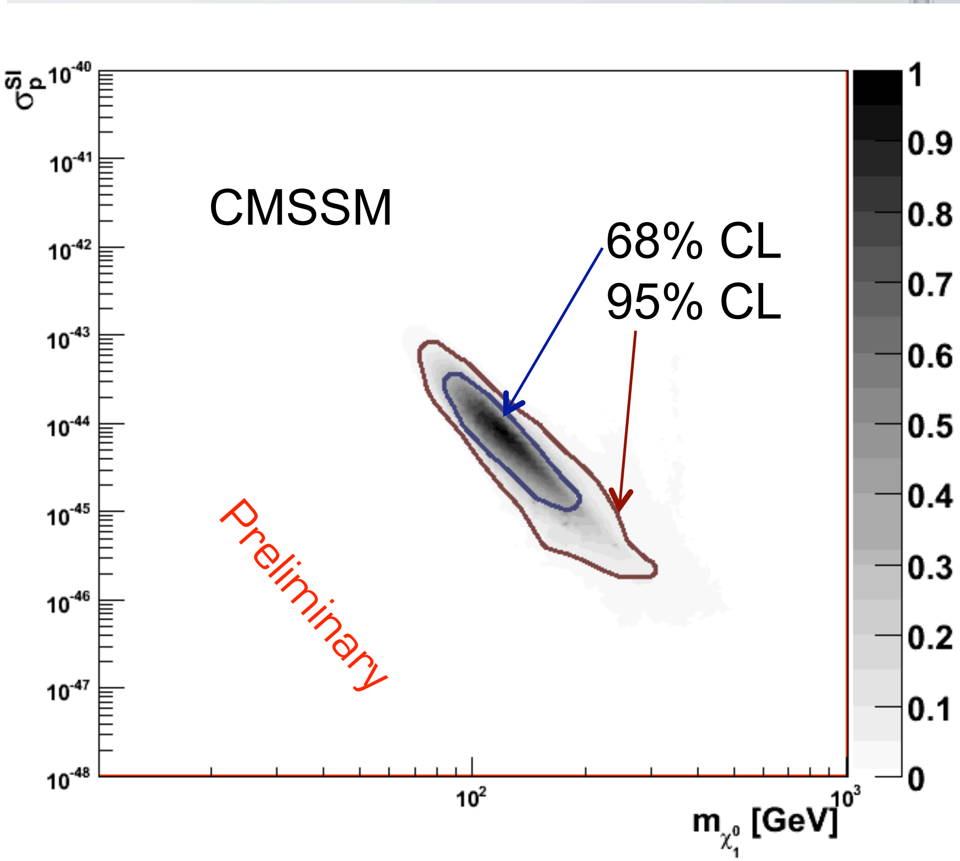
WIMP(LSP) Mass vs. σ_p^{SI}

σ_p^{SI}: spin-independent dark matter - WIMP elastic scattering cross section on a free proton.

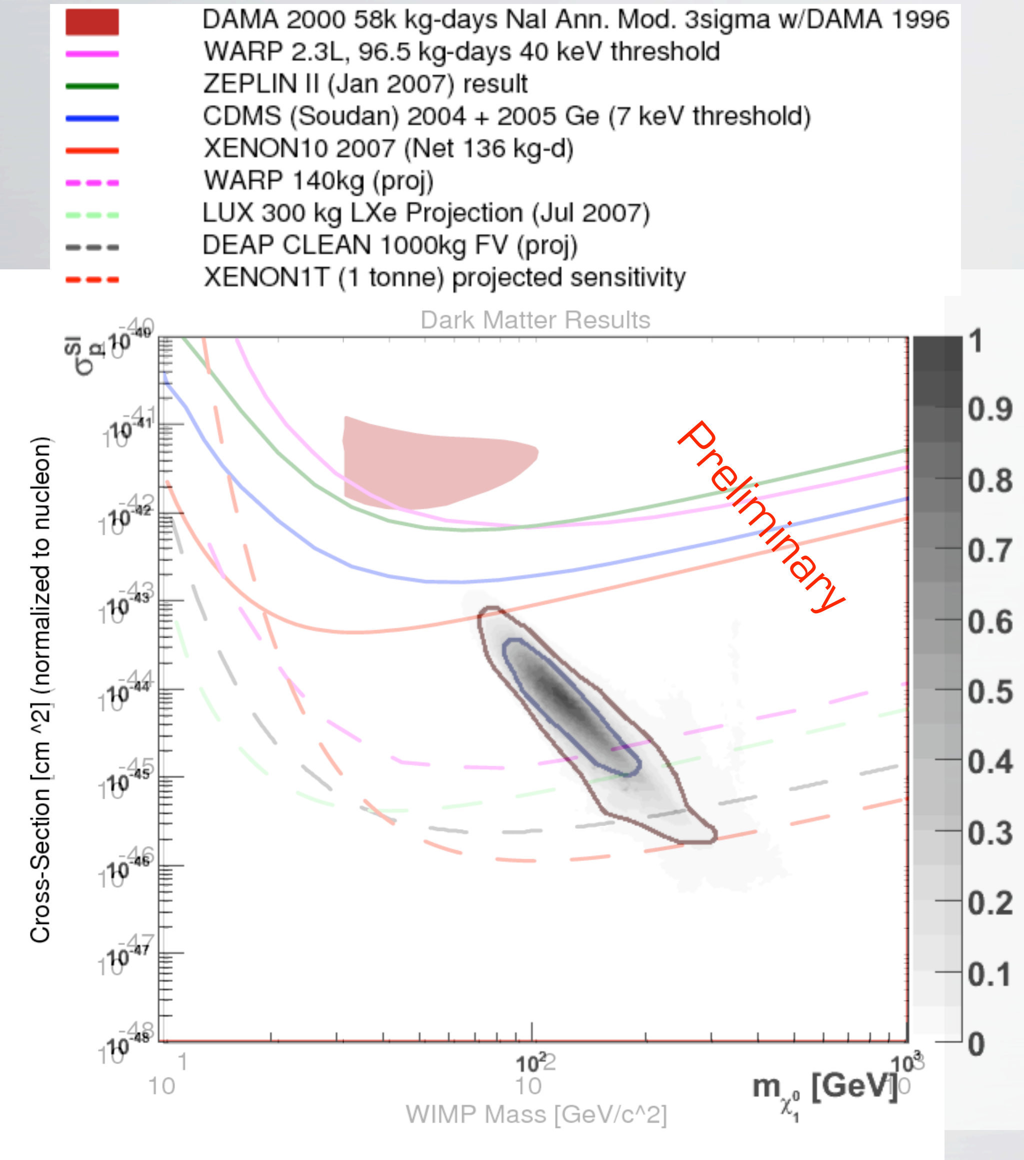
A convenient way to illustrate direct and indirect WIMP searches

Dark Matter -WIMP(LSP) contours





WIMP (LSP) sensitivity



Sensitivity will further increase once auxiliary measurement are made, e.g. lepton edges, m_{Higgs}

Example how combination of direct and indirect measurements can provide information about validity of specific new physics models

