Searching for SUSY at the LHC

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Outline

Who is SUSY, does she exist ?

- SUSY's characteristics (looks) and why we search for her

Search Tools

- Detectors, reconstructed objects

Search Strategy

- Data selection, background subtraction, statistical analysis

Search Results: SUSY is still missing

- Results and exclusions of searched areas

Is SUSY dead, hiding ?

- Search strategies for 2012

Who is SUSY ?

Why not to start with a Google search …

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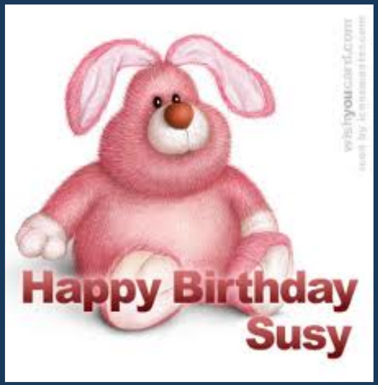

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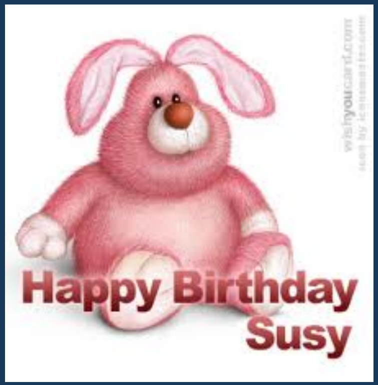
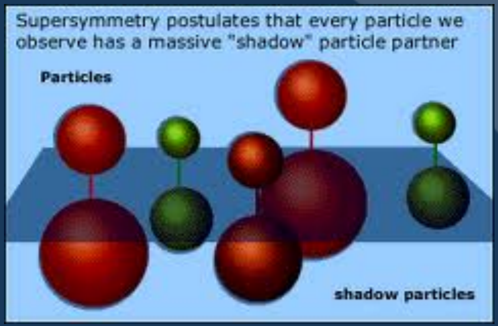


Wrong path !

What is Supersymmetry ?

"A SUSY Primer", S. Martin, hep-ph/9709356

Supersymmetry (SUSY)
is a physics theory



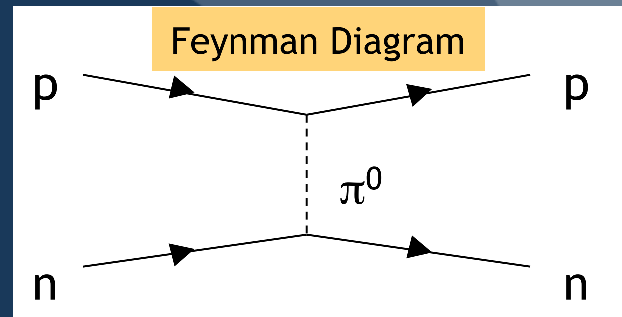
An extension of the *Standard Model of Elementary Particles and their interactions (SM)*

- Predicts twice as many particles as the SM – more complex
- No direct experimental evidence so far – SUSY particles not observed yet

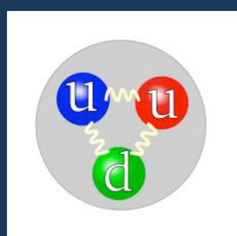
There better be a good reason to enlarge the particle zoo

Nuclear Forces

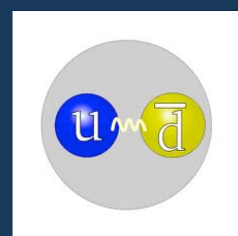
Yukawa theory (1934): nuclear interaction mediated by mesons *(pion)*



Through the 50's and 60's a depressingly large number of hadrons were discovered: π, K, Δ, Ξ, Λ, Σ, …



Baryon (i.e. proton)

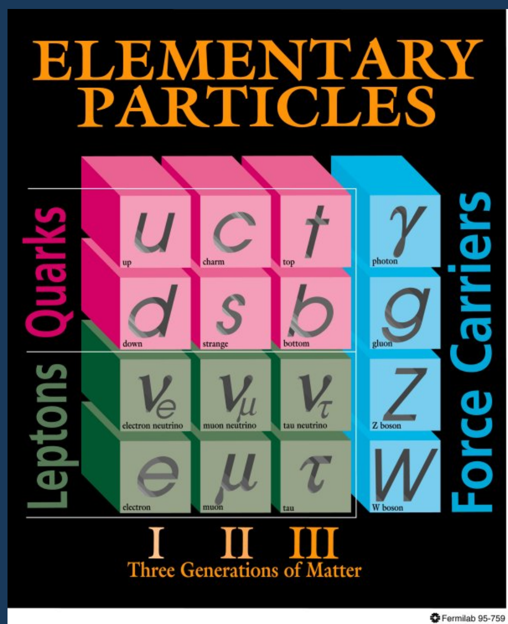


Meson (i.e. pion)

The quark model simplified the picture – all hadrons are composed of *quarks* interacting via exchange of *gluons*

The Standard Model

Everything in the Universe made of 12 fundamental particles governed by 4 fundamental forces



Quantum Chromodynamics (QCD)

- Strong "color" force, mediated by *gluons-g*

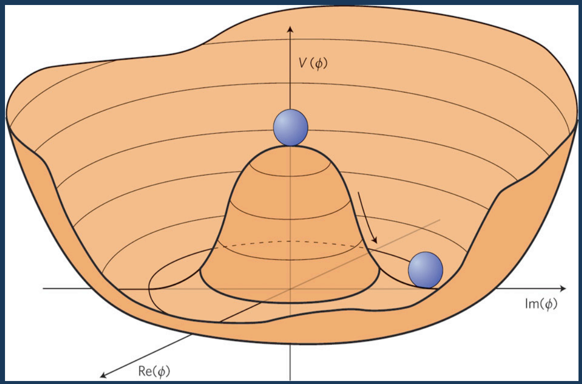
Quantum Electrodynamics (QED)

- "EM" and "weak" forces, mediated the photon-γ and *electroweak bosons-W, Z*

But Gravity is not included ! Quantum Theory and General Relativity not compatible within the Standard Model

The Higgs Boson

Massive elementary particle predicted by the SM



- System in a symmetric state is perturbed
- Symmetry is spontaneously broken
- System falls to a lower energy state and the underlying symmetry is hidden

Spontaneous Breaking of Electroweak Symmetry in SM

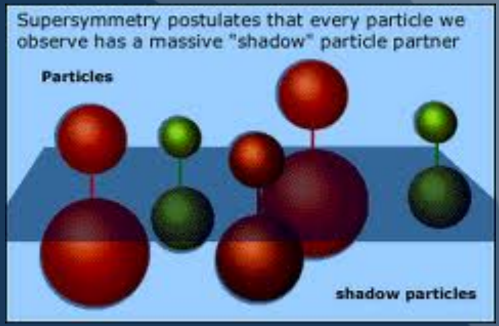
- Gauge bosons W, Z acquire mass
- New particle, the Higgs Boson
- Explains the particle mass hierarchy but M_H diverges

The Higgs Boson has not been observed yet

What is SUSY ? Revisited

SUSY Hypothesis: a symmetry relates bosons and fermions

- Predicts that each boson has a fermion super-partner with the same mass and quantum numbers and viceversa



Theorists find SUSY very compelling: (three examples)

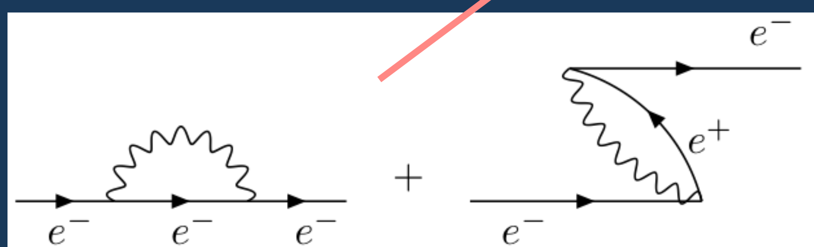
1. Provides a solution to the Higgs hierarchy problem
2. Allows unification of gauge couplings
3. Can predict a dark matter particle candidate

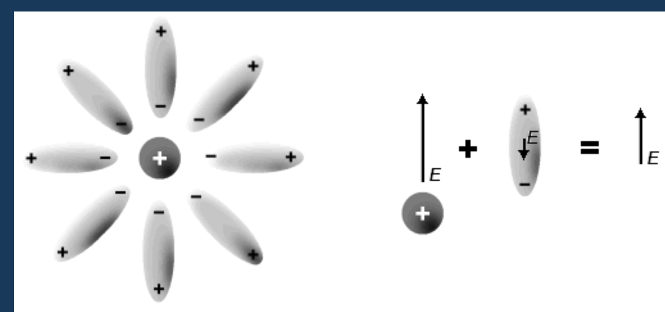
The Hierarchy Problem: Analogy

QED correction to the electron mass

- Classical electrostatic contribution of point-like electron to its energy is infinite

$$m_{e,physical} = m_{e,bare} + \Delta m_e, \quad \Delta m_e = \Delta E_{Coulomb}/c^2 = \frac{3e^2}{20\pi\varepsilon_0 R}$$





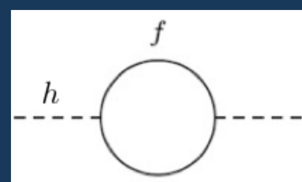
- The electron "partner", the positron, is responsible for eliminating the large divergence $m_{e,physical} = 0.511\ MeV/c^2$

The Hierarchy Problem: Higgs Mass

Radiative corrections to the Higgs mass

- The contribution from a Dirac fermion loop diverges

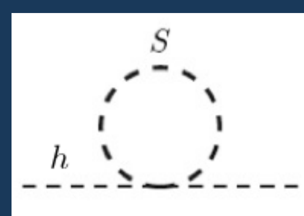
$$(\Delta m_h^2)_{SM} =$$



$$\sim -\frac{\lambda^2}{16\pi^2} M_{cutoff}^2$$

- The contribution from super-partner would cancel the divergence resolving the hierarchy problem

$$(\Delta m_h^2)_{MSSM} =$$



$$\sim \frac{\lambda^2}{16\pi^2} M_{cutoff}^2$$

1. SUSY provides a solution to the Higgs hierarchy problem ✔

The Standard Model Couplings

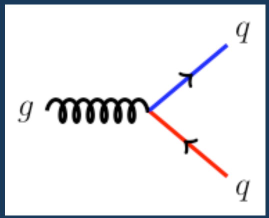
The strength of the fundamental forces given by "Coupling Constants"

Strong (QCD):

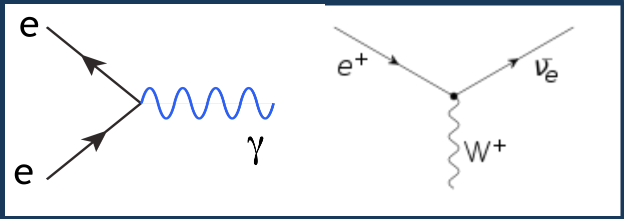
- Strong "color" force, mediated by *gluons g*

EM & Weak (QED)"

- "EM" and "weak" forces, mediated by the photon γ and *the bosons W, Z*



Strong	α_s	1
EM	α	1/137
Weak	α_w	10^{-6}
Gravity	α_g	10^{-39}



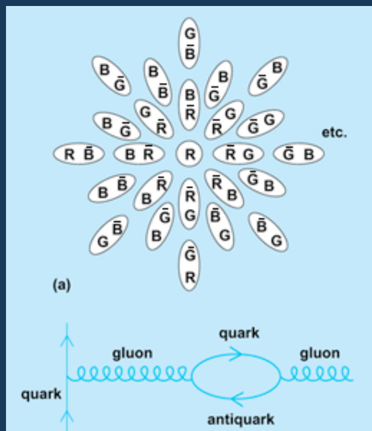
Strength of forces very different

Uncomfortable situation toward a Grand Unification Theory (GUT)

- All forces would have the same strength at GUT energy

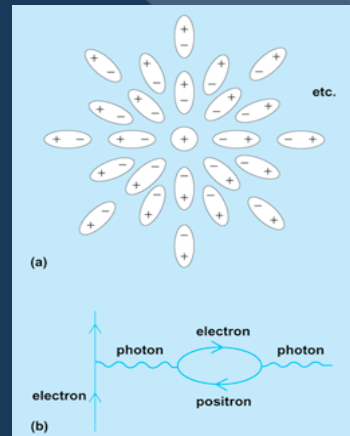
Running Coupling Constants

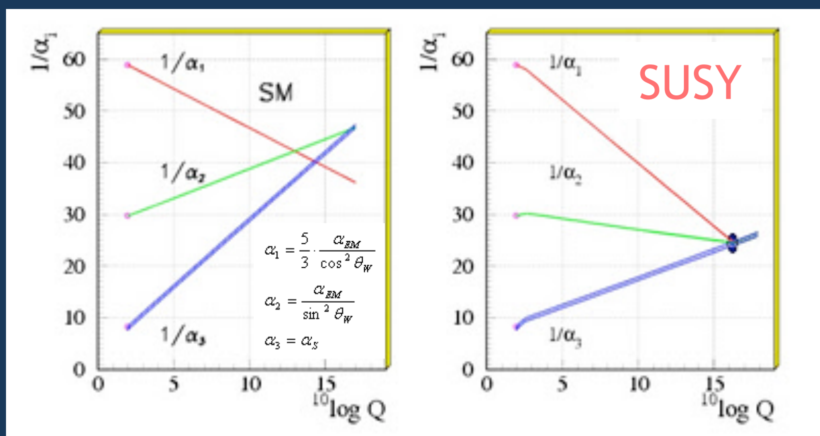
The Standard Models predicts that coupling constants are not "constants" but they "run" with energy



Quarks get closer within a hadron, effective color charge smaller, α_s smaller

Electrons get closer, effective charge larger, α larger





Standard Model: the couplings "run" but do not cross each other at the same energy

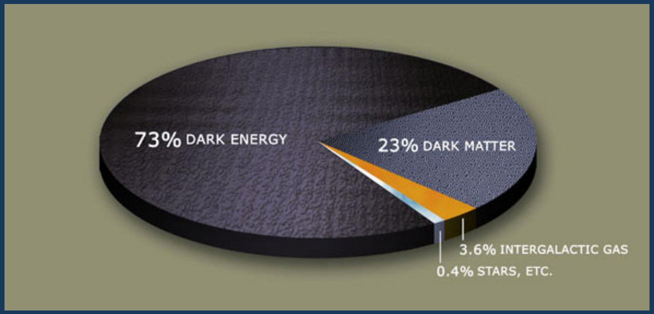
2. SUSY allows unification of gauge couplings

Dark Matter

Orbital velocities of galaxies in clusters, rotational speeds of galaxies, gravitational lensing → Dark Matter, 23% of total matter

Dark Matter
- Does not emit or scatter EM radiation
- Massive, interacts weakly → Weak Interactive Massive Particle (WIMP)

High-scale SUSY breaking scenarios coupled to MSSM with R-parity conservation: Lightest SUSY Particle (LSP) can be the WIMP



$R=(-1)^{3(B-L)+2S}$

1 (SM particles)

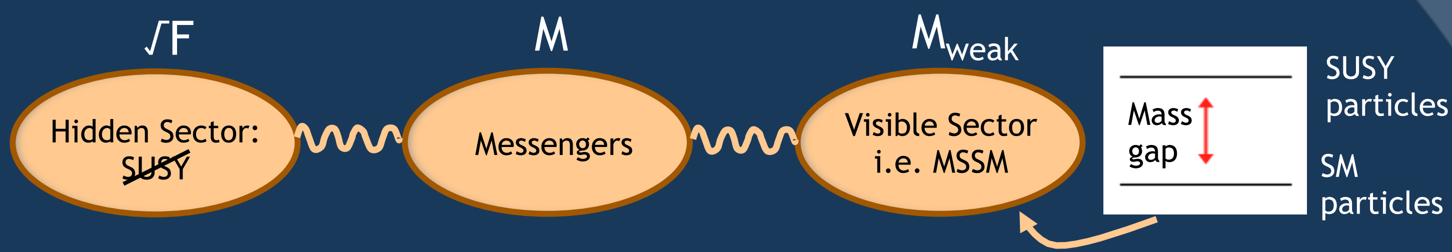
-1 (SUSY particles)

3. SUSY can predict a dark mater candidate ✓

SUSY Symmetry Breaking

SUSY predicts that fermions and bosons in a super-multiplet have the same mass

- None of the superpartners have been observed – SUSY would be a spontaneously broken symmetry
- SUSY particles more massive than SM particles but, how massive?