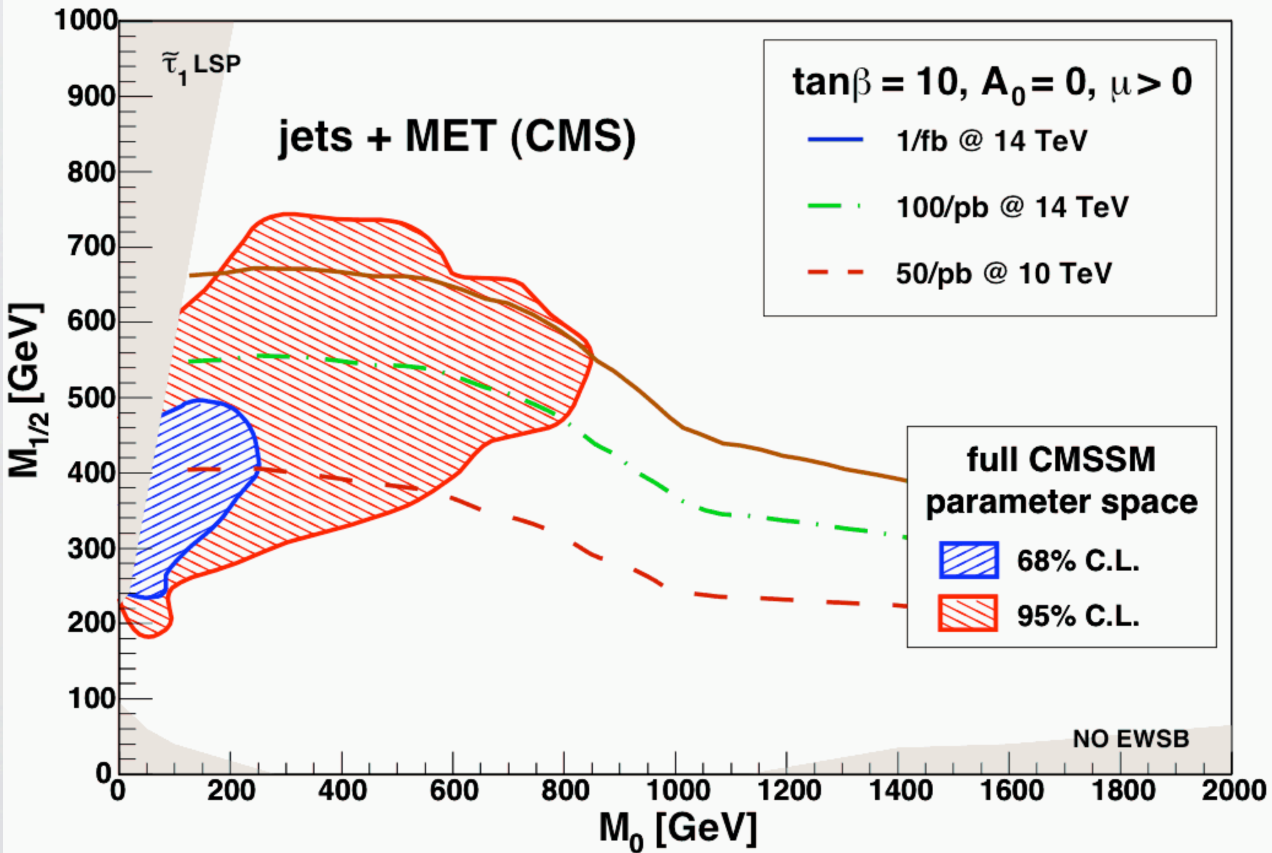
Could we expect to find CMSSM at LHC?

JHEP 0809:117,2008

O.Buchmueller, R.Cavanaugh, A.De Roeck, J.R.Ellis, **H.F.**, S.Heinemeyer, G.Isidori, K.A.Olive, P.Paradisi, F.J.Ronga, G.Weiglein

Simultaneous fit of CMSSM parameters m_0, $m_{1/2}$, A_0, $\tan\beta$ (μ>0) to more than 30 collider and cosmology data (e.g. M_W, M_{top}, g-2, BR ($B \to X\gamma$), relic density)

"LHC Weather Forecast"



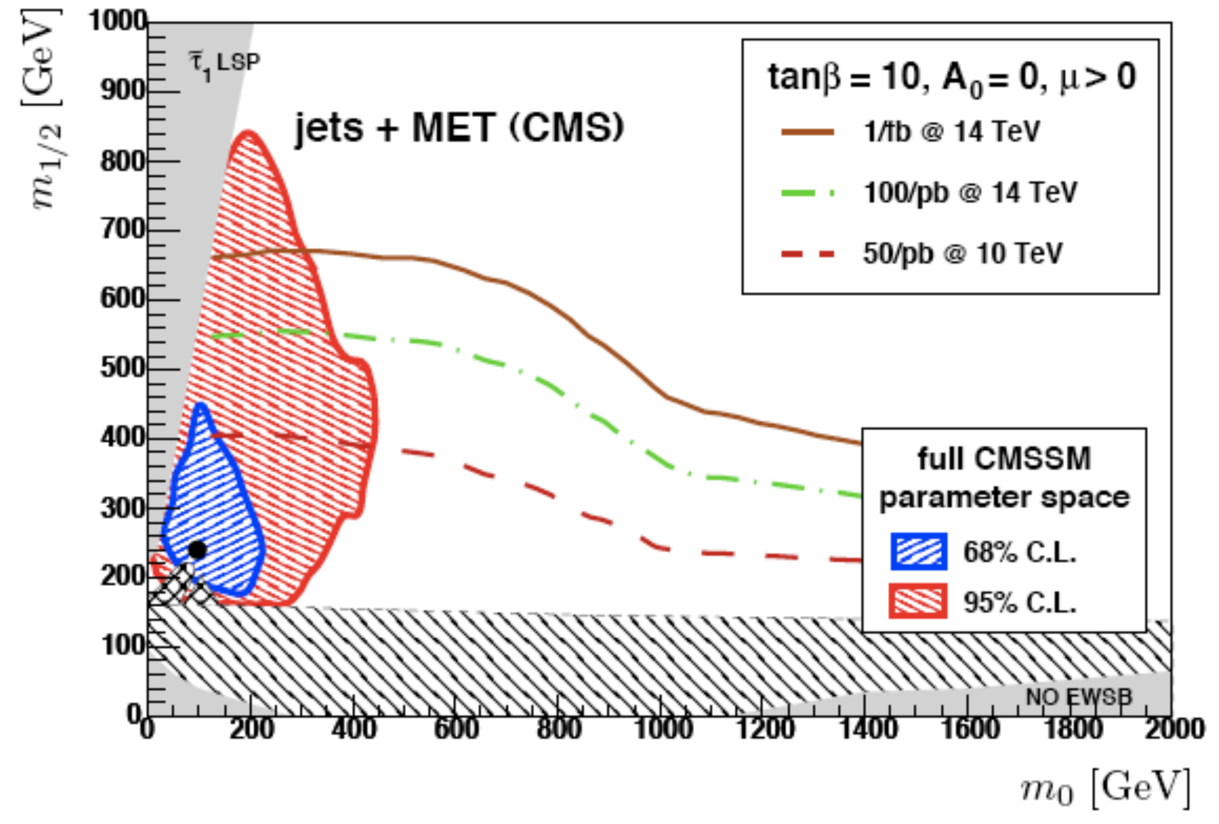
"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"

What about beyond CMSSM? – NUHM1

JHEP 0809:117,2008

O.Buchmueller, R.Cavanaugh, A.De Roeck, J.R.Ellis, **H.F.**, S.Heinemeyer, G.Isidori, K.A.Olive, P.Paradisi, F.J.Ronga, G.Weiglein