M	√F	$M_{3/2}$ (Gravitino)	Mediation Type
M_{pl} (~10^{18} GeV)	~10^{10} GeV	100 GeV …1 TeV	High scale ~~SUSY~~; gravity mediation
M_{pl}	~10^{12} GeV	10 TeV … 100 TeV	Very high scale ~~SUSY~~; anomaly mediation
$M \ll M_{pl}$	$\ll 10^{12}$ GeV	10 eV … 10 GeV	Low scale ~~SUSY~~; gauge mediation

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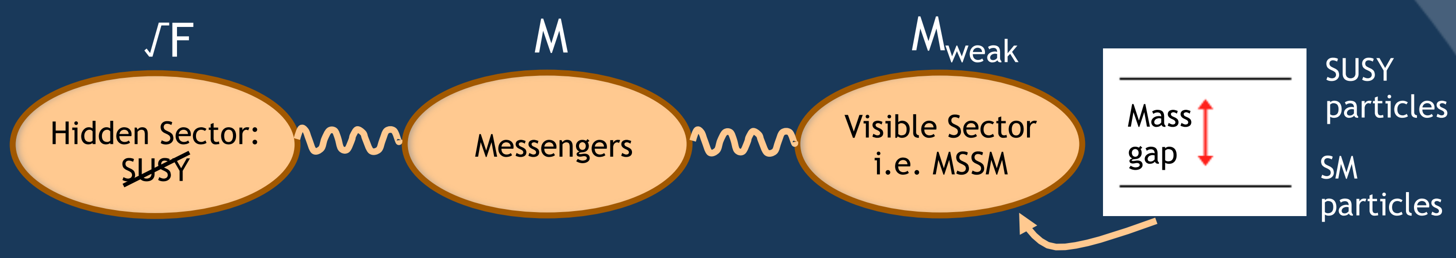


Lightest SUSY Particle (LSP)	$M_{3/2}$ (Gravitino)	Mediation Type
Lightest Neutralino	100 GeV …1 TeV	Gravity mediation (SUGRA)
Neutralino or sneutritro	10 TeV … 100 TeV	Anomaly mediation (AMSB)
Gravitino	10 eV … 10 GeV	Gauge mediation (GMSB)

The SUSY Particle Zoo (MSSM)

Minimal Supersymmetric Standard Model (MSSM) is the simplest supersymmetric extension to the SM

- Superpartners created in pairs
- LSP is stable and neutral
  - Neutralino is best candidate
- LSP is a candidate for Dark Matter (Big Bang survivor)

Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	$+1$	$h^0\ H^0\ A^0\ H^\pm$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$
squarks	0	-1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$ $\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$ $\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$	" " " " $\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$
sleptons	0	-1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$ $\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$ $\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$	" " " " $\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$
neutralinos	$1/2$	-1	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$
charginos	$1/2$	-1	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$
gluino	$1/2$	-1	$\widetilde{g}$	" "

S. Martin

Neutralinos, charginos also symbolized as: $\tilde{\chi}_i^0$ $\tilde{\chi}_i^\pm$

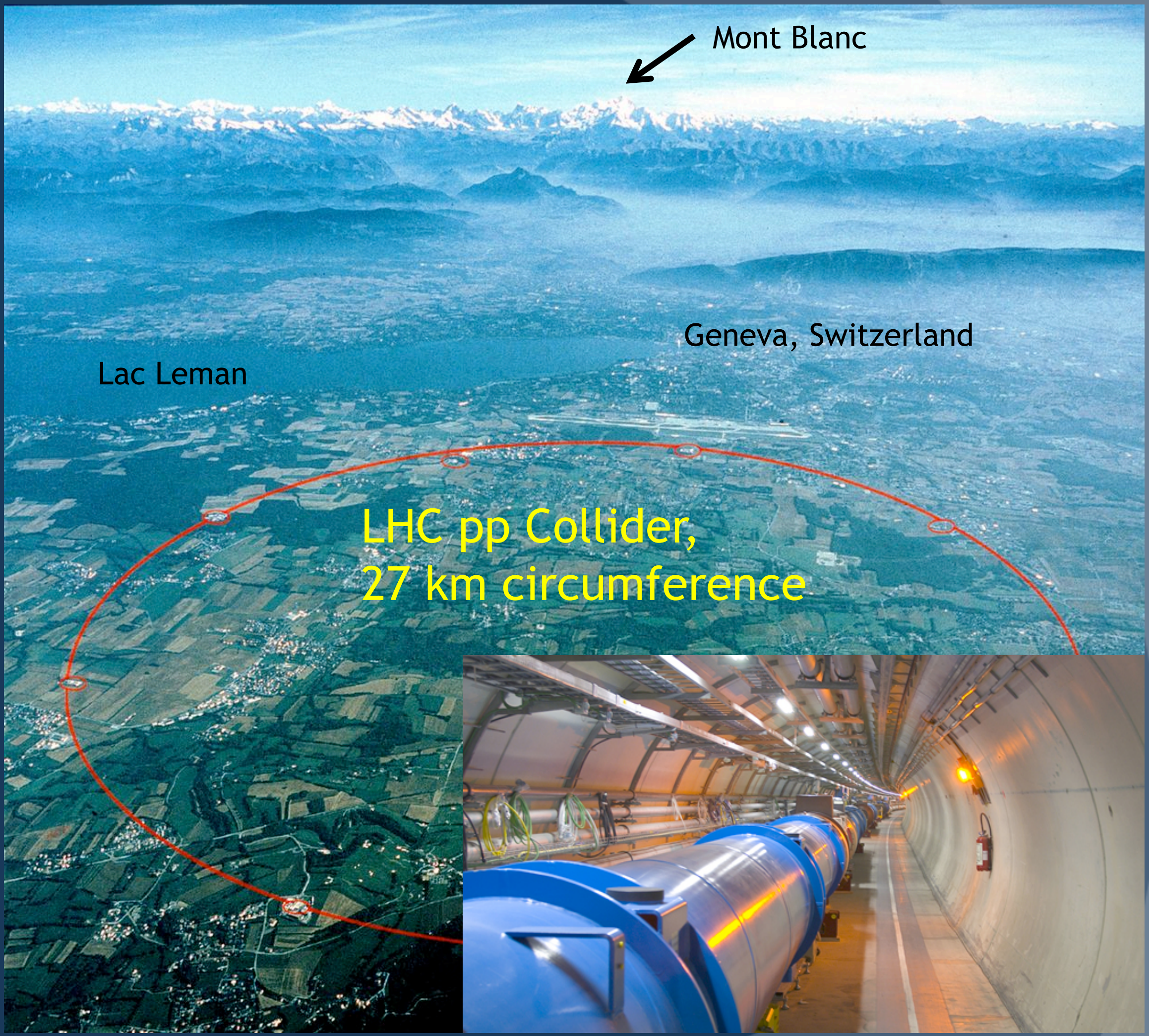
The LHC proton-proton Collider

The Large Hadron Collider (LHC) at CERN

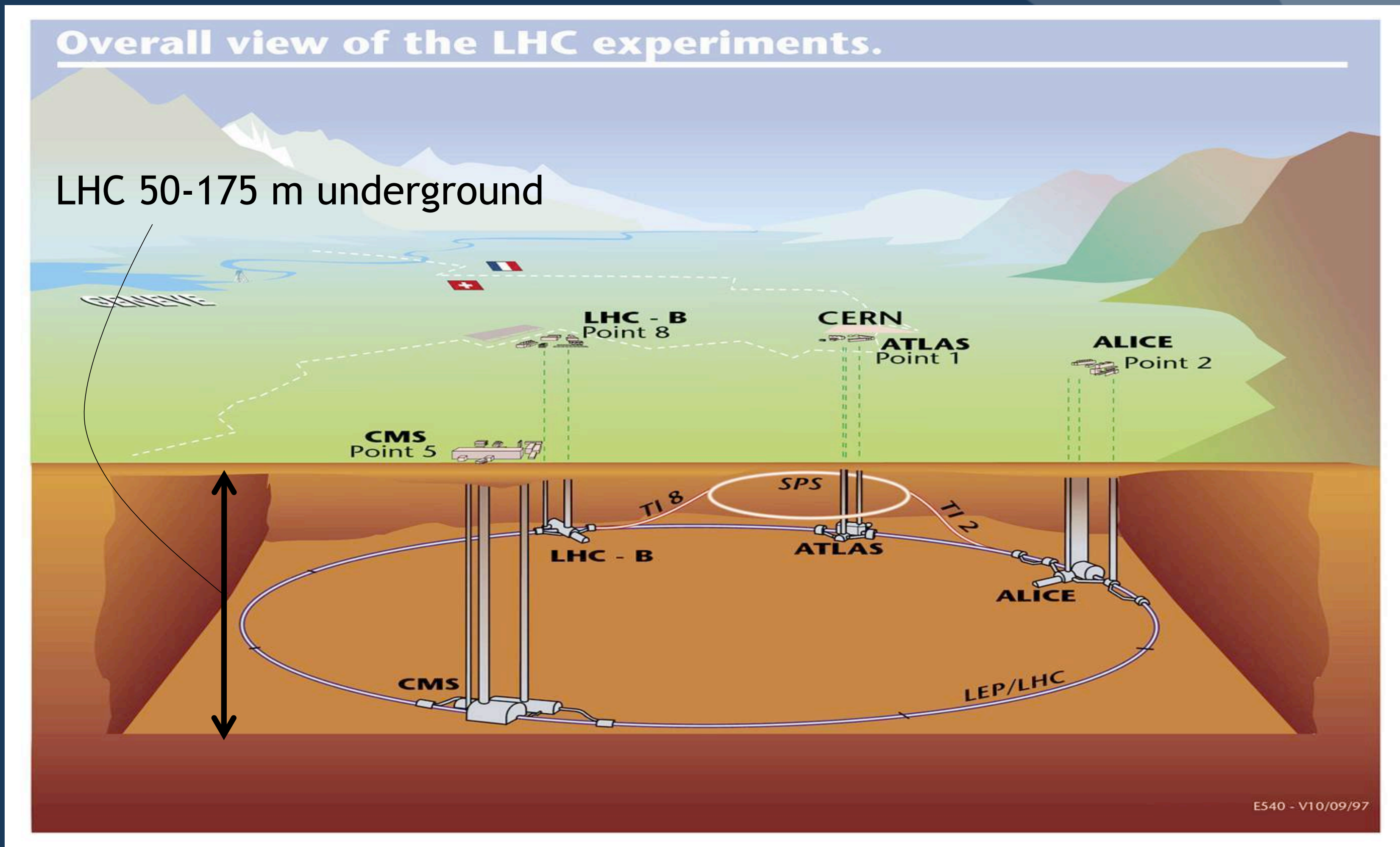
Proton-proton (pp) Collisions

Center-of-mass energy = 7 TeV

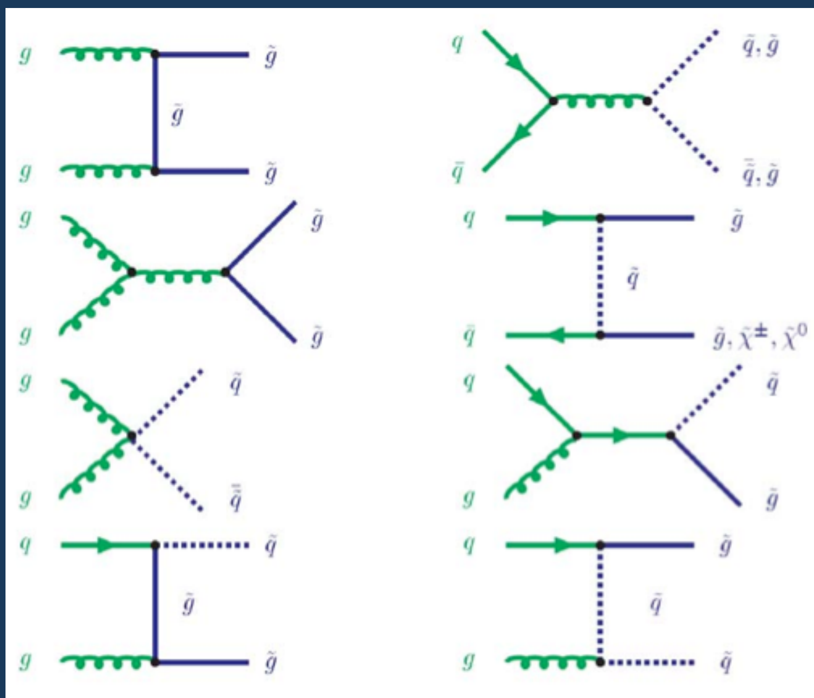
(largest collider in the world – best tool to search for BSM physics)

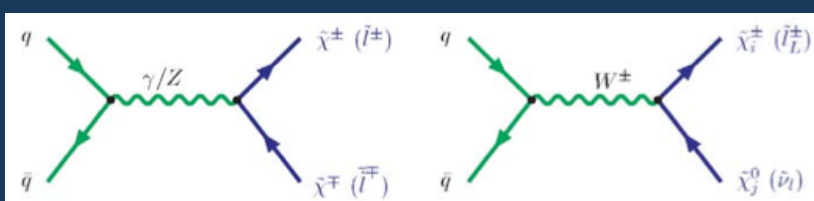


The LHC proton-proton Collider



SUSY Production in Hadron Colliders





D. Kazakov

- Strong production
  - Gluon fusion, quark anti-quark, quark-gluon scattering

  Dominant at the LHC

  (no valence anti-quarks in pp collisions)

- EWK production
  - Quark anti-quark annihilation

  More events would be available

  Significant amount of data collected

SUSY Events Signature

Production	Key Decay Modes	Signatures
$\tilde g\tilde g, \tilde q\tilde q, \tilde g\tilde q$	$\tilde g \to q\bar q\tilde\chi^0_1$, $q\bar q'\tilde\chi^\pm_1$, $g\tilde\chi^0_1$ } $m_{\tilde q} > m_{\tilde g}$ $\tilde q \to q\tilde\chi^0_i$, $\tilde q \to q'\tilde\chi^\pm_i$ } $m_{\tilde g} > m_{\tilde q}$	$\not E_T$ + multijets (+leptons)
$\tilde\chi^\pm_1\tilde\chi^0_2$	$\tilde\chi^\pm_1 \to \tilde\chi^0_1 l^\pm\nu$, $\tilde\chi^0_2 \to \tilde\chi^0_1 ll$ $\tilde\chi^\pm_1 \to \tilde\chi^0_1 q\bar q'$, $\tilde\chi^0_2 \to \tilde\chi^0_1 ll$,	Trilepton + $\not E_T$ Dilepton + jet + $\not E_T$
$\tilde\chi^+_1\tilde\chi^-_1$	$\tilde\chi^+_1 \to l\tilde\chi^0_1 l^\pm\nu$	Dilepton + $\not E_T$
$\tilde\chi^0_i\tilde\chi^0_i$	$\tilde\chi^0_i \to \tilde\chi^0_1 X$, $\tilde\chi^0_i \to \tilde\chi^0_1 X'$	$\not E_T$ + Dilepton + (jets) + (leptons)
$\tilde t_1\tilde t_1$	$\tilde t_1 \to c\tilde\chi^0_1$ $\tilde t_1 \to b\tilde\chi^\pm_1, \tilde\chi^\pm_1 \to \tilde\chi^0_1 l^\pm\nu, \tilde\chi^\pm_1 \to \tilde\chi^0_1 q\bar q'$ $\tilde t_1 \to b\tilde\chi^\pm_1, \tilde\chi^\pm_1 \to \tilde\chi^0_1 l^\pm\nu, \tilde\chi^\pm_1 \to \tilde\chi^0_1 l^\pm\nu$	2 acollinear jets + $\not E_T$ single lepton + $\not E_T$ + $b's$ Dilepton + $\not E_T$ + $b's$
$\tilde l\tilde l, \tilde l\tilde\nu, \tilde\nu\tilde\nu$	$\tilde l^\pm \to l \pm \tilde\chi^0_i$, $\tilde l^\pm \to \nu_l\tilde\chi^\pm_i$ $\tilde\nu \to \nu\tilde\chi^0_1$	Dilepton + $\not E_T$ Single lepton + $\not E_T$ + $(jets)$ $\not E_T$

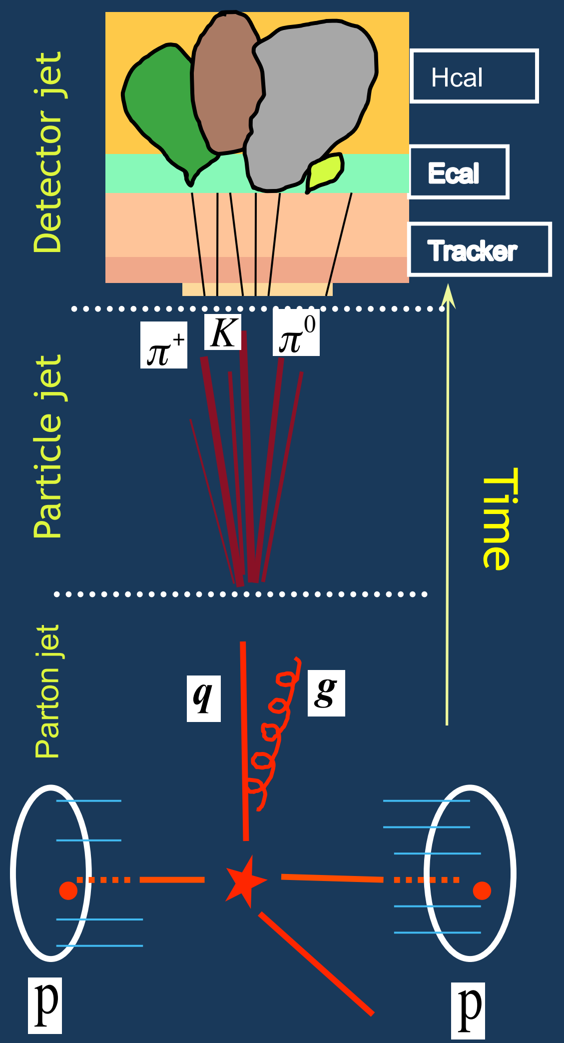
LSP (e.g. $\tilde\chi^0_1$) undetectable ➔ $\not E_T$

q & g parton shower and hadronization ➔ jets

D.I. Kazakov

Common element in all final states: Missing Transverse Energy $\not E_T$

Jets in Hadron Colliders



Jets are the experimental signature of quarks and gluons: spray of collimated colorless particles.

- Parton jet: made of quarks and gluons (after hard scattering and before hadronization).
- Particle jet: composed of final state colorless particles (after hadronization).
- Detector jet: reconstructed from measured energy depositions and tracks.

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Is SUSY dead, hiding ?

- Search strategies for 2012

Bibliography

CMS Physics Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

- Plots and Results
- Journal Publications
- Physics Analysis Summaries – public documents

ATLAS Physics Results

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

What do we look for?

Events with many jets, missing transverse energy (MET), leptons, electrons, photons

- Good understanding of how these "physics objects" leave their mark in the detector

Design detectors with the capability to identify and measure these "physics objects"

- High identification efficiency and low fake rate
- Linear energy response and excellent energy and position resolution
- High particle isolation efficiency
- Full angular coverage and hermeticity

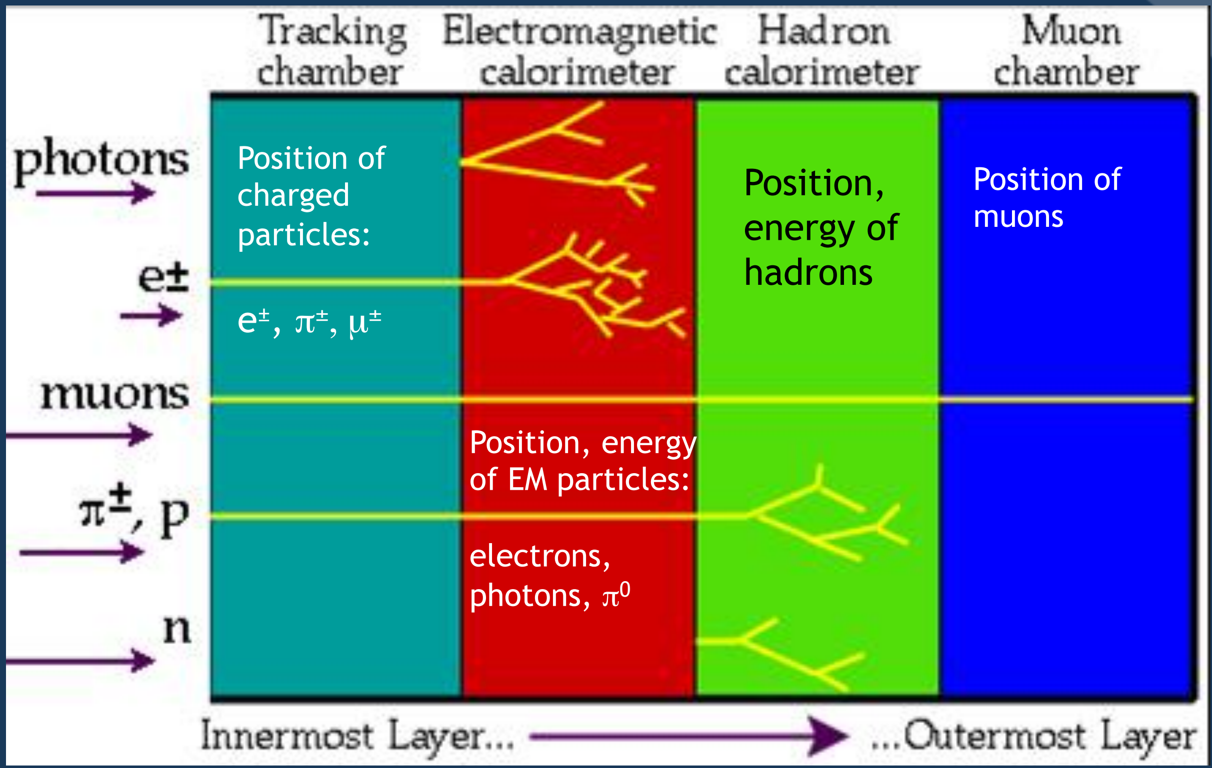
Main challenge is Background

Events with the same detector signature (same physics objects, similar kinematics) as signal events

Generic HEP Detector

Beam Direction

$\hat{z}$ ⊙



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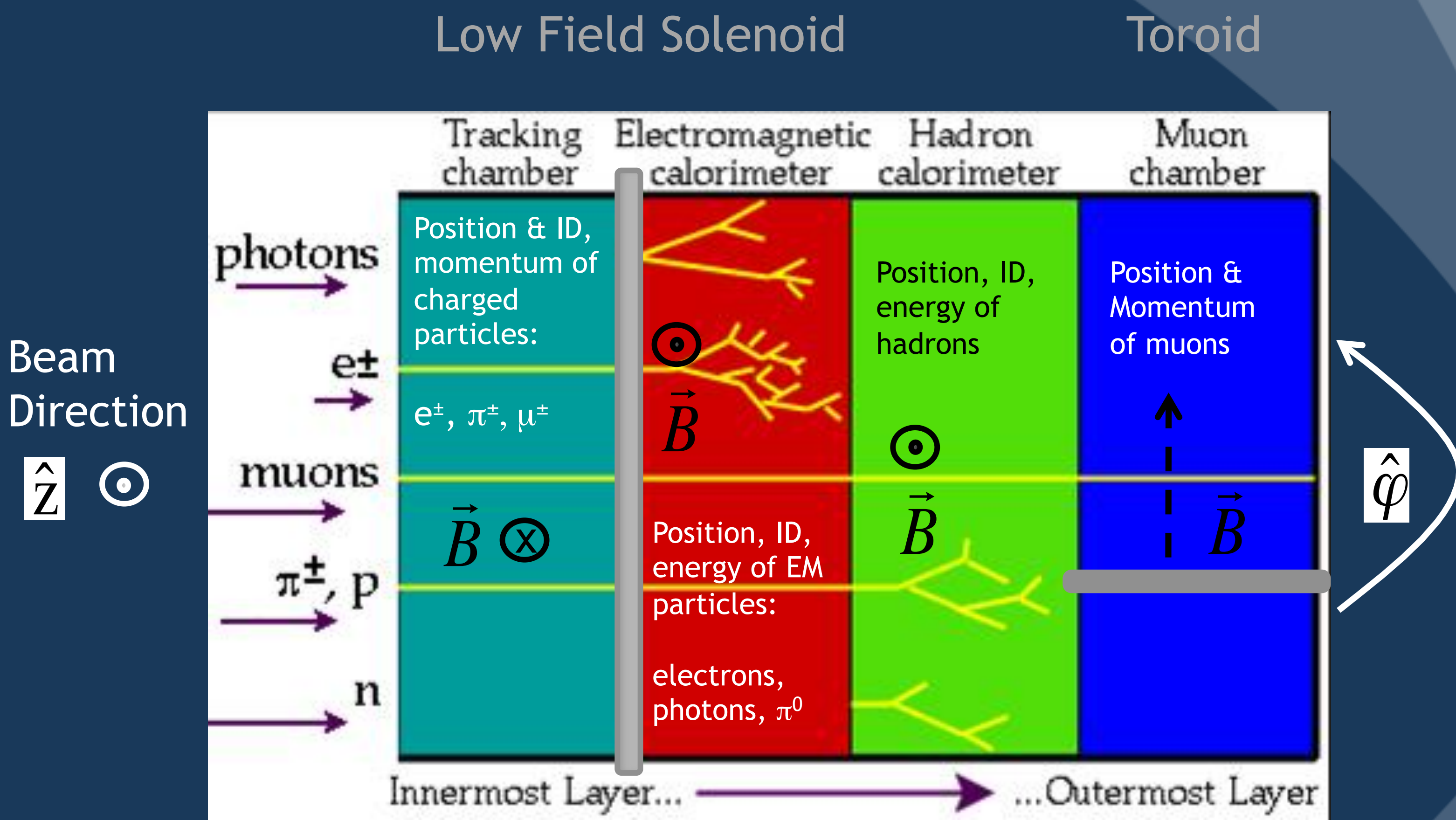
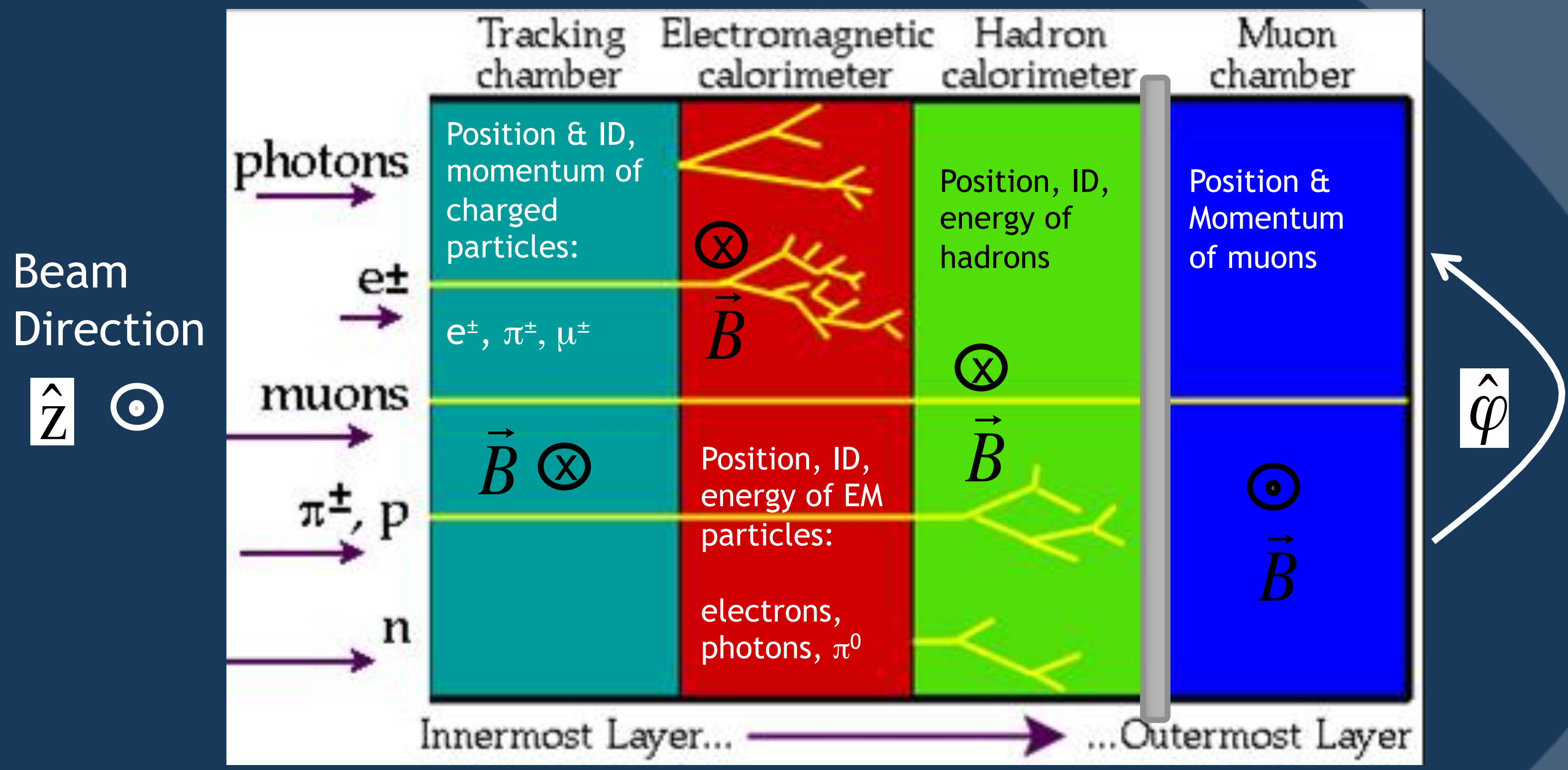
ATLAS Detector



Solenoidal + Toroidal Field ➔ Thick Calorimeter, but two magnets

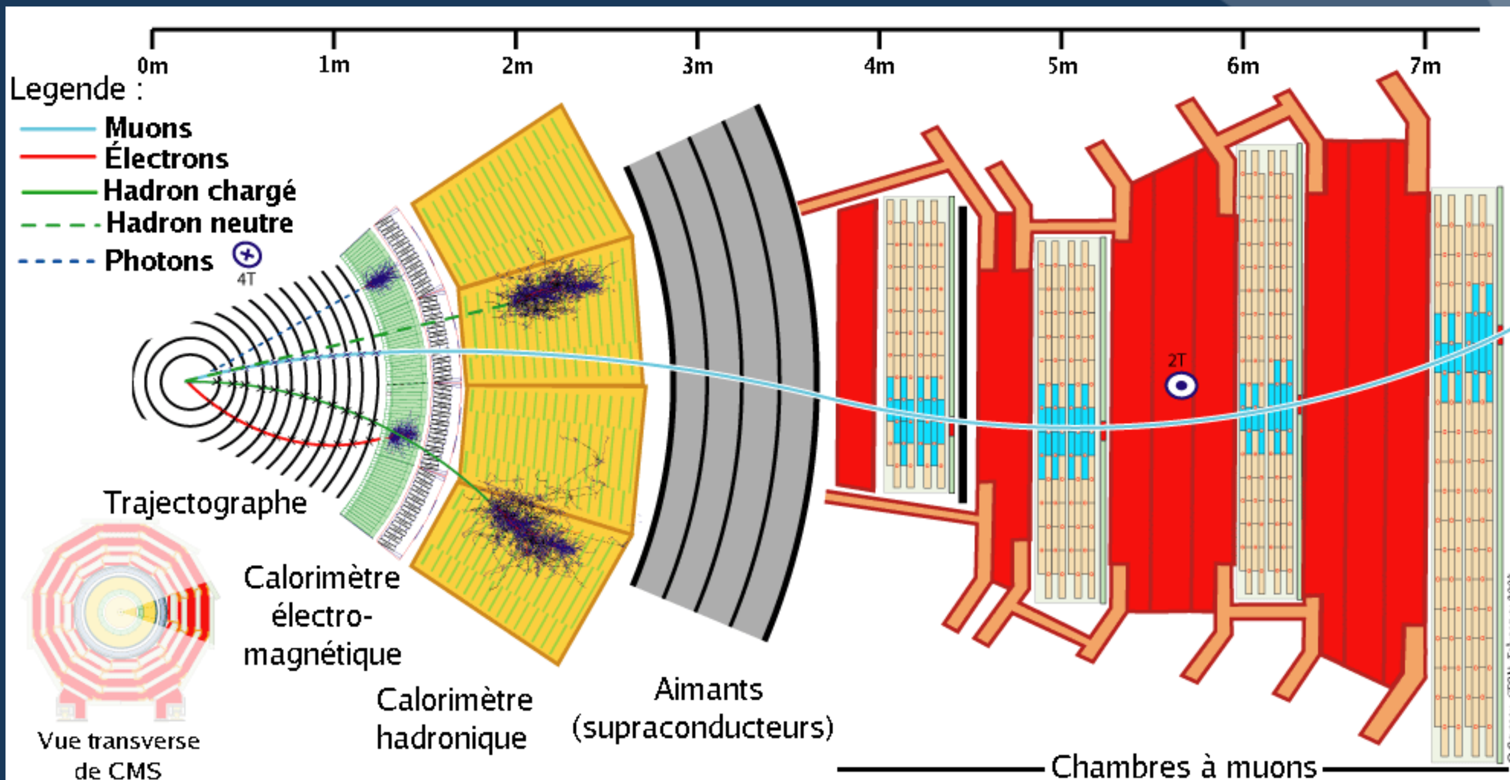
CMS Detector

High Field Solenoid



Solenoidal Field ➔ Thinner Calorimeter, but one magnets

The CMS Detector



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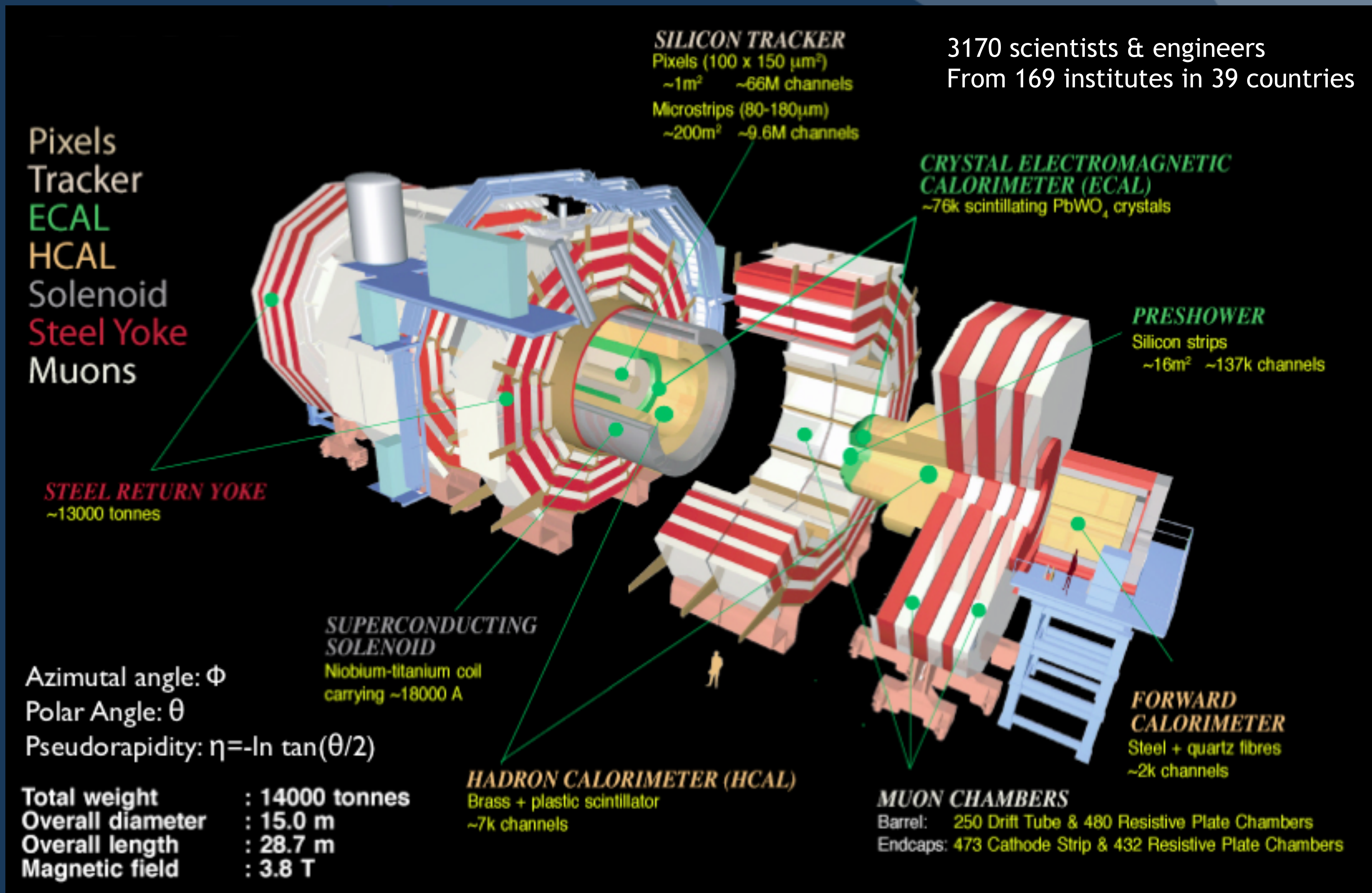
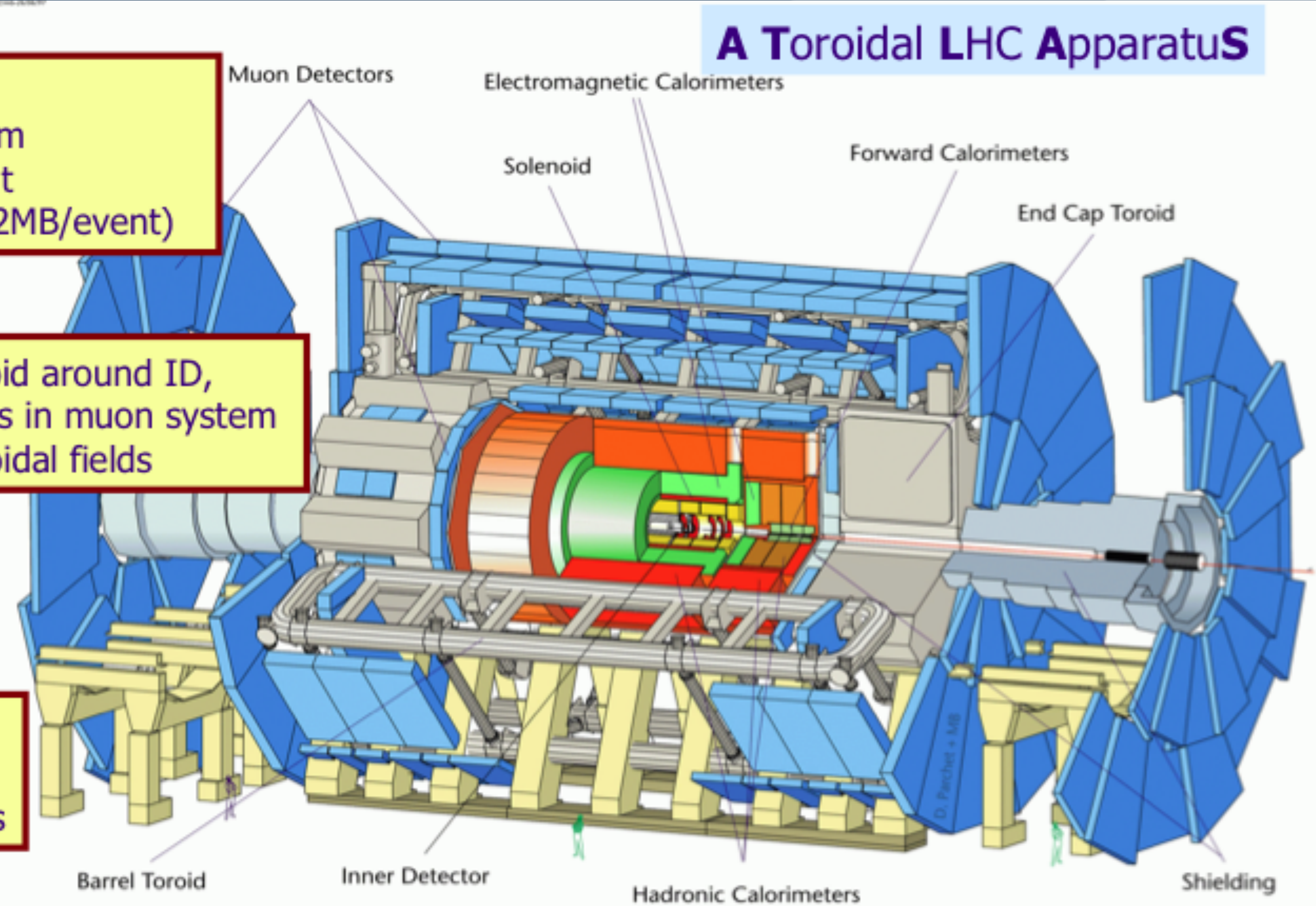