"LHC Weather Forecast"



Non Universal Higgs Model1:
- one extra free parameter

scalar contributions to Higgs masses at GUT scale allowed to differ from those to squark and slepton masses

Simultaneous fit of NUHM1 parameters m_0, $m_{1/2}$, A_0, tanβ, m_H^2 and μ to more than 30 collider and cosmology data (e.g. M_W, M_{top}, g-2, BR(B→Xγ), relic density)

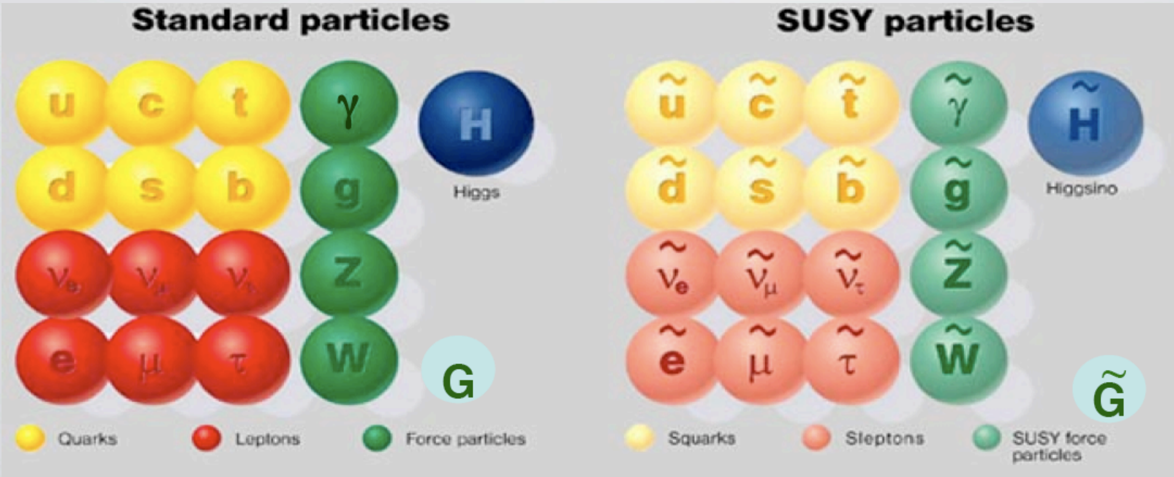
NUHM1 fit also favours low-mass SUSY

Conclusions

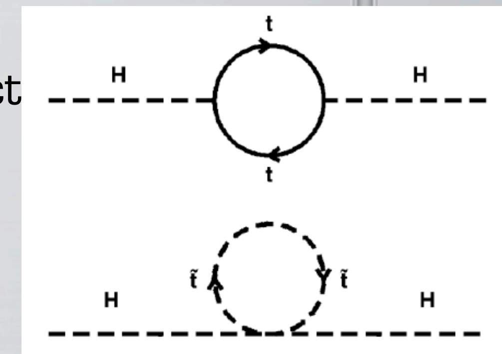
- **Mounting evidence for existence of Dark Matter from Cosmology**
- **LHC offers unique opportunity to search for Dark Matter candidate at a collider**
  - many new physics models provide viable WIMP candidates
    - e.g., SUSY, Extra Dimensions , Little Higgs
- **Missing Energy signature hard to control experimentally**
  - need robust measurement techniques based on kinematics and event topology
  - very promising studies with di-jet and multi-jet events using e.g. α_T
  - favourable models could be seen with ~100pb^{-1} of understood data
- **Development of Data-driven backgrounds determinations is underway**
  - Subtraction of all backgrounds using matrix method, Data control sample identified
- **Current EW, flavour and cosmology data allow to constrain simple SUSY models**
  - preferred parameter regions could be discovered very early!
- **Eagerly looking forward to collision data at the end of this year**
  - Exciting times are ahead!

BACKUP

Brief intro to SUSY



- SUSY partner for every SM particle (with ½ unit of spin different)
  - spin 0 Sfermions (squark, sleptons)
  - spin ½ Gauginos (chargino, neutralino)
- SUSY mass scale expected to be ~1TeV in order to:
  - Solve hierarchy problem (stabilize Higgs mass to radiative correct
  - Allow unification of strong and electroweak forces
  - Provide sensible dark matter candidate (R-parity)
  - Naturalises scalar (Higgs) sector of SM
- Downside of SUSY
  - Large parts of parameter space ruled out already
  - Many parameters



SUSY models

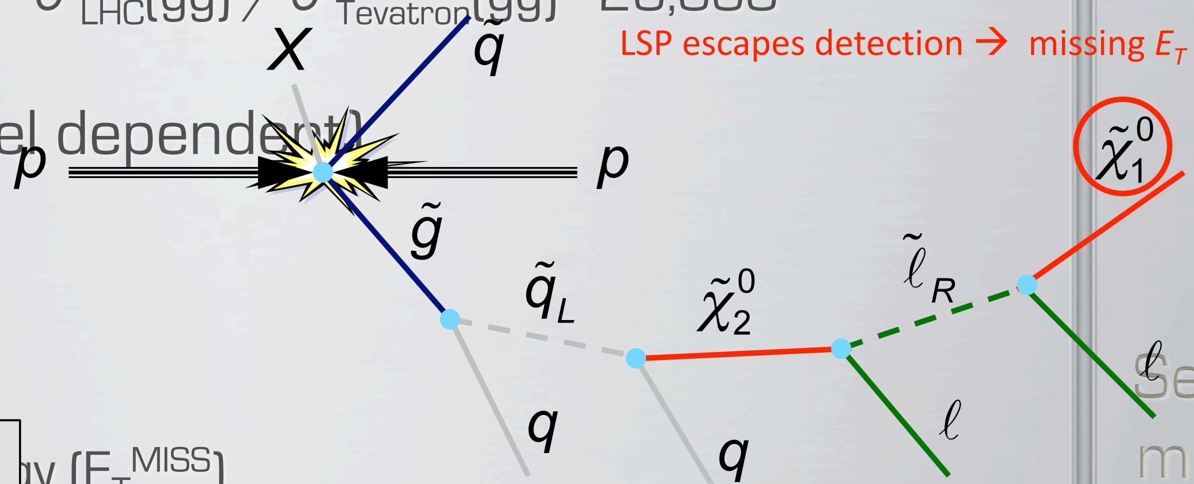
- Different models with different SUSY breaking mechanisms via interaction with hidden sectors
- Many models available, leading to very different phenomena
  - CMSSM / mSUGRA
    - SUSY breaking by gravity mediation in hidden sector
    - Model defined by 5 parameters at the GUT scale
    - Neutralino LSP
  - GMSB
    - SUSY breaking by gauge mediation in hidden sector
    - Can have long lived NLSP
    - Graviton LSP
  - Other
    - AMSB, Split SUSY (heavy sfermions), ...
- R-Parity conservation
  - Avoid proton decay
  - Sparticles produced in pairs
  - Lightest Supersymmetric Particle (LSP) undetected
    - Missing energy signature
- I will concentrate on R-Parity conserving models in this talk

mSUGRA parameters:

m_0 – common mass of squarks/sleptons
$m_{1/2}$ – common mass of Gauginos
A_0 – common trilinear coupling
tan β – ratio of Higgs expectation values
sign(μ) - value set by EWSB