The ATLAS Detector

- Length ~40 m
- Diameter ~25 m
- Weight ~7000 t
- 10^8 channels (2MB/event)

- Central: solenoid around ID,
  Toroids in muon system
- End caps: Toroidal fields

~40 Nations
~150 Institutes
~2000 physicists



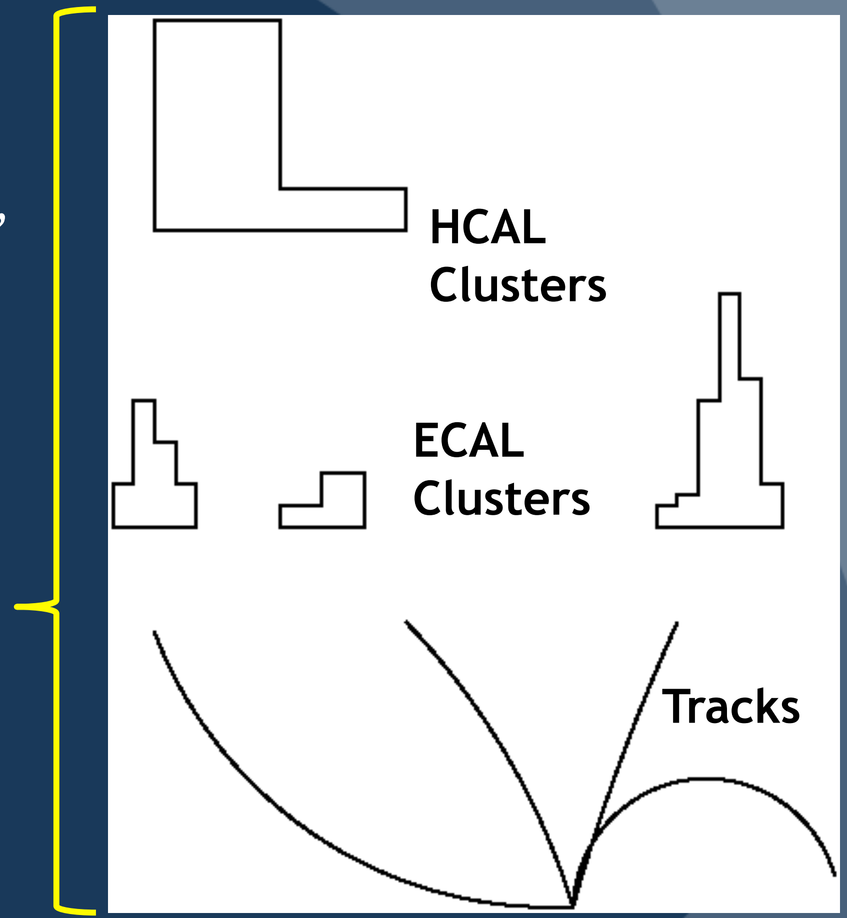
The Particle Flow Algorithm (PF)

The PF algorithm is designed to:

• Reconstruct & identify all particles: γ, e, μ, charged & neutral hadrons, pileup, and converted photons & nuclear interactions

• Use a combination of all CMS sub-detectors to get the best estimates of energy, direction, particle ID

1. Associate hits within each detector



CMS-PAS-PFT-09-001

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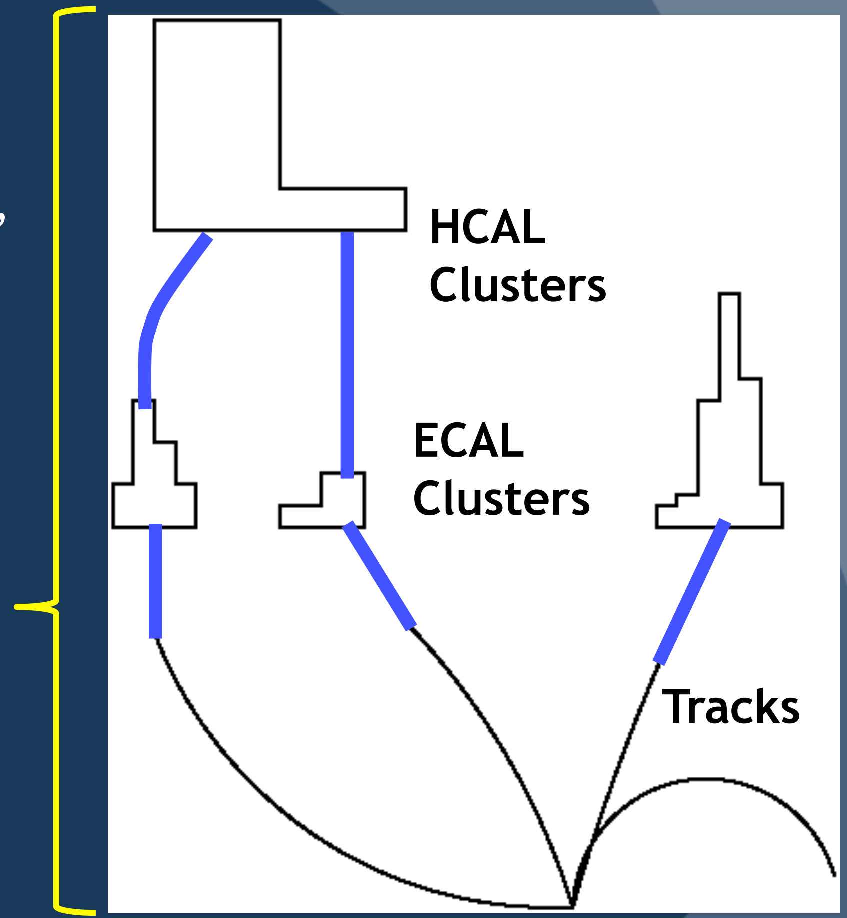
2. Link across detectors

CMS-PAS-PFT-09-001



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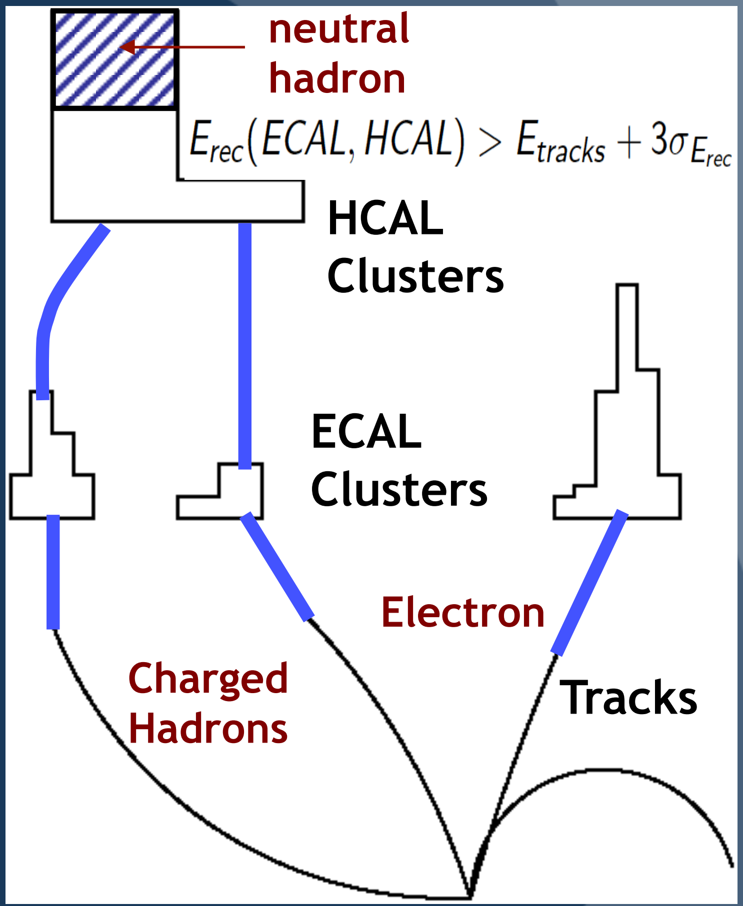
2. Link across detectors
3. Particle ID and separation.

CMS-PAS-PFT-09-001



The output is a collection of particles:
γ, e, μ, charged & neutral hadrons

Jet Reconstruction

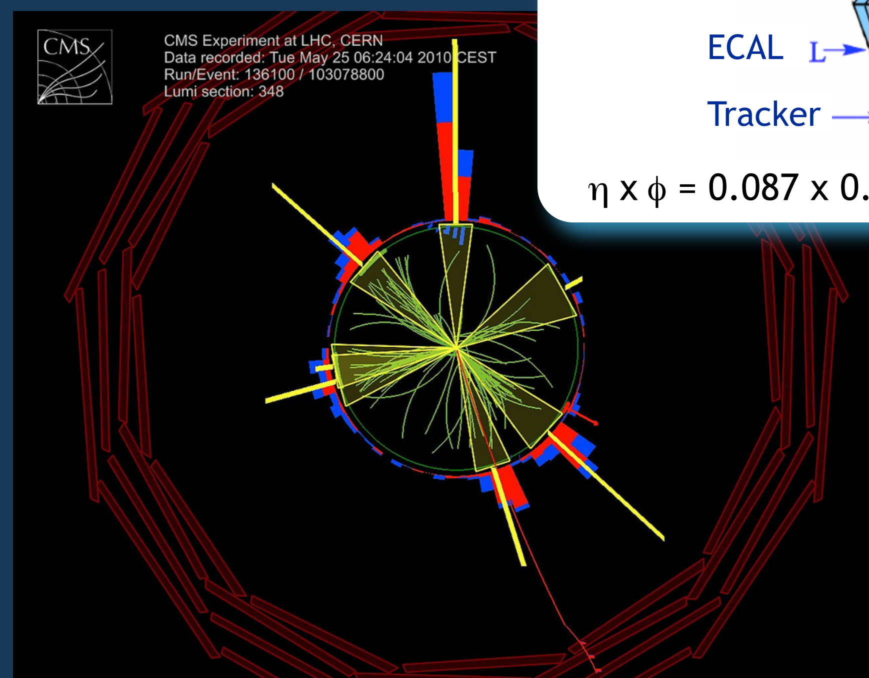
Use sequential clustering algorithm (Anti-K_T, R=0.5)

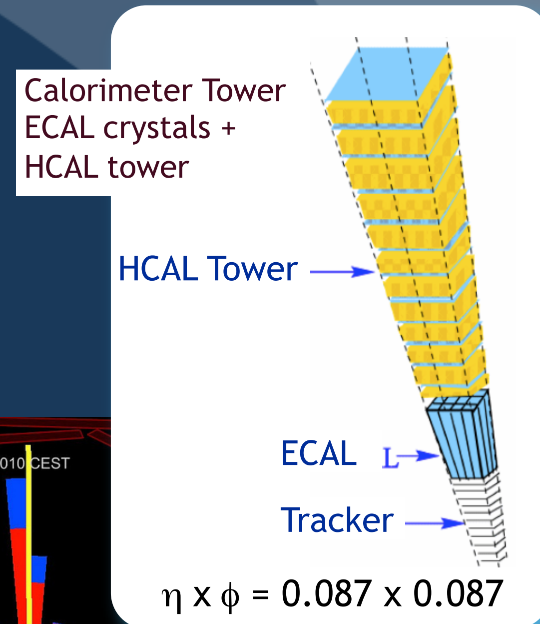
- Combine particles into jets following a prescription dependent on their relative space separation and p_T

$$\vec{p}^{\,Jet} = \sum_{i=1}^{n} \vec{p}_i\,, \quad E^{Jet} = \sum_{i=1}^{n} E_i$$

with n = # of PF particles clustered into a jet

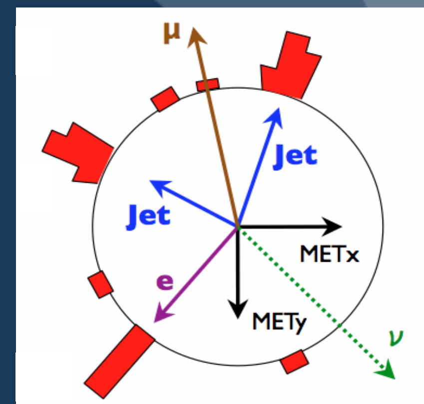
Clustering algorithm applied to PF particles – PF Jets, or calorimeter towers – CaloJets





Missing Transverse Energy (MET)

Indicates non-uniform detector response or the presence of particles that have escaped detection (weak interactions, cracks).



- SM particles decaying into neutrinos: Small MET
  - top, W leptonic decays.
- New physics: Large MET
  - e.g. LSP in cascade decays, undetected.

- Particle Flow MET (pfMET) is the transverse momentum vector sum over all PF particles: $\vec{\not{E}}_T = -\sum_{\text{particles}} (p_x\hat{\mathbf{i}} + p_y\hat{\mathbf{j}})$
- Calorimeter MET (CaloMET) is the transverse momentum vector sum over all calorimeter towers:

$$\vec{\not{E}}_T = -\sum_{n \,\text{CaloTowers}} (E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}}) = \not{E}_x \hat{\mathbf{i}} + \not{E}_y \hat{\mathbf{j}}$$

Corrected for jet E scale, μ/τ p_T, unclustered energy

The Real Question: Is E_T Missing ?

The Real Question: Is E_T Missing ?

E.T. phone home

MET-like Variables

$$HT = \sum_{i=1}^{Njets} p_T^{jet\,i}$$

HT is the scalar sum of the p_T of the jets in the event. It is the "scale" of the interaction in a fully hadronic event

$$MHT = -\sum_{i=1}^{Njets} \vec{p}_T^{\,jet\,i}$$

MHT is exactly an object based MET in a fully hadronic event. Less sensitive noise than CaloMET

$$M_{EFF} = MET + \sum_{i=1}^{Njets} p_T^{jet\,i} + \sum_{i=1}^{Nleptons} p_T^{lepton\,i}$$

Effective Mass representing the scale (invariant mass) of the primarily produced SUSY pair

$$m_{T2}(\vec{p}_T^{(1)}, \vec{p}_T^{(2)}, \not{\vec{p}}_T) \equiv \min_{\vec{q}_T^{(1)} + \vec{q}_T^{(2)} = E_T^{miss}} \{\max(m_T(\vec{p}_T^{(1)}, \vec{q}_T^{(1)}), m_T(\vec{p}_T^{(2)}, \vec{q}_T^{(2)}))\}$$

MT2 represents the scale of the SUSY particle

SUSY searches are based on different variables defined to enhance signal and reduce backgrounds

We also define more complex variables such as α_T, Razor
(Razor material not covered today – to become public at HCP11)

Outline

Who is SUSY, does she exist ?

- SUSY's characteristics (looks) and why we search for her

Search Tools

- Detectors, reconstructed objects

Search Strategy

- Data selection, background subtraction, statistical analysis

Search Results: SUSY is still missing

- Results and exclusions of searched areas

Is SUSY dead, hiding ?

- Search strategies for 2012

Search Deconstruction

The components of a search analysis:

- Theoretical models motivate the search, but they are not essential for a discovery – until you care about its nature

  (A statistically significant deviation of the data from the Standard Model predictions is a signature of new physics)

- Sensitive variables, used to observe the data – event counting is the simplest way
- Background predictions, # of events from SM processes is subtracted from observed data
- Interpretation
  - Statistically significant excess of events – discovery

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- Background predictions, # of events from SM processes is subtracted from observed data, in case of event counting
- Interpretation
  - Statistically significant excess of events – discovery (and glory)

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- Background predictions, # of events from SM processes is subtracted from observed data, in case of event counting

- Interpretation
  - No excess does not mean failure !