SUSY @ the LHC

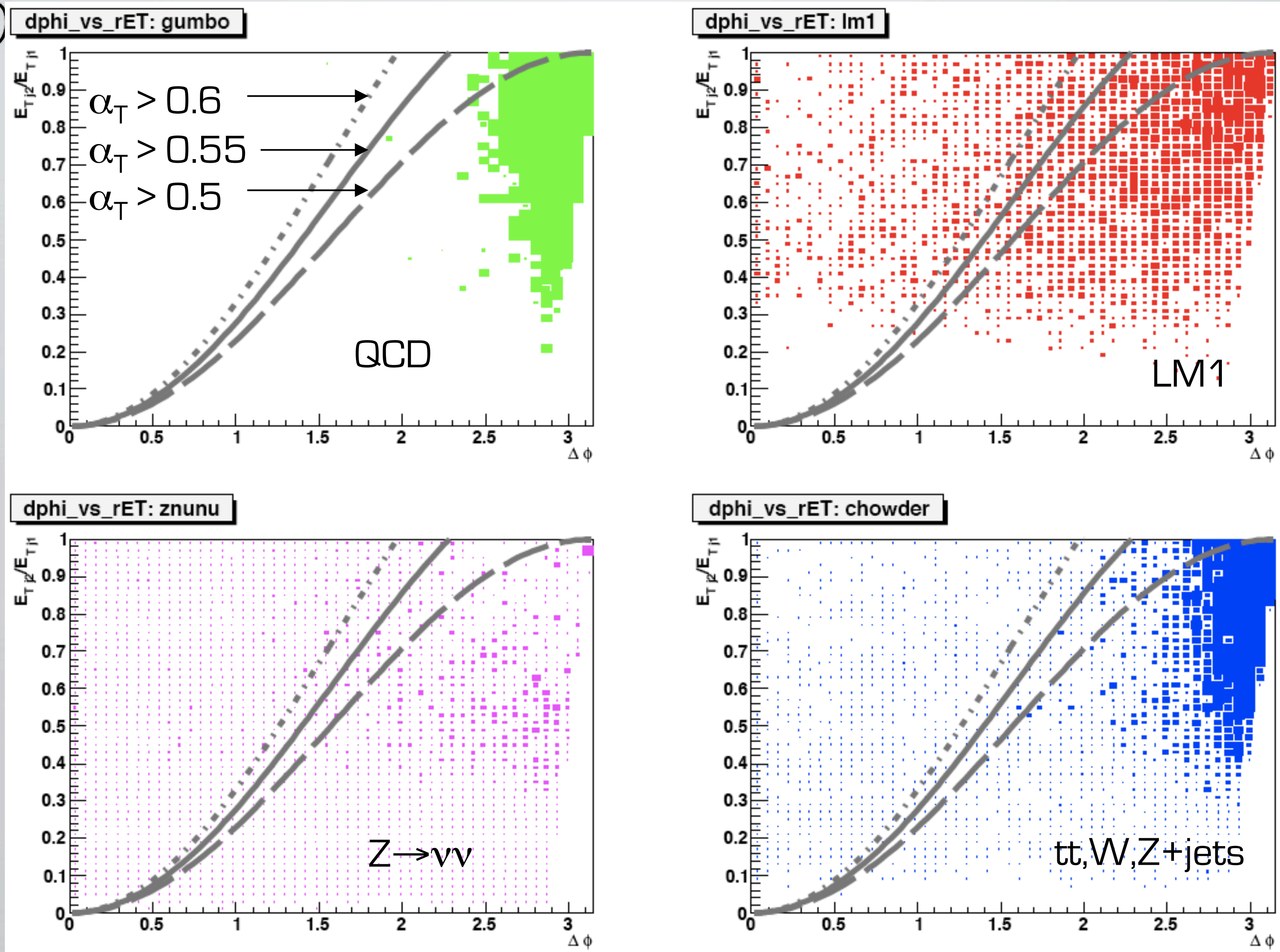
- SUSY production cross sections fairly independent of SUSY breaking model
  - Mostly driven by SUSY particle masses
  - For ~1 TeV SUSY, σ ~O(10) pb, ~ O(0.01) Events/s (for L=10^{34} $cm^{-2}s^{-1}$)
- Production cross section at LHC >> at Tevatron
  - eg. For M_{gluino}=400 GeV, $\sigma_{LHC}(gg) / \sigma_{Tevatron}(gg)$ ~20,000
- SUSY signatures (model dependent)
  - Cascade decays
  - High P_T Jets
  - Isolated Lepton(s)
  - gy (E_T^{MISS})



"Typical" SUSY decay chain at the LHC

Look at transverse missing energy (and not overall missing energy) because hard scattering reaction usually has longitudinal boost

Relation of α_T to E_{Tj2}/E_{Tj1} and $\Delta\varphi$

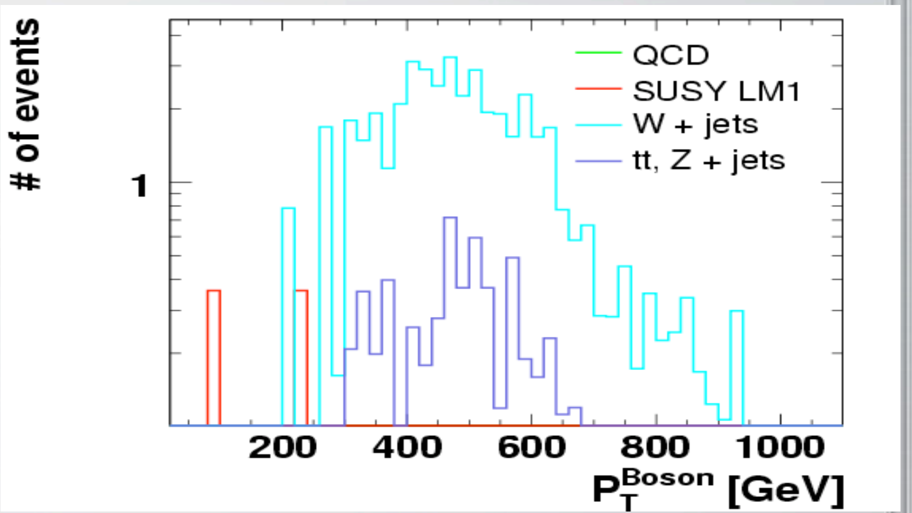


Data-driven $Z \rightarrow \nu\nu$ Background Estimation

$Z \rightarrow \nu\nu$ background estimation from W

Data driven estimations for Z to invisible have been developed for 3 jet SUSY searches (CMS-AN 36/2008).