Search Deconstruction

The components of a search analysis:

- Theoretical models motivate the search, but they are not essential for a discovery – until you care about its nature

  (A statistically significant deviation of the data from the Standard Model predictions is a signature of new physics)

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- Background predictions, # of events from SM processes is subtracted from observed data, in case of event counting

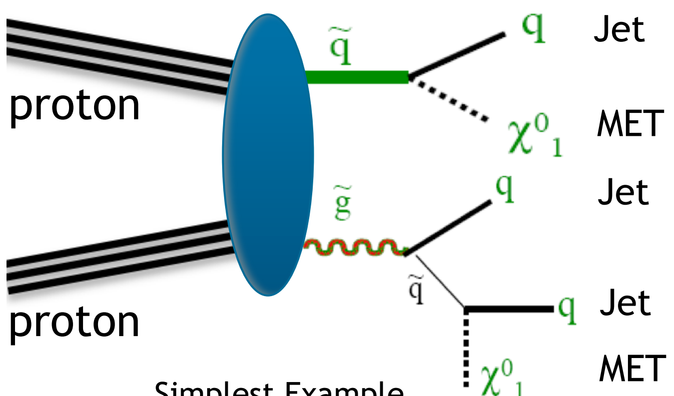
- Interpretation

  - Observation consistent with SM prediction means that new physics is not present at the mass scale we are probing – limit on mass or x-section follows

Physics Signals

A generic search for jets and MET in the all hadronic channel is motivated by R-parity conserving SUSY

- Strong production of $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$
- Largest cross section, most sensitive channel - *if backgrounds are well understood*



Simplest Example

SUSY particles eventually decay to LSP (stable, neutral)

Experimental signature: Jets + Missing Transverse Momentum

In the example, LPS is χ^0_1 (neutralino)

Model independent analysis means:

Concept

- Inclusive sample selection
- High efficiency for a broad range of models associated with final state

cMSSM Framework Parameters

The Constrained MSSM (cMSSM) framework includes mSUGRA

- Depends on a few independent parameters defined at the M_{GUT} scale
  - ✓ sleptons/squarks/Higgs have the same common scalar mass m_0
  - ✓ gauginos unify at the common mass $m_{1/2}$
  - ✓ Universal trilinear coupling (higgs-sfermion-sfermion) A_0
  - ✓ Ratio of the two higgs doublets VEVs is $\tan\beta$
  - ✓ Sign of higgs/higgsino mass parameter μ, $\mathrm{sgn}(\mu)$
- RGEs evolve parameters, compute couplings/masses at EWK scale
- LSP is often the neutralino

Different parameter values correspond to different production cross section for SUSY particles, flavor content, masses and mass hierarchy, length of the decay chain

Backgrounds

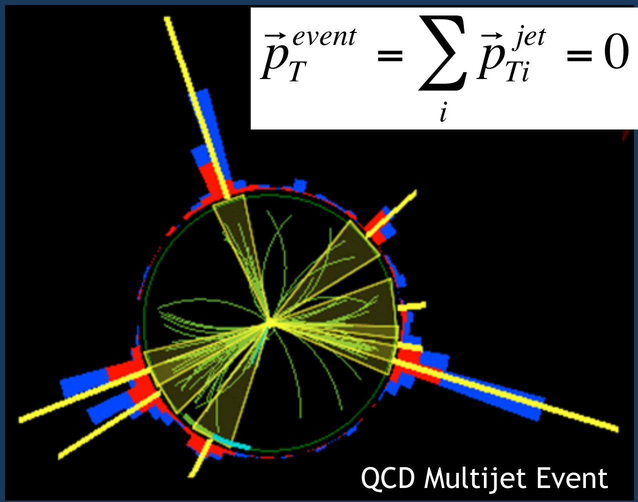
Background events are events that mimic the signal — Concept

- Reducible: same final state but one or more objects are fake due to detector acceptance, response, efficiency
- Irreducible: indistinguishable from signal events, all objects are real

QCD background:

- Multijets come from QCD Standard Model production
- Large MET created by extreme detector response mis-measurement

$$\vec{p}_T^{\,event} = \sum_i \vec{p}_{Ti}^{\,jet} = 0$$ In the case of an ideal detector (perfect response)



QCD Multijet Event

Backgrounds

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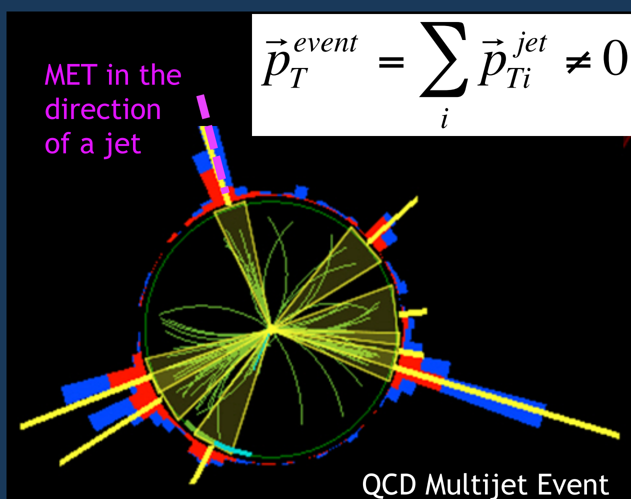

$$\vec{p}_T^{\,event} = \sum_i \vec{p}_{Ti}^{\,jet} \neq 0$$

Detector response <1
Fake MET

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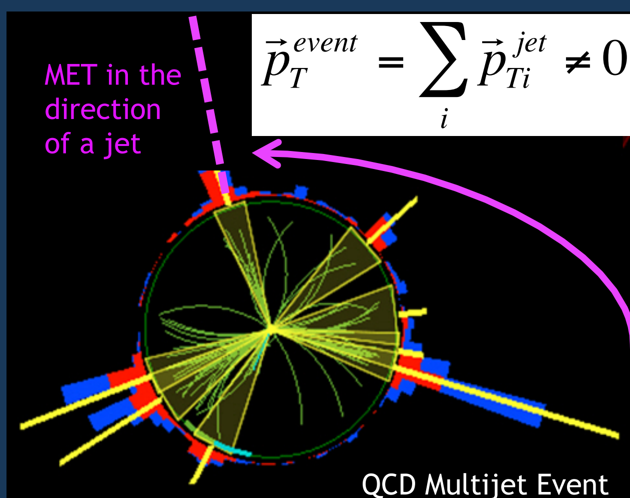

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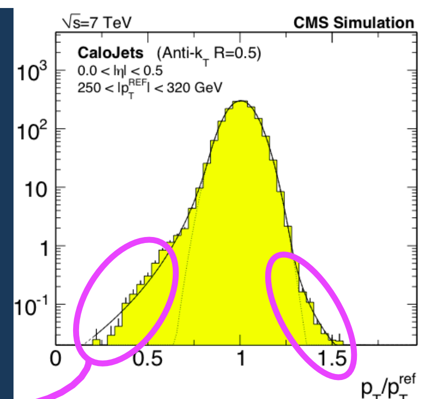


Extreme mis-measurement
⇩
Large fake MET consistent with SUSY signals

(events in the "tails")

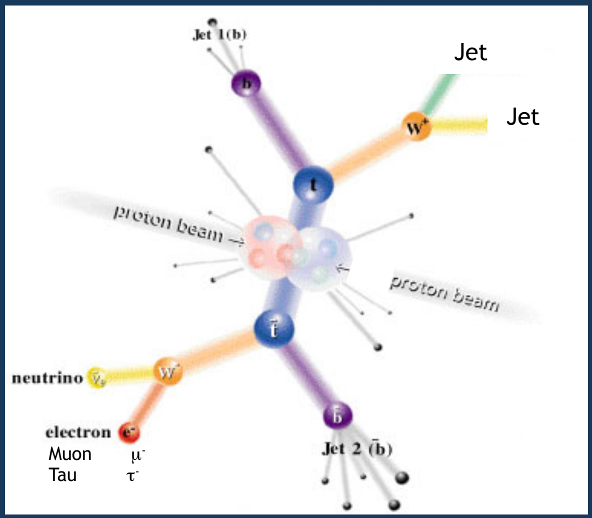
Physics Background

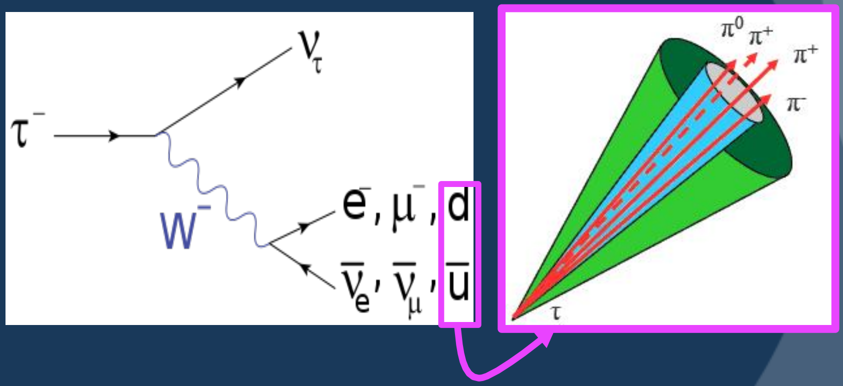
Electroweak (EWK) background:

- W+jets and top production

$$t \rightarrow W(l\nu / jets)b \equiv multijet + MET$$

If W decays to $\tau\nu$ and τ decays hadronically (irreducible background)





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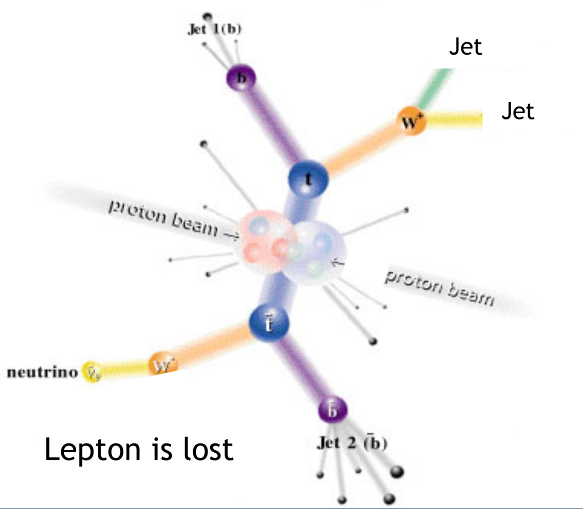
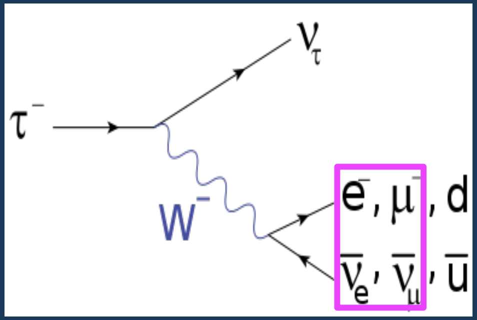
If W decays hadronically or leptonically and e/μ is “lost” (not detected or reconstructed)





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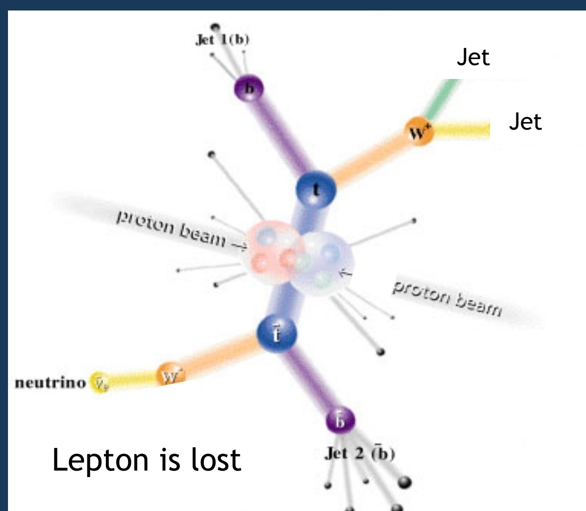
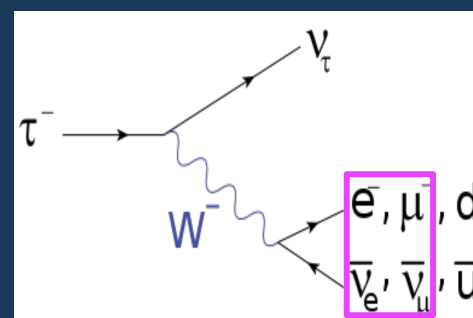




- Z+jets with Z decaying to neutrinos $Z(\nu\bar{\nu}) + jets \equiv multijet + MET$

This background is irreducible: real jets and real MET

MHT All Hadronic Search

Baseline Event Selection (PF objects):

- At least 3 jets with p_T>50 GeV, $|\eta|$<2.5 ⟵ central production
- HT>350 GeV, MHT>200 GeV [From jets with p_T>50 GeV, $|\eta|$<2.5]
- $\Delta\phi$(MET, jet[1,2,3])>[0.5,0.5,0.3] ⟵ suppress QCD background
- Isolated electron and muon veto ⟵ reduce W/top background

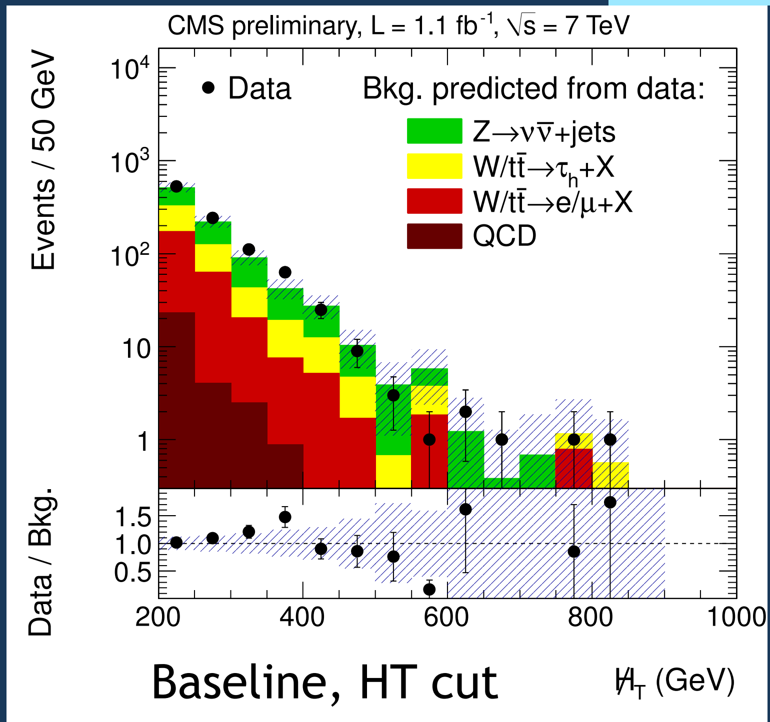
Search regions:

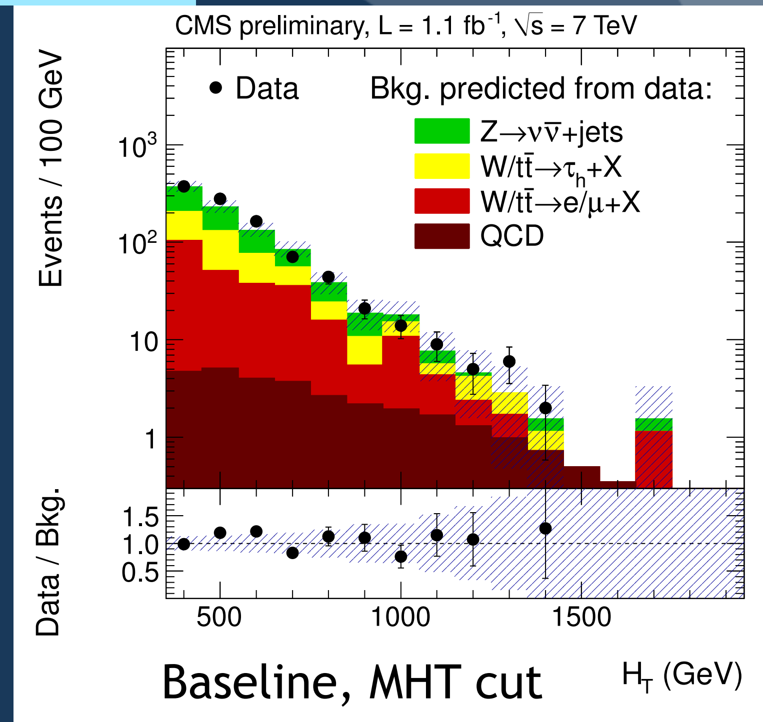
- High-MHT: Baseline + HT>800 GeV, MHT>500 GeV
  (DM candidate - good bkgd rejection)
- High-HT: Baseline + HT>800 GeV
  (heavy particle - long cascade, high multiplicity)
- Medium HT & MHT: Baseline + HT>800 GeV, MHT>500 GeV

Based on 1.1 fb^{-1} of CMS data (Summer 2011)

MHT All Hadronic Search

CMS-PAS-SUS-11-004





Physics generators not accurate enough (QCD multijets, W/Z+jets) → Background predictions extracted from data

Observed data & data driven background prediction

MHT All Hadronic Search

No excess of events is observed in any of the three search regions for 1.1 fb^{-1}

	Baseline (H_T >350 GeV) ($\not{H}_T$ >200 GeV)	Medium (H_T >500 GeV) ($\not{H}_T$ >350 GeV)	High H_T (H_T >800 GeV) ($\not{H}_T$ >200 GeV)	High $\not{H}_T$ (H_T >800 GeV) ($\not{H}_T$ >500 GeV)
$Z \to \nu\bar{\nu}$ from γ+jets	$376 \pm 12 \pm 79$	$42.6 \pm 4.4 \pm 8.9$	$24.9 \pm 3.5 \pm 5.2$	$2.4 \pm 1.1 \pm 0.5$
$t\bar{t}/W \to e, \mu$+X	$244 \pm 20^{+30}_{-31}$	$12.7 \pm 3.3 \pm 1.5$	$22.5 \pm 6.7^{+3.0}_{-3.1}$	$0.8 \pm 0.8 \pm 0.1$
$t\bar{t}/W \to \tau_h$+X	$263 \pm 8 \pm 7$	$17 \pm 2 \pm 0.7$	$18 \pm 2 \pm 0.5$	$0.73 \pm 0.73 \pm 0.04$
QCD	$31 \pm 35^{+17}_{-6}$	$1.3 \pm 1.3^{+0.6}_{-0.4}$	$13.5 \pm 4.1^{+7.3}_{-4.3}$	$0.09 \pm 0.31^{+0.05}_{-0.04}$
Total background	928 ± 103	73.9 ± 11.9	79.4 ± 12.2	4.6 ± 1.5
Observed in data	986	78	70	3

CMS-PAS-SUS-11-004

At the 95% C.L. the data is consistent with no more than 26, 28 (5) signal events for the medium & high-MHT(HT) search regions

- If I repeat the experiment N→∞ times, 95% of the times the background will fluctuate to accommodate zero to no more than 26, 28 (5) signal events

No Excess Means … Limits

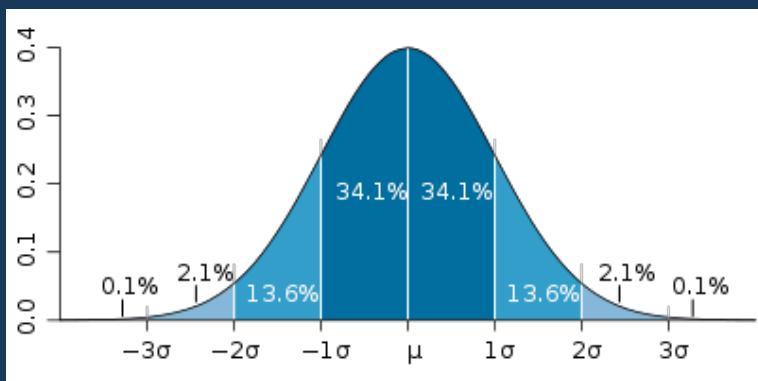
Confidence Intervals (C.I.)