Select W's by inverting muon veto (selecting an isolated muon), leaving all other cuts unchanged

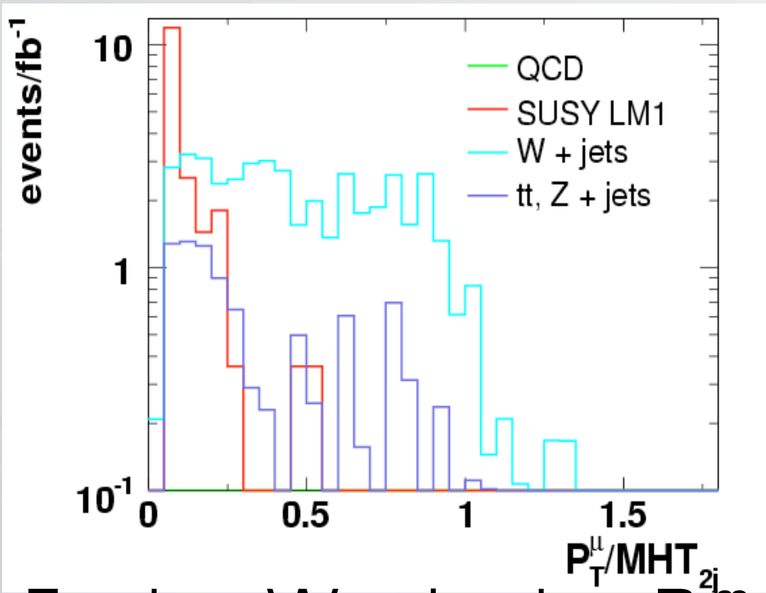


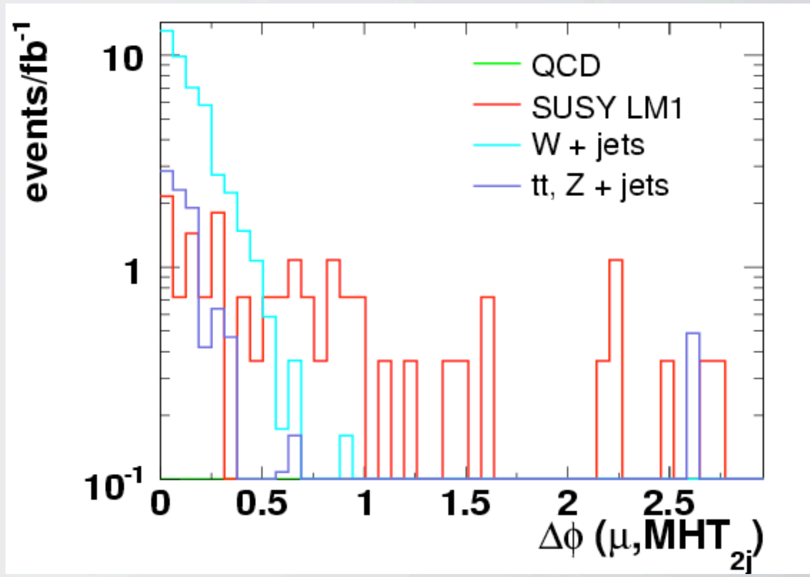
Event selection leads to bosons of hight P_T.

=> Muons correlated to MHT

=> Can be used for clean selection.

Data-driven Z→νν Background Estimation





Further W selection: P_t^{m} / MHT_{2j} > 25% and Df < 0.75.

Leads to 37 W candidates with ~90% purity (tt background).

- W_{reco}/W_{true} from MC -> acceptance*efficiency (later: from data)
- Z_{true}/W_{true} from MC -> later from tuned MC or data
- V-A: $Z \to \nu\nu = 6 * Z \to \mu\mu$
- $Z \to \nu\nu = W_{reco} * W_{true}/W_{reco} * Z_{true}/W_{true} * 6$

→ 61.6 ± 10.1 expected, well in agreement (c.f. 57 events from $Z \to \nu\nu$ MC)
→ Further systematic uncertainties of acceptance, efficiency and MC ratio.

Data-driven Z→nn Background Estimation

Further Studies and Ideas.

- 3.6 Z → mm candidates can be selected in the signal region.
→ Can be used to directly estimate Z to invisible

- Relaxed HT cut >300 GeV leads to 20 Z → mm Candidates
  and can be used to measure ratio W/Z
  186 clean (90% purity) W candidates.
→ Can be used to measure Z/W ratio in close phase space

- A strategy to use photon + jets to estimate Z to invisible could be adopted from CMS-AN 36/2008.

Systematic Studies

- Variation of jet energy scale and resolution
  - 10% gaussian smearing of jet p_T's and of 0.1 rad of φ measurement
  - Scaling of jet energy by ± 5%
  - Scaling of jet energy by ± 3% for endcap/forward ($|\eta|>1.4$)

	LM1	$Z \to \nu\bar{\nu}$	$t\bar{t}$,W+jets,Z+jets	QCD	S/B
default	432	57	19	0	5.6
10% smeared	421	55	18	0	5.4
+ 5% scaled	455	67	23	0	5.0
- 5% scaled	378	49	15	0	5.9
forward +3% scaled	432	58	18	0	5.6
forward -3% scaled	432	55	18	0	5.8

- Smearing has only small influence (~3%)
- Scaling changes effective HT cut
- **Stable S/B for all variations!**

Conclusions

- Inclusive di-jet analysis is an extension to the PTDR-II
- SUSY searches looking for a complementary signature
- Analysis promising, exploiting particular event topology
  - α (αT) and $\Delta\phi$ very powerful
  - Shown results do not rely on calorimetric MET
- Data-driven backgrounds determinations have been developed
  - Subtraction of all backgrounds using matrix method
    - define signal enriched and depleted |eta| regions
    - checks on real data in place
  - $Z\rightarrow\nu\nu$ can be obtained from $W\rightarrow\mu\nu$
    - See also approved analysis CMS AN 2008/036
- Extension to calo MET independent multi-jet analyses under study
- Benchmark points (e.g. LM1) could be observed in dataset of ~100pb-1
  - Assuming detector performance is understood

Extending the search to n-jets

$$\alpha_T = \frac{\text{min.}\left(E_T^{j_1},\, E_T^{j_2}\right)}{M_T^{j_1,\, j_2}}$$

Merging the jets into pseudo-jets

α_T uses M_T... we should use a merging scheme that keeps M_T the same no matter which jet combination used to form the pseudo-jets.

i.e.

$$M_T\left(j_1,\, j_2,\, j_3\right) = M_T\left(j_1,\, \{j_2,\, j_3\}\right) = M_T\left(\{j_1,\, j_2\},\, j_3\right)$$

where

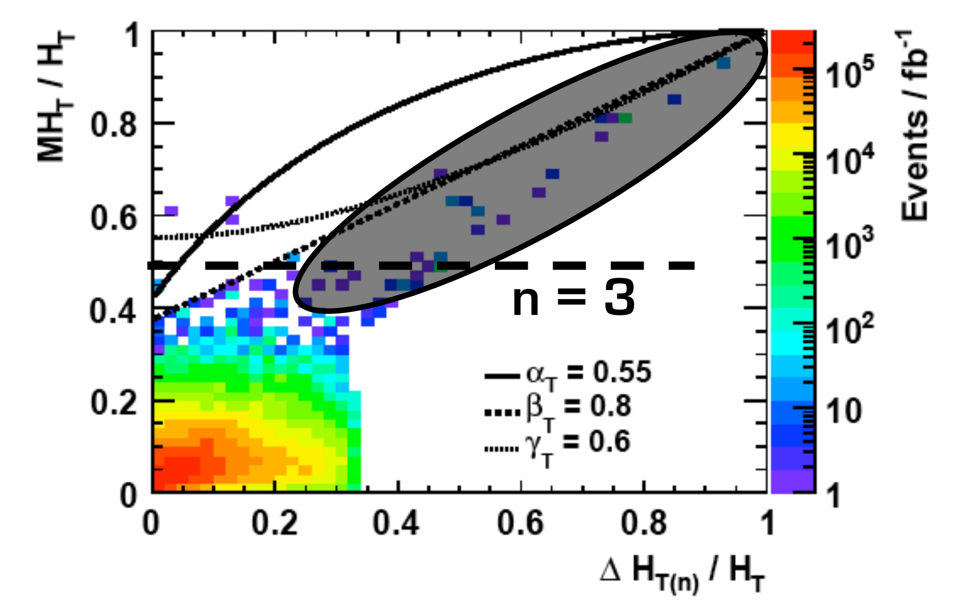
$$M_T(j_1,\, ...\, ,\, j_i,\, ...\, ,\, j_n) = \sqrt{\left[\sum_{i=1}^{n} E_T(j_i)\right]^2 - \left[\sum_{i=1}^{n} p_x(j_i)\right]^2 - \left[\sum_{i=1}^{n} p_y(j_i)\right]^2}$$

So we use the **Transverse Object Merging** scheme:

$$E_{t(kl)} = E_{t(k)} + E_{t(l)};\ p_{x(kl)} = p_{x(k)} + p_{x(l)};\ p_{y(kl)} = p_{y(k)} + p_{y(l)}$$

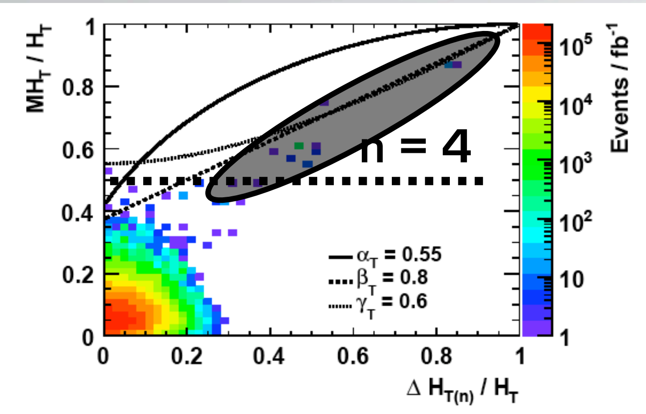
i.e. add the lengths (E_T) together, point in the direction of the vectorial sum.

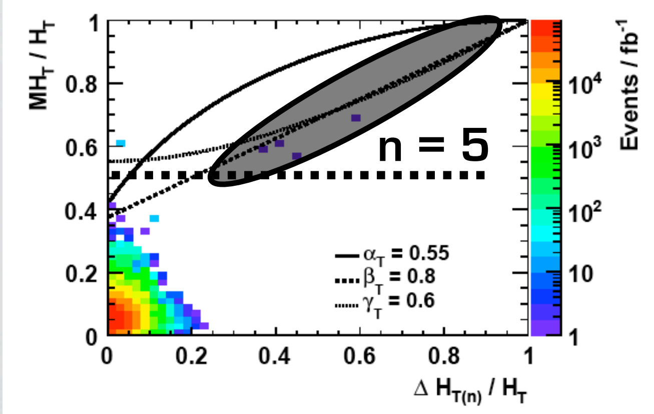
Optimising QCD rejection

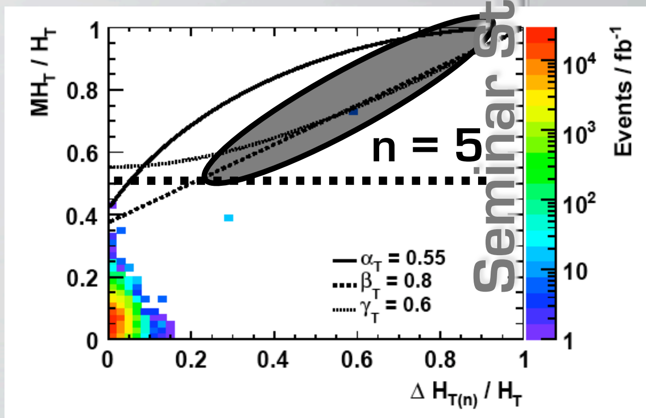


This plot is very insightful: we can see that a cut on $MH_T/H_T>0.5$ would remove most QCD events except for events where ΔH_T and MH_T are strongly correlated. If we can say this is due to severe mismeasurement, might there be another way of removing them?

- $\Delta\Phi(M\mathbf{h}_T, \mathbf{j}_i)$ cut? (M. Stoye)
- H_T binning i.e. flat MH_T cut? (D. Stuart)
- Topology: Fox-Wolfram moments (H. Flächer), transverse thrust? (M. Stoye)