A confidence interval gives an estimated range of values which is likely to include the unknown true value μ of a population parameter X

$$\hat{\mu} = \langle X \rangle = \frac{1}{N}\sum_{i=1}^{n} X_i$$

The estimator of the true parameter value $\hat{\mu}$ is calculated as the mean value $\langle X \rangle$ in a given data sample

I repeat the experiment N (e.g. 100) times, each experiment generating M (e.g. 1000) values of X



Central C.I. for Normal Distribution

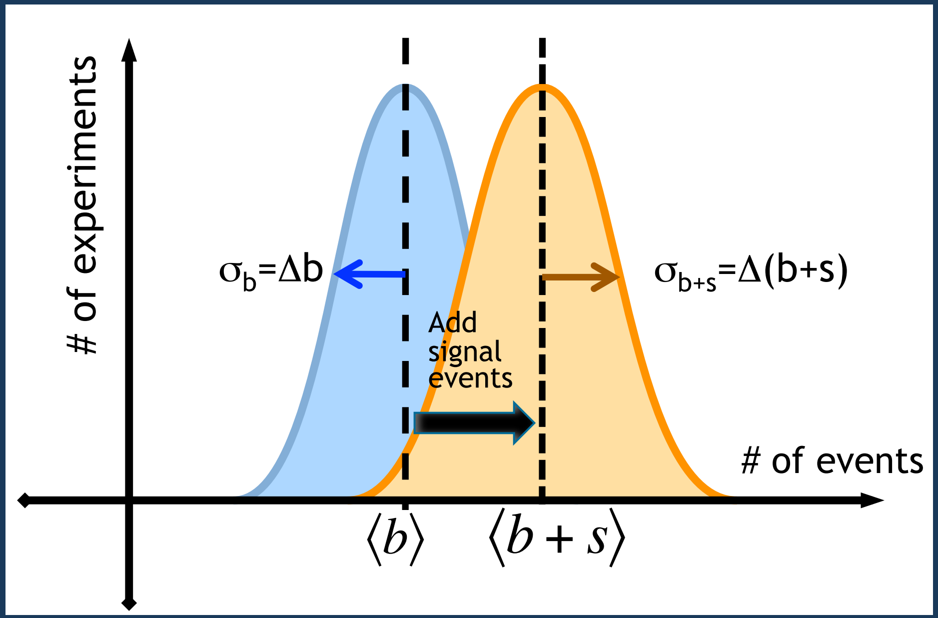
- 1σ → 68.27%
- 2σ → 95.45%
- 3σ → 99.75%
- 5σ → 99.99994%

The "level" of a confidence interval (C.L. 90%, 95%, 99%, …) refers to the number of times (n/N*100 experiments) the interval will contain the true value

Expected Limit

- Generate ensemble of N experiments using the measured <b>+Δb distribution (<b> is mean of a Poisson, Δb is Gaussian)

- Question: how many signal events (s) can I add so that the b+s C.I. includes the background only prediction, <b>, 95% of the times?



Expected Limit on signal at the 95% C.L.

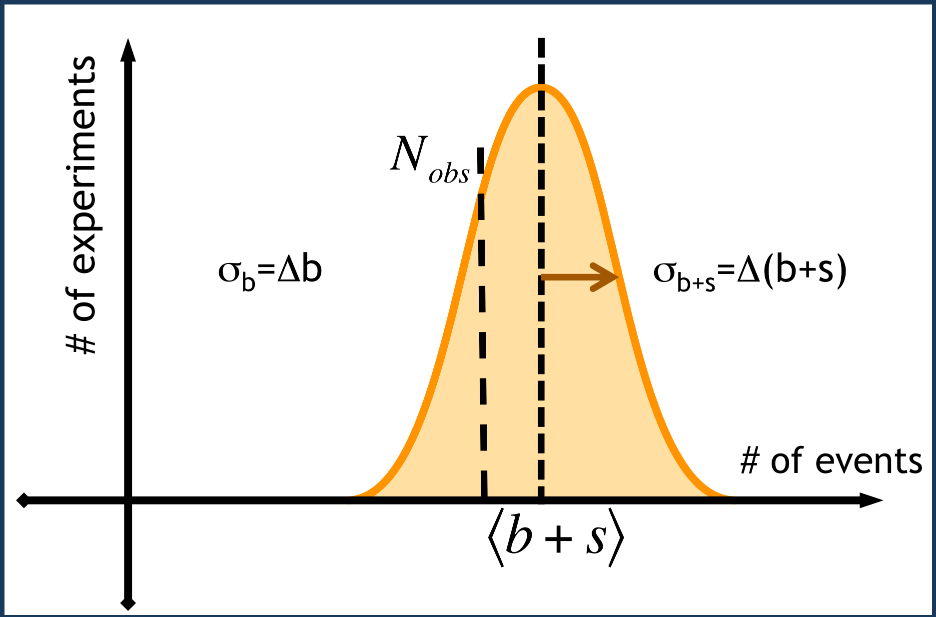
- maximum # of signal events the sample may contain consistent with <b>
- Limit translated to production x-section or masses

  (theory models and signal acceptance/efficiency)

Observed Limit

- Generate ensemble of N experiments using the measured <b>+Δb distribution (signal contamination subtracted ~3 evts.)

- Question: how many signal events (s) can I add so that the b+s C.I. includes the # of observed events, N_{obs}, 95% of the times?



Observed Limit on signal at the 95% C.L.

- maximum # of signal events the sample may contain consistent with N_{obs}
- Limit translated to production x-section or masses

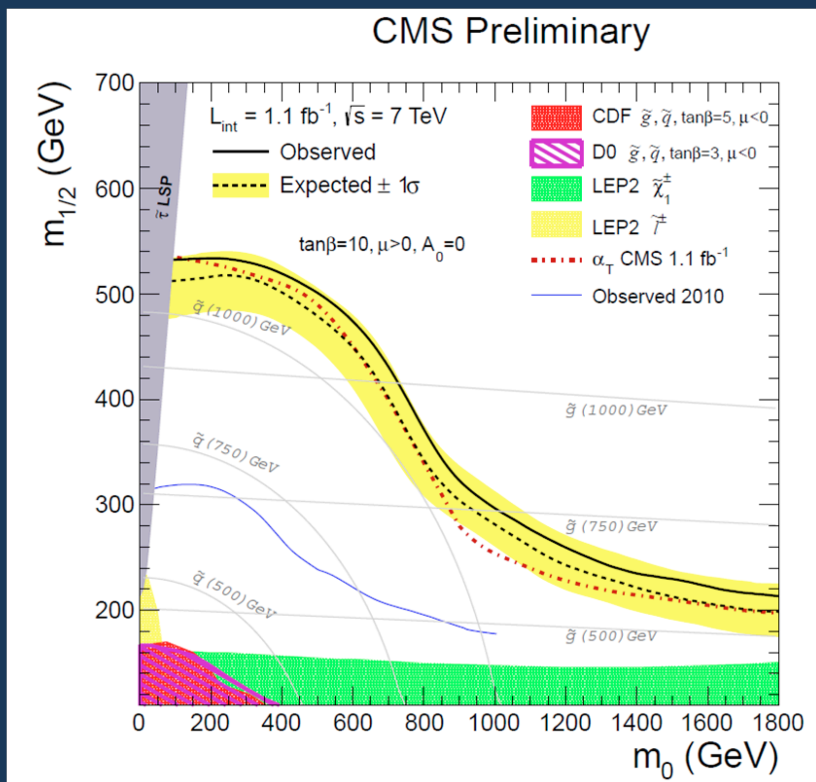
  (theory models and signal acceptance/efficiency)

Comments on Limits

- Expected Limit is expressed as a band consistent with $\langle b \rangle \pm \Delta b$
- If N_{obs} is greater than $\langle b \rangle$, the observed limit is less than the expected
  - ✓ Small excess not "significant", most probably occurred by chance
- If N_{obs} is less than $\langle b \rangle$, the observed limit is greater than the expected
  - ✓ Deficit means that data fluctuated low
- Zero background hypothesis is the most conservative for setting a limit
  - ✓ Lowest limit
- Zero background hypothesis is the least conservative for a discovery
  - ✓ Largest probability of wrongly accepting the signal hypothesis

Interpretation within the cMSSM

The contours are the envelope with respect to the best sensitivity of the three HT & MHT search selections

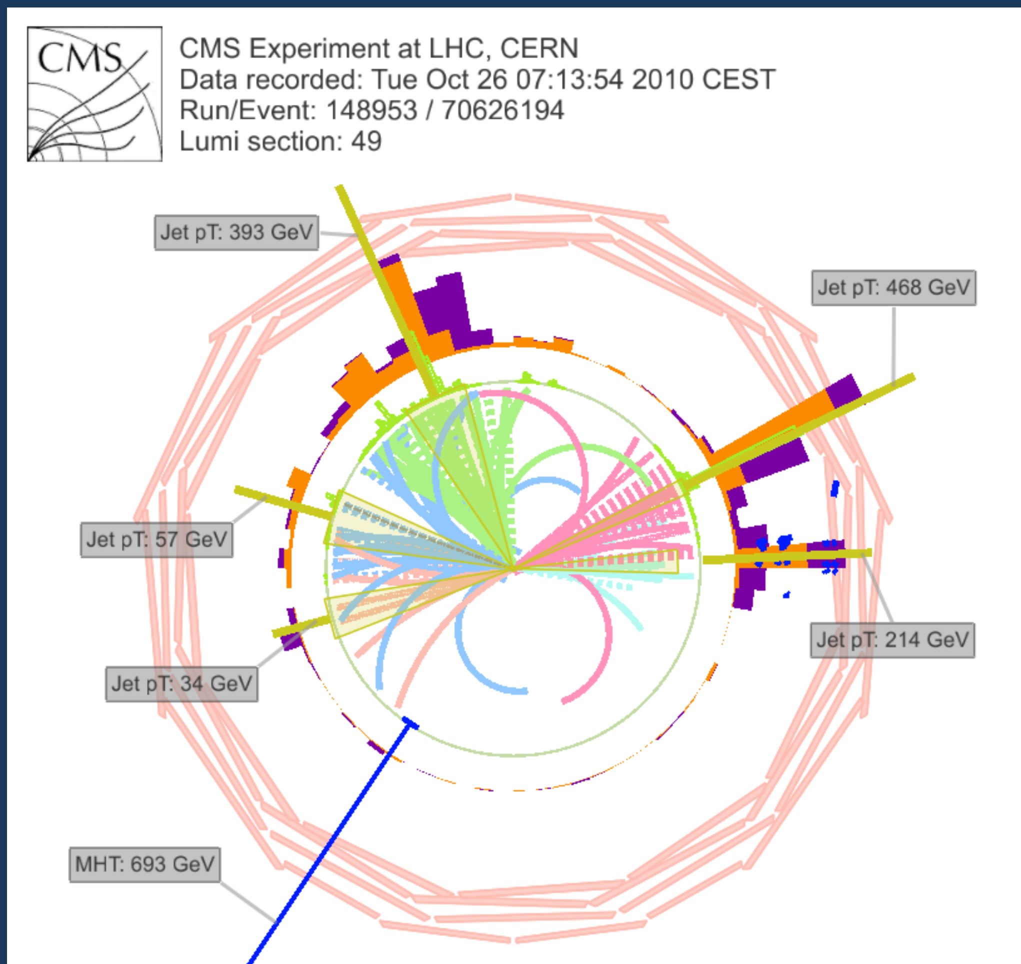


CMS-PAS-SUS-11-004

tan β=10, μ>0, A_0=0

- At low m_0 , gauginos at excluded at the 95% C.L. for a common mass at the GUT scale $m_{1/2}$ < 530 GeV
- At m_0 = 1.5 TeV, the exclusion reaches $m_{1/2}$ < 230 GeV
- m_{gluino} < 0.6 TeV and m_{squark} <1.1 TeV are excluded a the 95% C.L.
- Significant extension with respect to the 2010 35 pb^{-1} (solid blue line)

A Candidate Event



MHT = 693 GeV
HT= 1132 GeV
M_{eff}= MHT+HT = 1.83 TeV
No b-tagged jet
No isolated lepton
Incompatible with W or top mass

Outline

Who is SUSY, does she exist ?

- SUSY's characteristics (looks) and why we search for her

Search Tools

- Detectors, reconstructed objects

Search Strategy

- Data selection, background subtraction, statistical analysis

Search Results: SUSY is still missing

- Results and exclusions of searched areas

Is SUSY dead, hiding ?

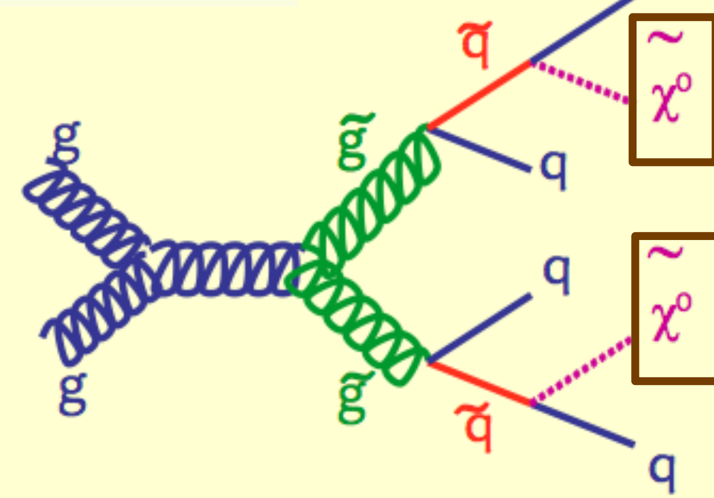
- Search strategies for 2012

CMS Search Strategy: Topologies

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Most sensitive channel for strongly produced SUSY
- Complementary analyses:
  - Generic search using MHT (previous slides) – detector understanding
  - Search using α_T - background mitigation (kinematics)
  - "Razor" variables – background mitigation with high signal efficiency (kinematics)

Example diagram

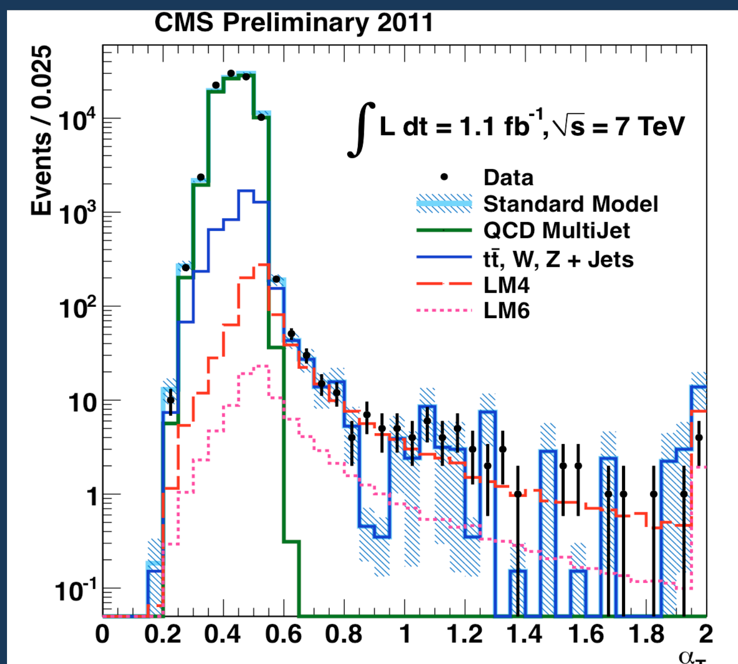


Gravity mediation – LSP: neutralino

Jets+MET Search using α_T

Simple and robust analysis with emphasis on background reduction at the cost of signal efficiency ➔ appropriate for early data

- Cut on kinematic info (α_T variable): signal region nearly QCD free
- Background dominated by events with real MET: W/Z+jets and top

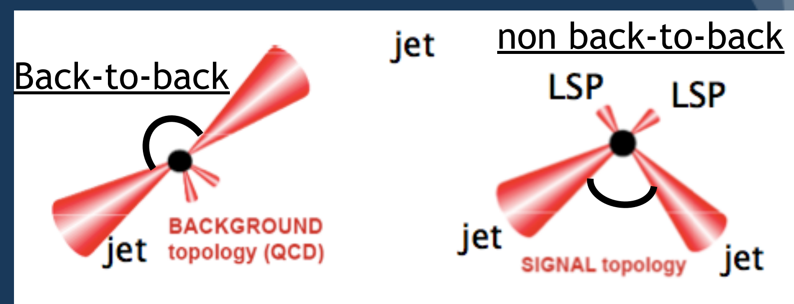


α_T for HT ≥ 375 GeV and MHT > 100 GeV.

Accepted by PRL & arXiv:1109.2352

PRL 101:221803 (2008) & arXiv:1101.1628

$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}} = \frac{1}{2}\frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \not{H}_T^2}}$$



Expectation for QCD: α_T=0.5

Jet mis-measurement: α_T<0.5

Signal enhanced: α_T>0.5

Jets+MET Search: Summary

Multi-variable strategy: redundancy, complementarity for discovery

MHT Search 1.1 fb^{-1}	Baseline (H_T >350 GeV) ($\not{H}_T$ >200 GeV)	Medium (H_T >500 GeV) ($\not{H}_T$ >350 GeV)	High H_T (H_T >800 GeV) ($\not{H}_T$ >200 GeV)	High $\not{H}_T$ (H_T >800 GeV) ($\not{H}_T$ >500 GeV)
Total background	928 ±103	73.9 ±11.9	79.4 ±12.2	4.6 ±1.5
Observed in data	986	78	70	3

α_T Search 1.1 fb^{-1}	H_T bin (GeV)	275–325	325–375	375–475	475–575	575–675	675–775	775–875	>875
	SM hadronic	787^{+32}_{-22}	310^{+8}_{-12}	202^{+9}_{-9}	$60.4^{+4.2}_{-3.0}$	$20.3^{+1.8}_{-1.1}$	$7.7^{+0.8}_{-0.5}$	$3.2^{+0.4}_{-0.2}$	$2.8^{+0.4}_{-0.2}$
	Data hadronic	782	321	196	62	21	6	3	1

MT2 Search 1.1 fb^{-1}

$Bkgd(M_{T2} \geq 400\text{GeV}) = 12.6 \pm 1.3 \pm 3.5$ events 12 events observed

$Bkgd(M_{T2} \geq 150\text{GeV}) = 10.6 \pm 1.9 \pm 4.8$ events 19

CMS-PAS-SUS-11-005

Many search regions in HT, MHT, MT2, α_T explore different ranges of m_0-$m_{1/2}$ phase space within cMSSSM

No significant excess observed with respect to SM background predictions in any of the hadronic searches

Jets+MET Search: Summary

Interpretation within the CMSSM framework

α_T:

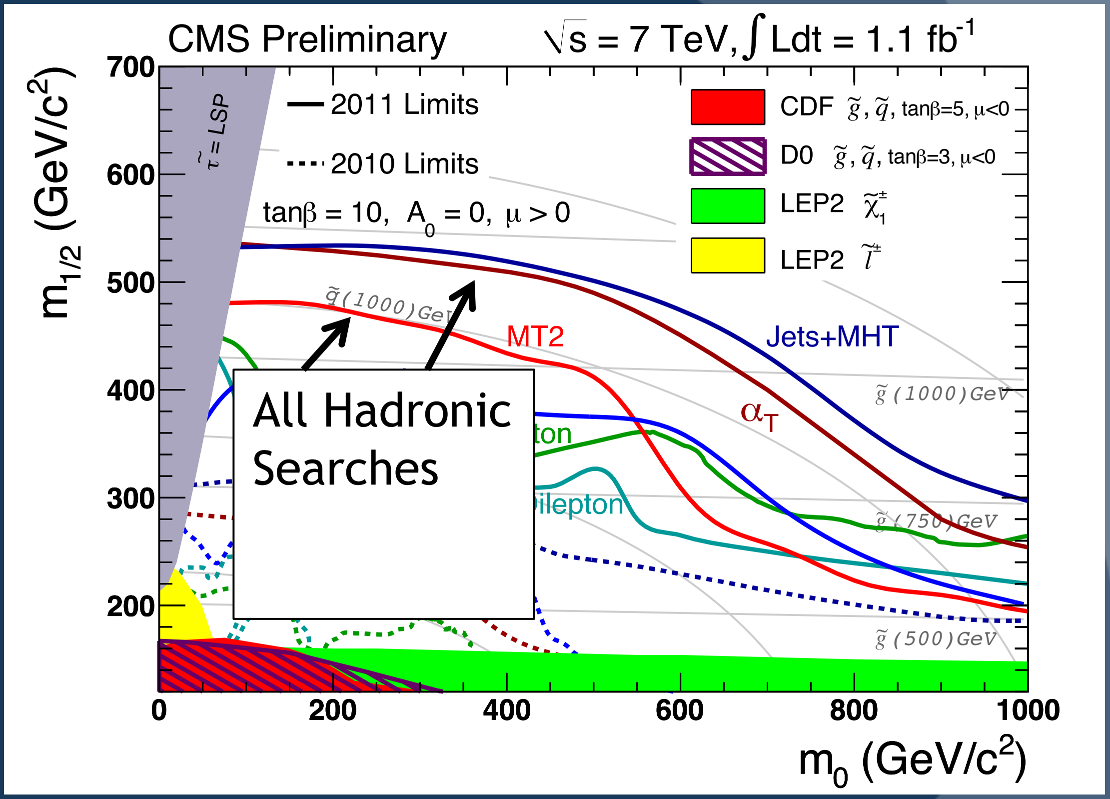
- First LHC SUSY paper
- Target discovery with early data

MHT:

- Good understanding of detector for …
- High signal efficiency, accurate bkgnd prediction

MT2:

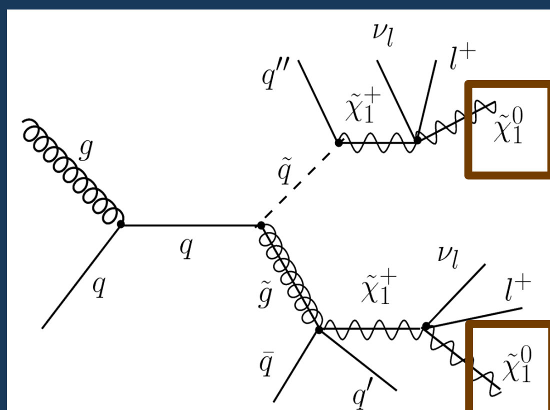
- Reflects the mass of the produced particle
- New physics would show at high MT2 through excess

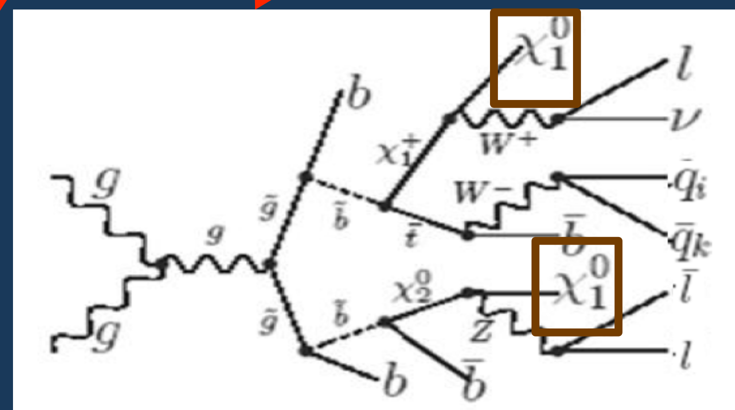


Relative performance of variables depend on signal efficiency, background uncertainty, search region optimization

CMS Search Strategy: Topologies

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET





Gravity mediation

LSP: is the neutralino

Leptons requirement: low background but also low signal efficiency

- Single lepton – QCD small, W+jets/ttbar largest
- Two leptons – OS: QCD tiny, W+jets small, ttbar dominates (OS). SS: bkgnd reduced to dibosons, charge mis-ID, fake leptons
- Multi-leptons – bkgnd is tiny: WZ, ZZ, WW, fake leptons

Leptonic Searches: Summary

CMS-PAS-SUS-11-015/011/010

Lepton Projection:
High MET ➔ low $p_T(l)$

$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

$$S_T^{lep} = p_T(\ell) + \not{E}_T$$

Single Lepton 1.1 fb^{-1}	Signal Region (L_P <0.15)			
S_T^{lep} Range (GeV)	QCD	EWK	SM estimate	Data
[150-250]	1.0±0.3	60.8±4.1	61.8±8.7	69
[250-350]	0	22.2±2.2	22.2±4.4	21
[350-450]	0	6.9±1.5	6.9±1.7	7
> 450	0	4.3±1.3	4.3±1.5	3

e^-e^+
$\mu^-\mu^+$
$e^\pm\mu^\mp$

OS lepton Search 1 fb^{-1}	$E_T^{miss} > 275$ GeV, $H_T > 300$ GeV high E_T^{miss} signal region	$E_T^{miss} > 200$ GeV, $H_T > 600$ GeV high H_T signal region
observed yield	8	4
MC prediction	7.3 ± 2.2	7.1 ± 2.2
ABCD′ prediction	4.0 ± 1.0 (stat) ± 0.8 (syst)	4.5 ± 1.6 (stat) ± 0.9 (syst)
$p_T(\ell\ell)$ prediction	14.3 ± 6.3 (stat) ± 5.3 (syst)	10.1 ± 4.2 (stat) ± 3.5 (syst)
N_{bkg}	4.2 ± 1.3	5.1 ± 1.7

SS lepton Search 1 fb^{-1}

Different Search Regions in HT, MET for: $ee, \mu\mu, e\mu, e\tau, \mu\tau, \tau\tau$

Observation consistent with SM predictions for all channels

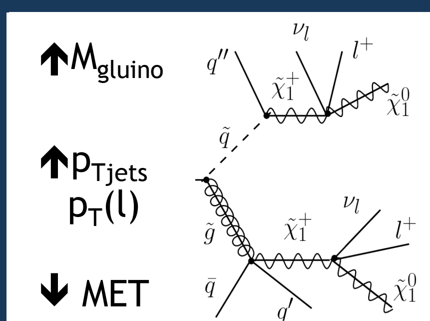
No excess of events with respect to SM background predictions for single lepton, OS, and SS dilepton channels

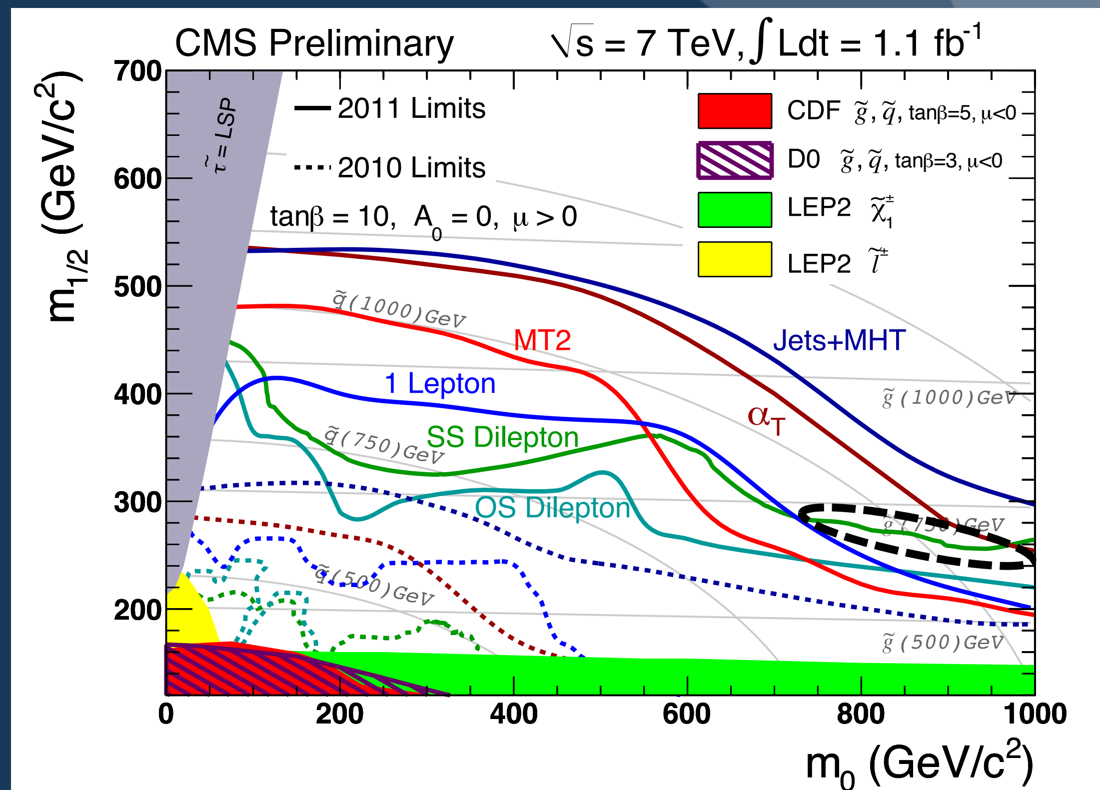
Leptonic Searches: Summary

Interpretation within the CMSSM framework

- Leptonic < hadronic limits at low & medium m_0
- Leptonic limits (SS) competitive at high m_0

H_T> 400 GeV
MET> 50 GeV





2011 Leptonic limits based on 1.1 fb^{-1} significantly higher than 2010 limits based on 35 pb^{-1}

Multilepton Search

At least 3 isolated leptons, ≥ 1 electron or μ

- Multiple signal regions: 3 or ≥4 leptons, MET/HT, Z or no-Z, N(τ) → 52 exclusive bins

CMS-PAS-SUS-11-013

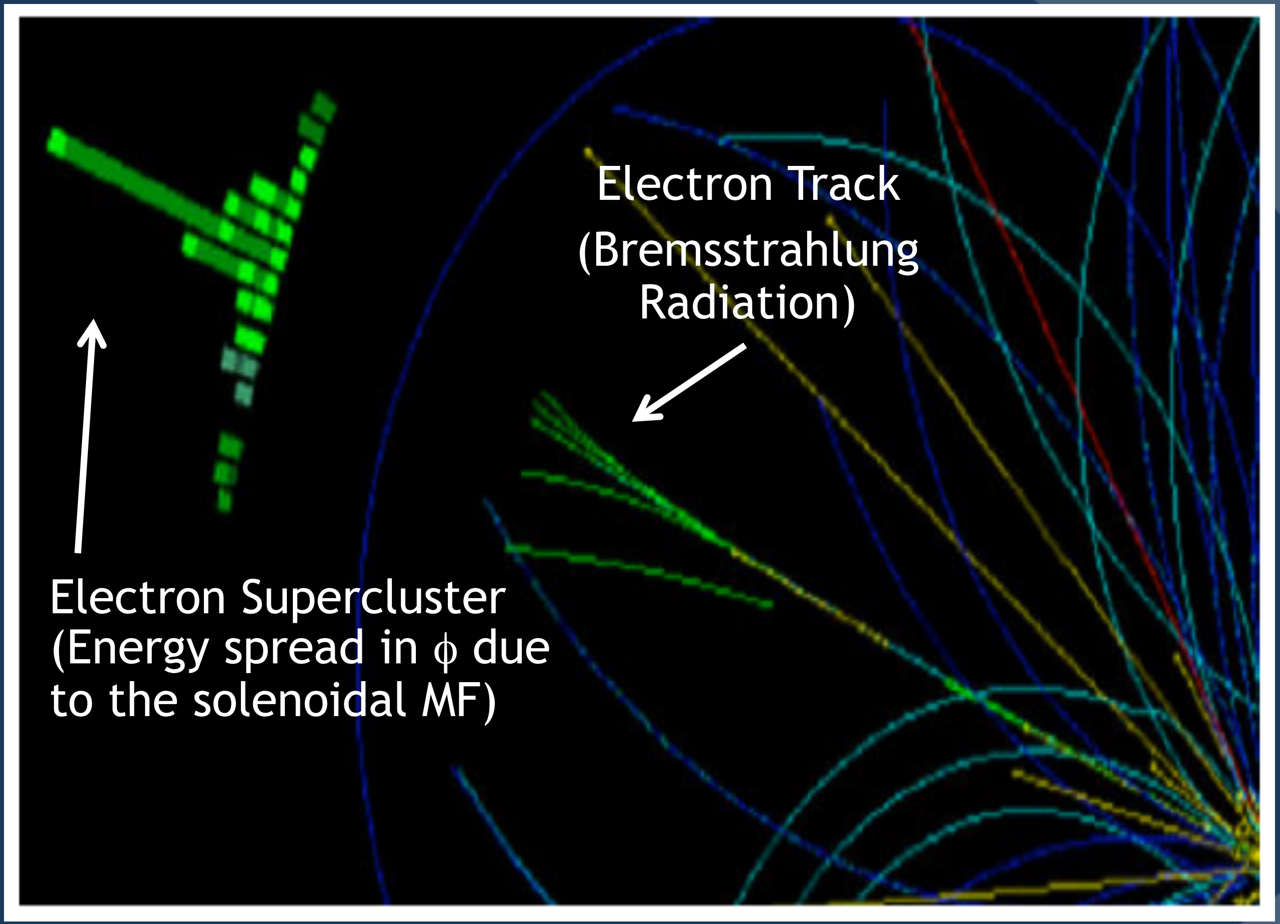
2.1 fb^{-1}

Results largely consistent with SM expectations

Slight excess in some channels no surprising in low statistics analysis

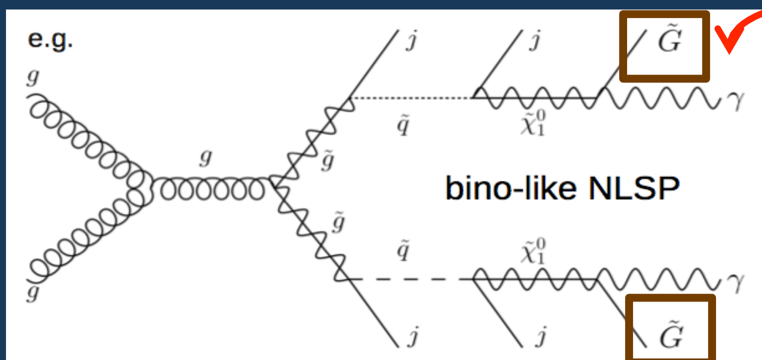
Selection	N(τ)=0		N(τ)=1		N(τ)=2	
	obs	expected SM	obs	expected SM	obs	expected SM
≥FOUR Lepton Results						
MET>50,H_T >200,noZ	0	0.003 ± 0.002	0	0.01 ± 0.05	0	0.30 ± 0.22
MET>50,H_T >200, Z	0	0.06 ± 0.04	0	0.13 ± 0.10	0	0.15 ± 0.23
MET>50,H_T <200,noZ	1	0.014 ± 0.005	0	0.22 ± 0.10	0	0.59 ± 0.25
MET>50,H_T <200, Z	0	0.43 ± 0.15	2	0.91 ± 0.28	0	0.34 ± 0.15
MET<50,H_T >200,noZ	0	0.0013 ± 0.0008	0	0.01 ± 0.05	0	0.18 ± 0.07
MET<50,H_T >200, Z	1	0.28 ± 0.11	0	0.13 ± 0.10	0	0.52 ± 0.19
MET<50,H_T <200,noZ	0	0.08 ± 0.03	4	0.73 ± 0.20	6	6.9 ± 3.8
MET<50,H_T <200, Z	11	9.5 ± 3.8	14	5.7 ± 1.4	39	21 ± 11
THREE Lepton Results						
MET>50,H_T >200,no-OSSF	2	0.87 ± 0.33	21	14.3 ± 4.8	12	10.4 ± 2.2
MET>50,H_T <200,no-OSSF	4	3.7 ± 1.2	88	68 ± 17	76	100 ± 17
MET<50,H_T >200,no-OSSF	1	0.50 ± 0.33	12	7.7 ± 2.3	22	24.7 ± 4.0
MET<50,H_T <200,no-OSSF	7	5.0 ± 1.7	245	208 ± 39	976	1157 ± 323
MET>50,H_T >200,noZ	5	1.9 ± 0.5	7	10.8 ± 3.3	–	–
MET>50,H_T >200, Z	8	8.1 ± 2.7	10	11.2 ± 2.5	–	–
MET>50,H_T <200,noZ	19	11.6 ± 3.2	64	52 ± 13	–	–
MET<50,H_T >200,noZ	5	2.0 ± 0.7	24	26.6 ± 3.3	–	–
MET>50,H_T <200, Z	58	57 ± 21	47	44.1 ± 7.0	–	–
MET<50,H_T >200, Z	6	8.2 ± 2.0	90	119 ± 14	–	–
MET<50,H_T <200,noZ	86	82 ± 21	2566	1965 ± 438	–	–
MET<50,H_T <200, Z	335	359 ± 89	9720	7740 ± 1698	–	–
Totals 4L	13.0	10.4 ± 3.8	20.0	7.8 ± 1.5	45	30 ± 12
Totals 3L	536	539 ± 94	12894	10267 ± 1754	1086	1291 ± 324

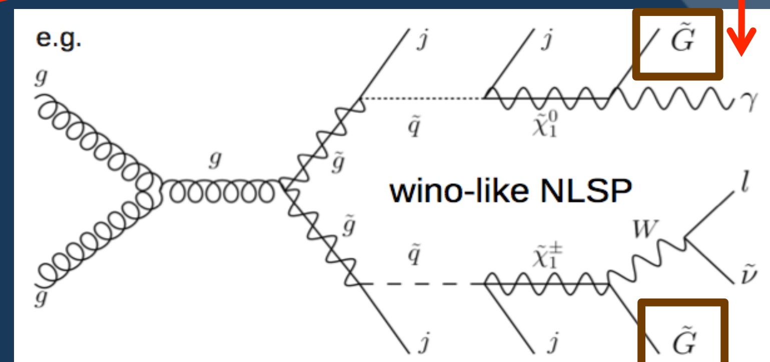
An Electron


Electron Track
(Bremsstrahlung
Radiation)
Electron Supercluster
(Energy spread in ϕ due
to the solenoidal MF)