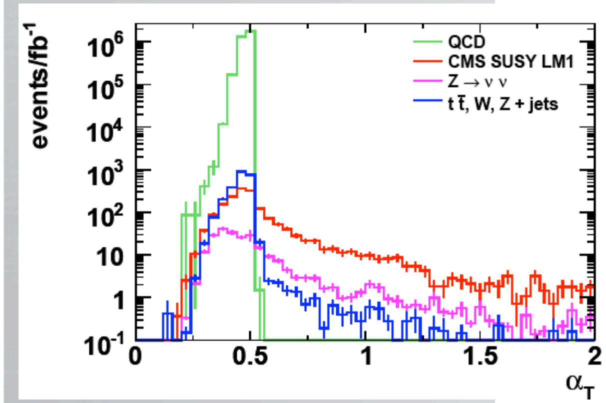


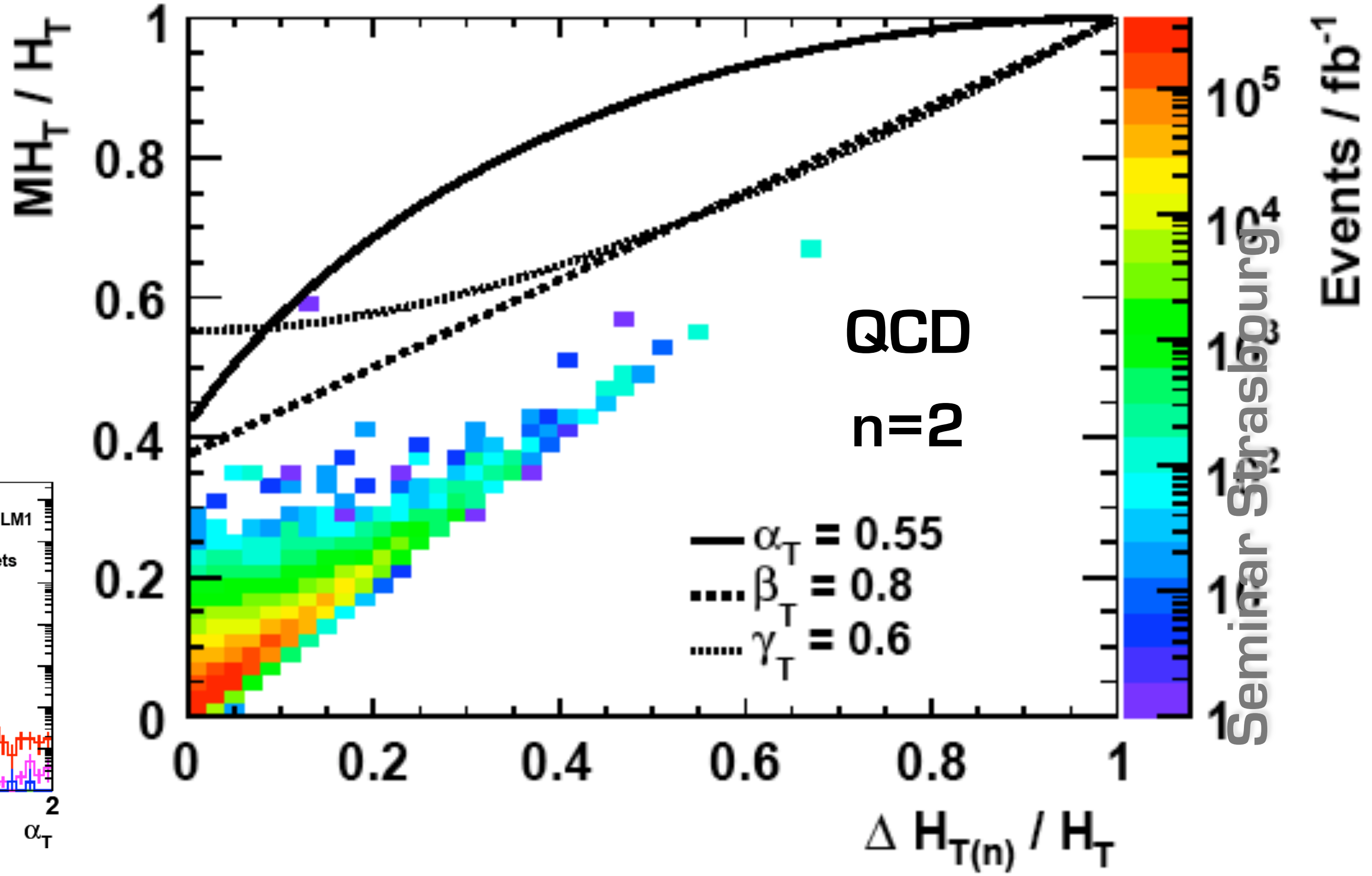


The dijet system revisited

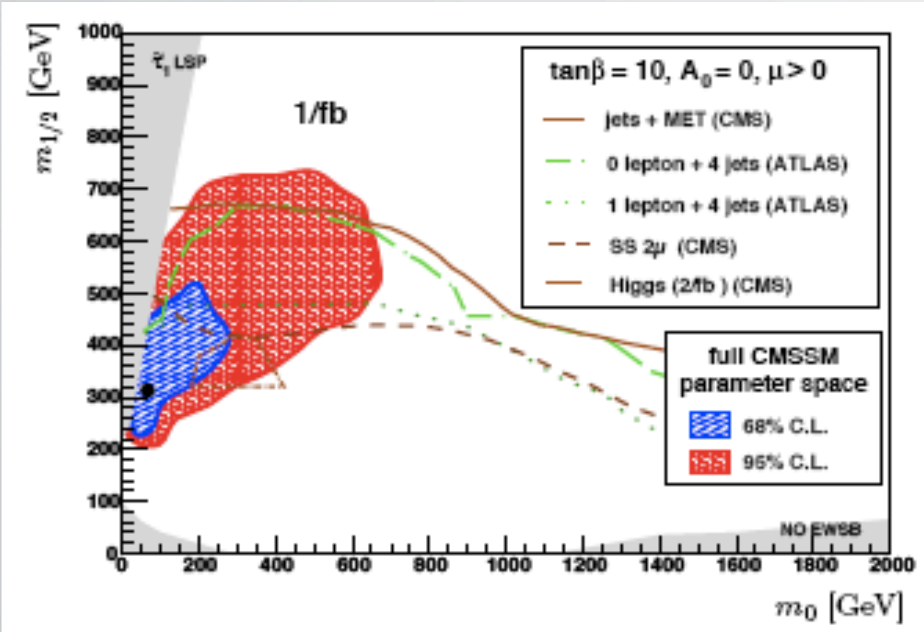
Making the same 2D plot for the n = 2 system, we can start to gain an insight into the success of α_T for the dijet case as presented in CMS AN-2008/071.

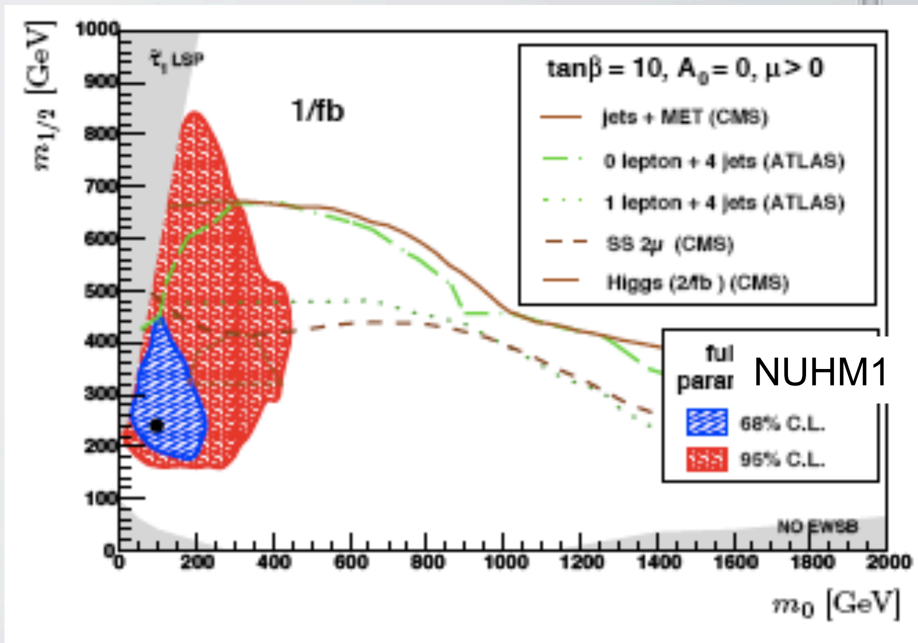
MH_T and ΔH_T are very strongly correlated in the dijet case. This explains the self-protection observed in α_T – i.e. the sharp edge at α_T = 0.5.





SUSY Discovery Potential CMSSM and NUHM1





Discover Potential for "multi-jet, multi-lepton and missing energy search" is described in the CMSSM.

Both ATLAS and CMS have very similar performance (as expected).

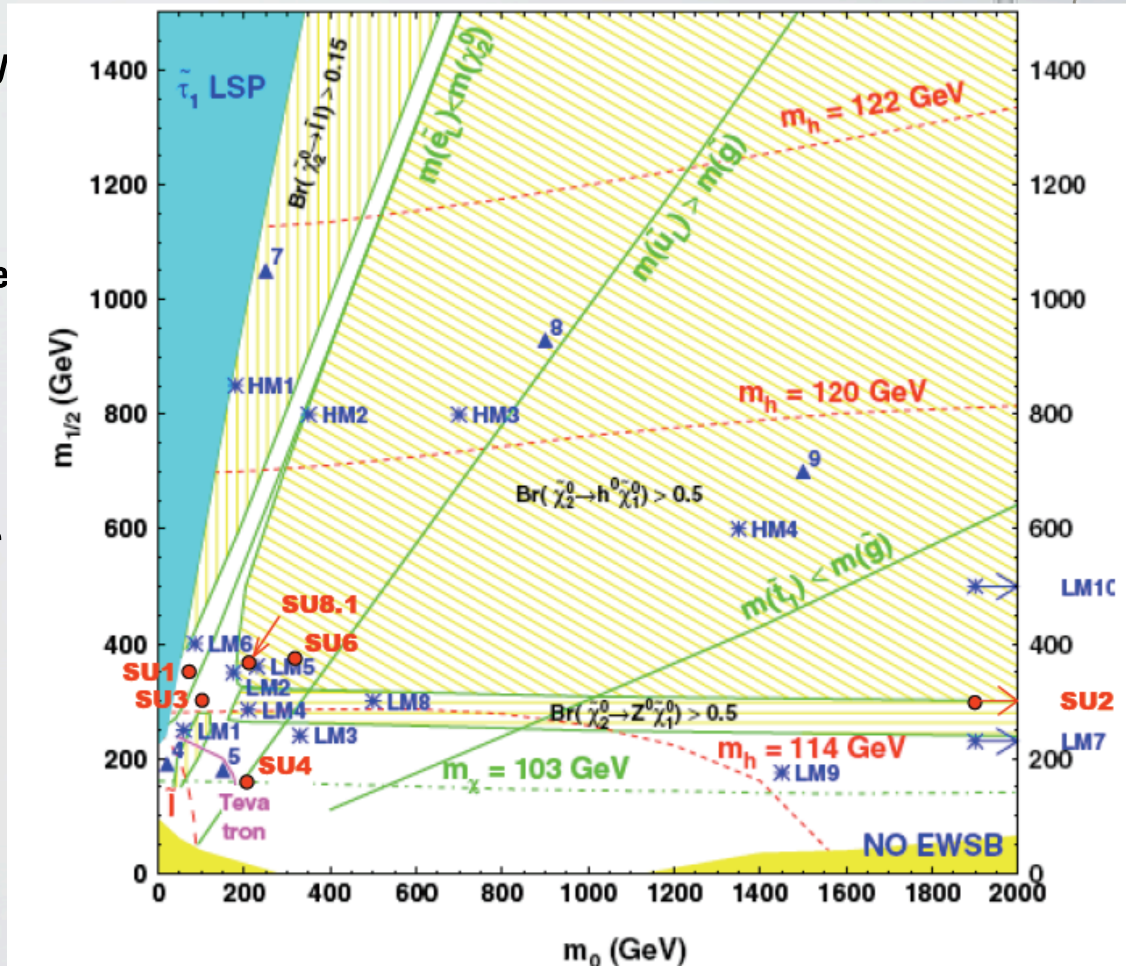
How do we characterize the search?

- We establish benchmark points to study the various different Signatures

- Almost all "Proper SUSY" BM points are defined in the CMSSM (Msugra)

- It's a convenient way to establish signature changes with only 4 parameter m0, m1/2, tanβ, A0, sign(μ)

- We hope that the set of CMSSM signatures will be close to reality but we can't be 100% certain



Frankly, we don't really know how exactly a "Dark Matter Candidate" model will manifest itself in form of a multi-Jet&multi-Lepton&MET signature in our Detector

- we only have a crude idea and this idea is mainly inspired by the CMSSM!

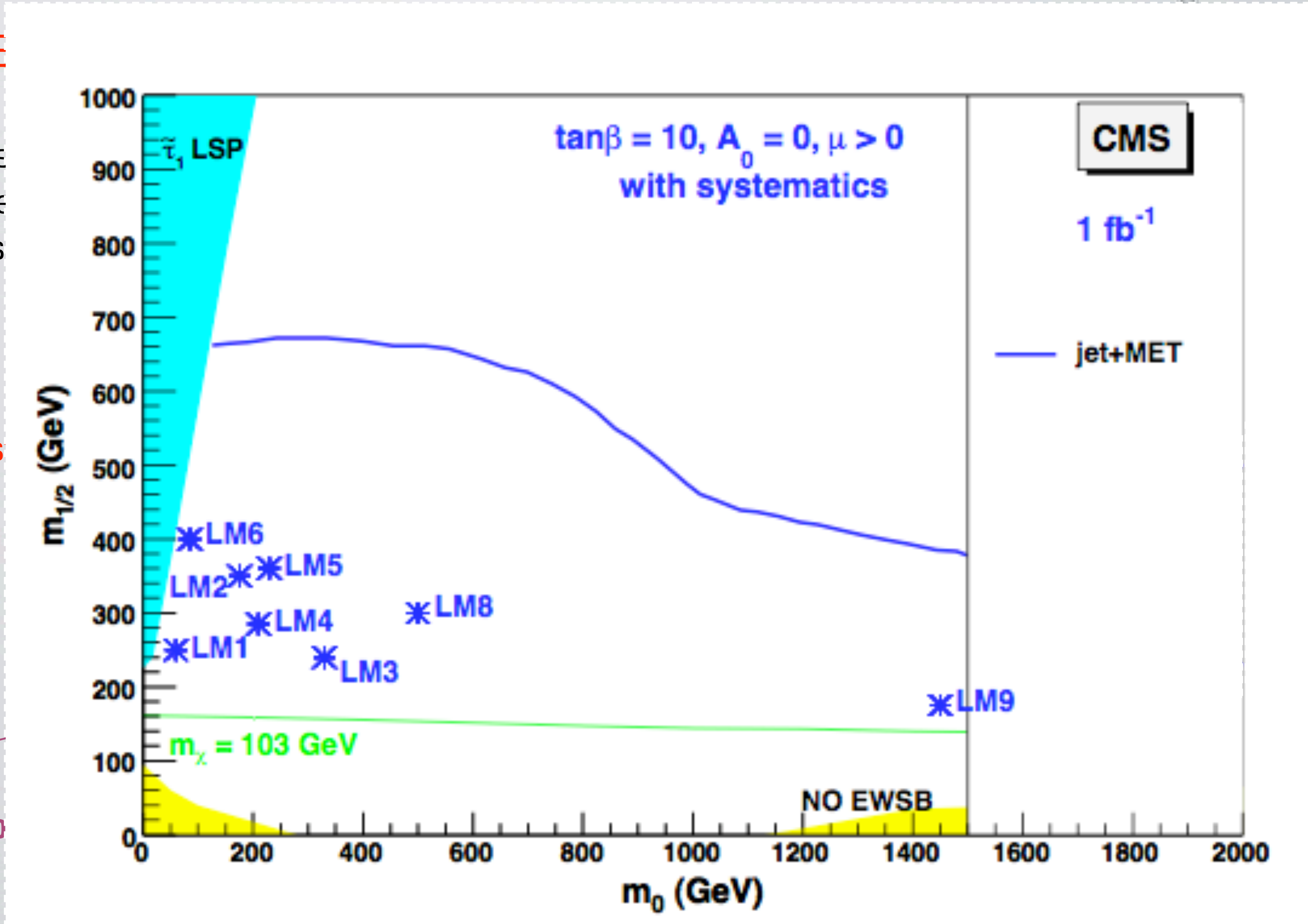
What is our Discovery Potential?

Use the JET&ME

Already with as little as
as 100/pb@14TeV we
cover easily all low mas
benchmark points!

Even with only 50/pb
@10TeV we cover almos
all low mass
benchmark points!

Comparison:
Exclusion reach of
D0 for 2.1/fb for
Jet&MET search
Phys.Lett.B660:449-457,200



If the CMSSM is of any reference, New Physics might show up very early in the "Proper SUSY" searches at the LHC...