CMS Search Strategy: Topologies

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET





Gauge Mediation - LSP: is the gravitino photons in final state

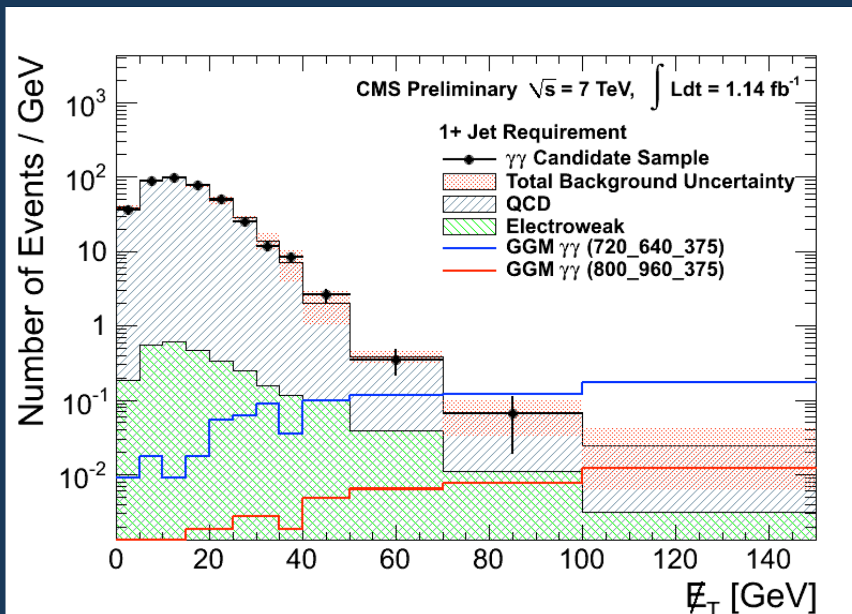
Backgrounds: fake MET (QCD), real MET (EWK)

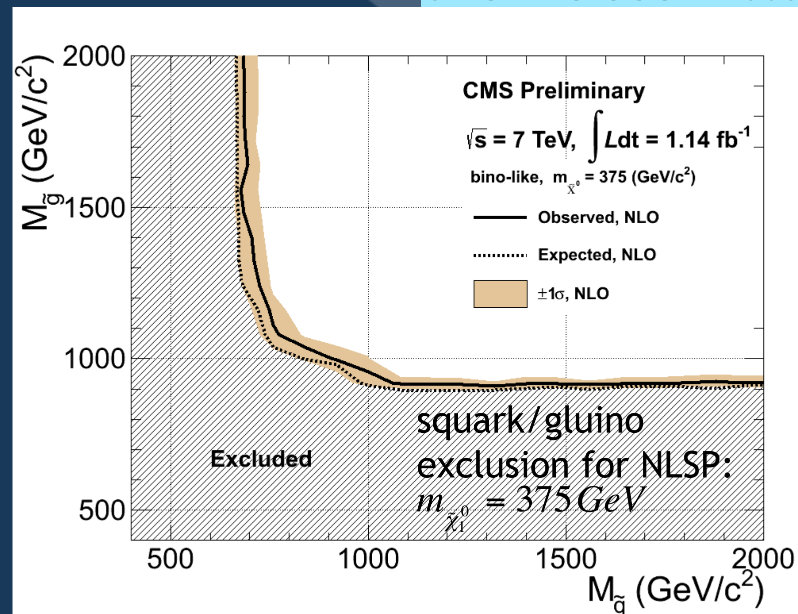
- Diphotons – QCD from prompt 2γ, γ+jets, multijets (MET from mis-measured jets). EWK from Wγ and top (e mis-ID as γ)
- Photon+lepton – Wγ. Z, ttbar (e mis-ID as γ). Multijets, W+jets

Diphoton Search

At least 2 photons, ≥ 1 jet, MET>100 GeV

CMS-PAS-SUS-11-009





Type	Events	stat. error	scal. error	norm. error
$\gamma\gamma$ candidates	0			
ff QCD background	2.3 ± 2.2	± 2.19	± 0.13	± 0.10
ee QCD background	1.0 ± 0.8	± 0.82	± 0.02	± 0.03
EWK background	0.3 ± 0.1	± 0.06	± 0.0	± 0.03
Total background (ff)	2.5 ± 2.2			
Total background (ee)	1.3 ± 0.8			

No evidence for GM SUSY particles

Outline

Who is SUSY, does she exist ?

- SUSY's characteristics (looks) and why we search for her

Search Tools

- Detectors, reconstructed objects

Search Strategy

- Data selection, background subtraction, statistical analysis

Search Results: SUSY is still missing

- Results and exclusions of searched areas

Is SUSY dead, hiding ?

- Search strategies for 2012

Is MSSM ruled out ?

If a Higgs between 114 and 135 GeV was excluded, then the answer would be yes but NMSSM & other extended models would remain

Assuming a SM-like Higgs is discovered:

- cMSSM (constrained MSSM) depends on only 5 parameters:
  - ✓ m_0, $m_{1/2}$, A_0, tan β, sgn(μ)

  A significant fraction of cMSSM phase space remains unexplored

- pMSSM (phenomenological MSSM) depends on 19 parameters:
  - ✓ 10 sfermion, 3 gaugino masses, 3 tri-linear couplings, 3 Higgs/Higgsino

  pMSSM has not been explored yet

- General CP-conserving MSSM with R-parity conservation has 124 parameters

  Offers an even larger fraction of unexplored phase space

MSSM is alive and kicking, not even cMSSM is dead

The Simplified Models

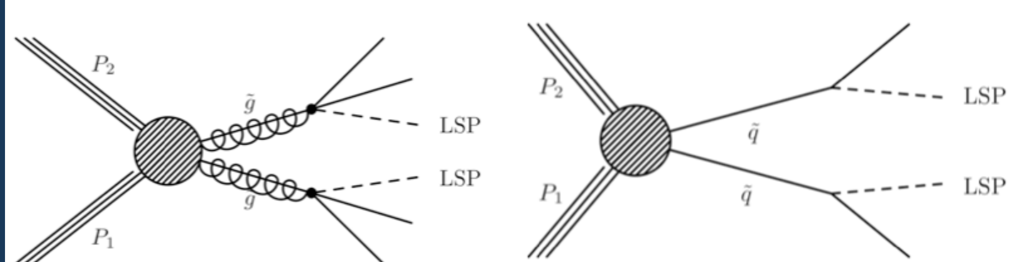
SUSY depends on a large number of unconstrained parameters

- Cross sections depend little on the details of the SUSY model
- Kinematics determined mostly by pdfs and phase space factors associated with 2/3-body decays

Simplified Models (SMS)

- Characterize data in terms of small number of basic parameters (~2 x-sections, ~3 masses, ~3 branching ratios)
- Group large sectors of parameter space into a few SMS with similar final state topologies
- Experimental data translated to more detailed frameworks using SMS

Alwall, Schuster, Toro: Phys. Rev. D79, 075020 (2009) arXiv:0810.3921[hep-ph]



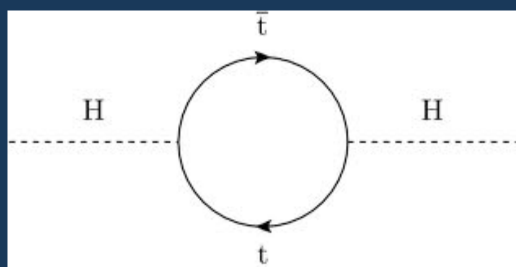
Gluino pair production   squark pair production

SMS currently used to set limits in CMS

The Hierarchy Problem Revisited

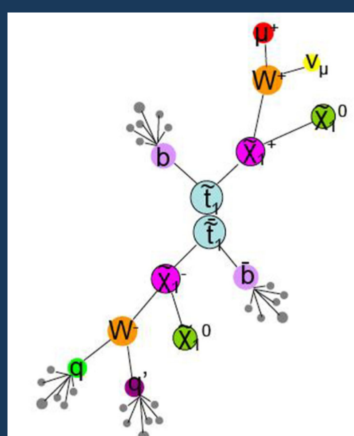
But CMS/ATLAS ruled out cMSSM squarks and gluinos above 1.1 TeV in a large region of m_0, $m_{1/2}$ space

- $M_{sparticles} \approx M_{particles}$ for Higgs mass to be stable (1.1 TeV >> 1 MeV-200 GeV range !)



Yukawa Coupling for H-q_{top} >> H-q_{others}

- Only the top loop really needs to be cancelled by the stop loop
- A light stop is all that is needed ~0.5-1 TeV



$$\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{\chi}_1^0 W^{\pm(*)} \rightarrow b\tilde{\chi}_1^0 l\nu \quad \text{or } b\tilde{\chi}_1^0 q\tilde{q}$$

Signature: 0/1/2 leptons + jets (2 b-jets)+ MET (high particle multiplicity, low MET)

2012: Focus on stop and sbottom searches
(searches with b-jets and τ in final state recently approved – not shown today)

The Unexplored cMSSM Region

High m_0 & low $m_{1/2}$

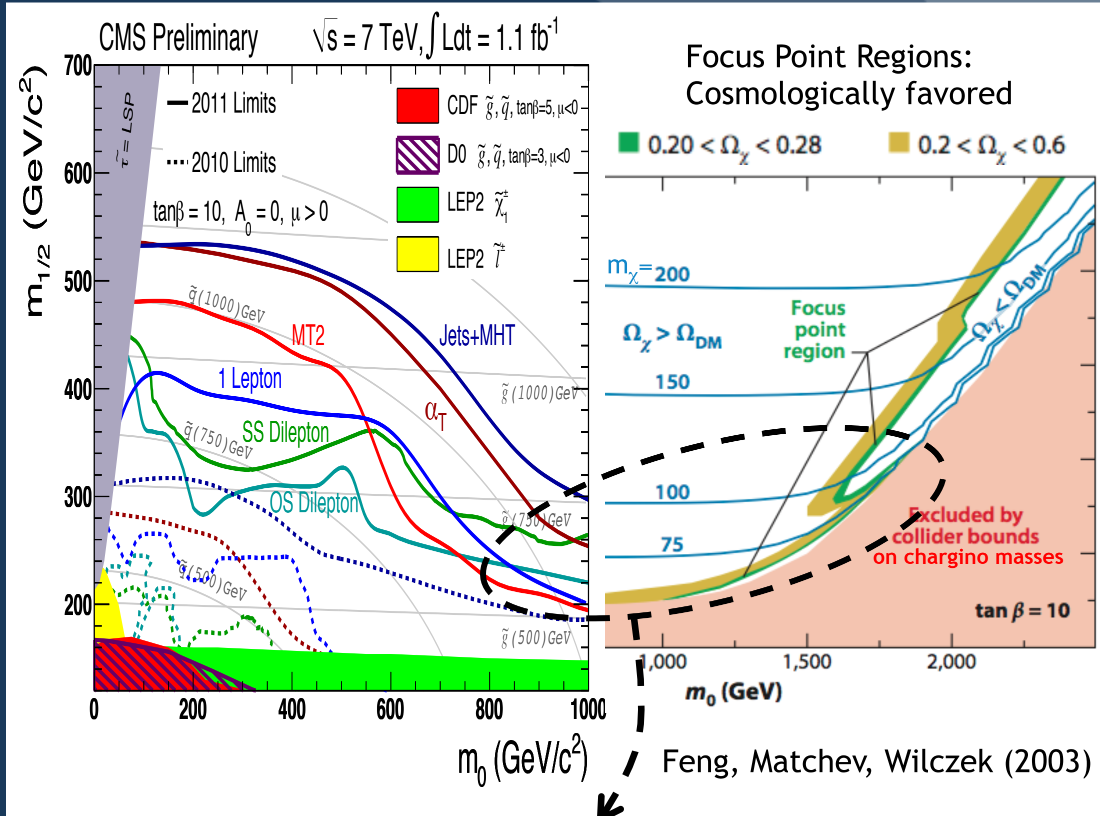
↓

High m_{sq}, gluino production dominates

(Long cascades, high jet multiplicity, ≥4, low MET

↓

Relatively light neutralino $m_\chi \approx 100$ GeV)



stop, sbottom, long cascades with low MET

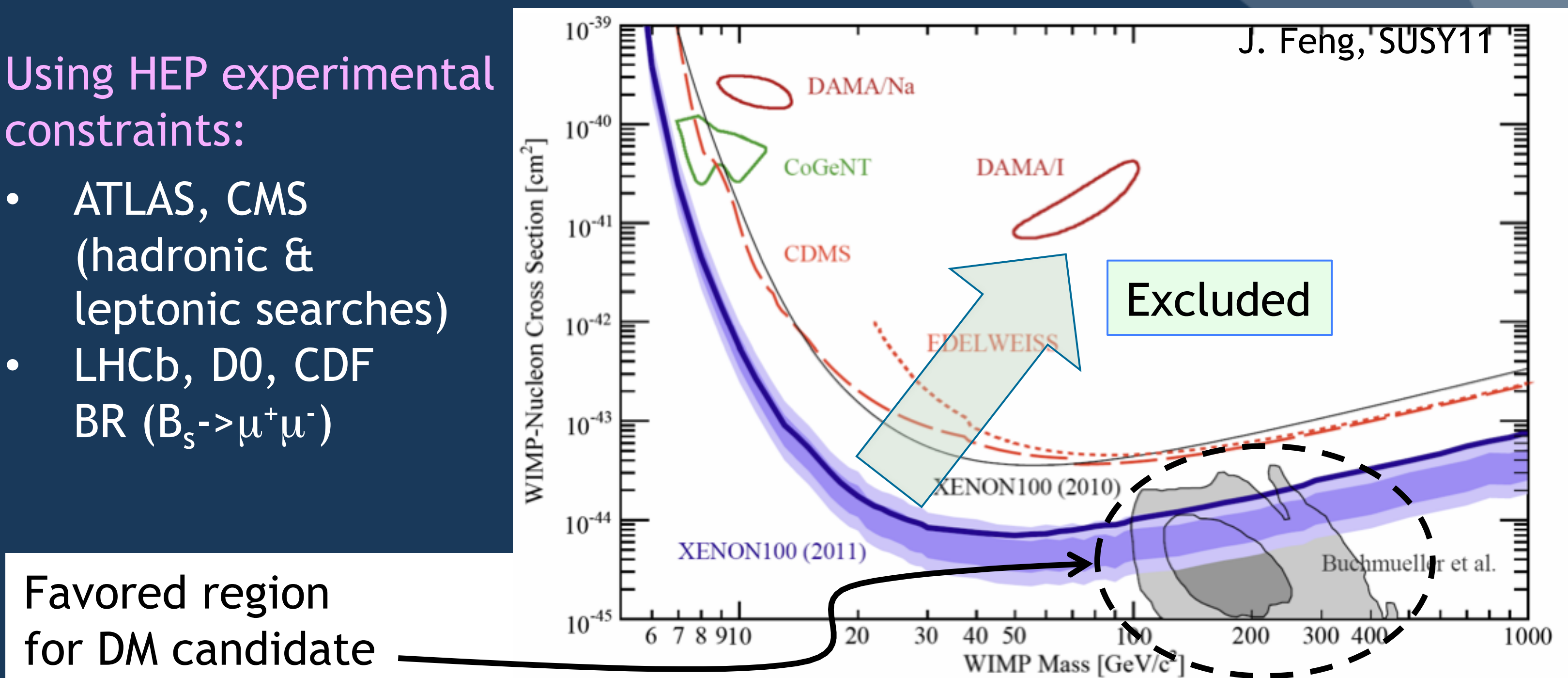
2012: Focus also on searches for events with high jet multiplicity and relatively low MET

A Message from the Cosmos

EDELWEISS, CDMS, XENON100 WIMP mass exclusion limits

Using HEP experimental constraints:

- ATLAS, CMS (hadronic & leptonic searches)
- LHCb, D0, CDF BR ($B_s \to \mu^+\mu^-$)



LHC has excluded models with low cross sections, and left those with extremely bright prospects for DM detection

This is not the end …

… but the beginning

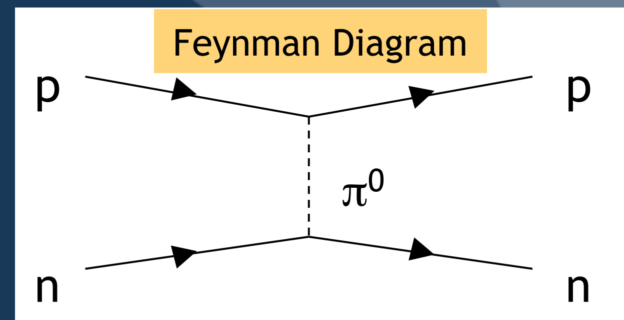
of one of the most exciting periods in the history of particle physics

Joint the search, the fun, and hopefully the thrill of discovery

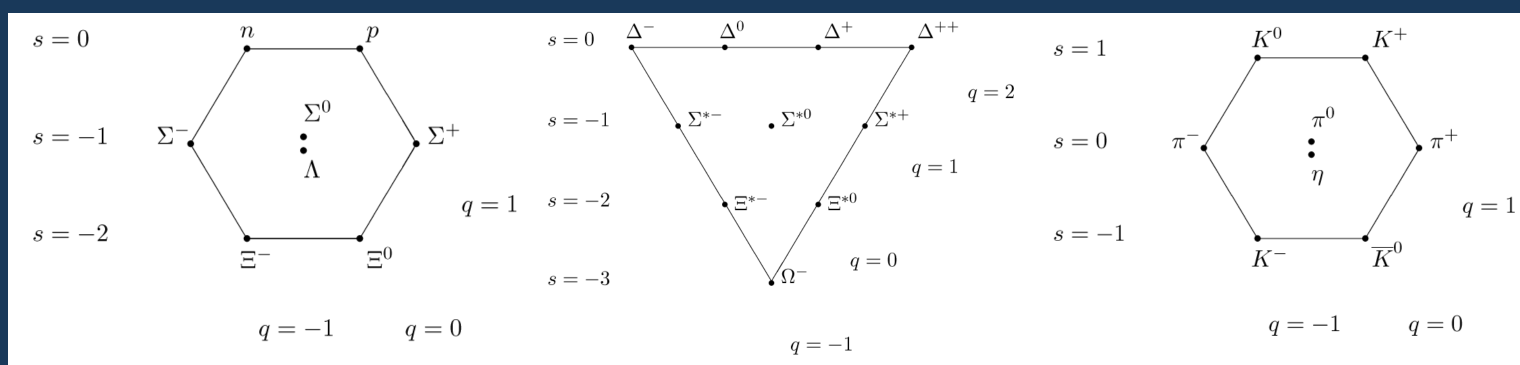
Backup Slides

Nuclear Forces

- Yukawa theory (1934): nuclear interaction mediated by mesons *(pion)*



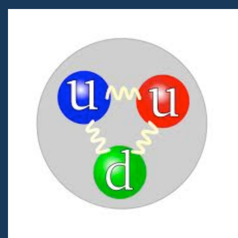
- Through the 50's and 60's a depressingly large number of hadrons were discovered



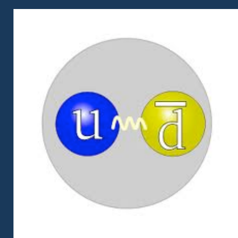
- "Eightfold Way" model first attempt at a classification

The Quark Model

<u>Gel-Mann and Zweig (1961):</u> all hadrons composed of *quarks*



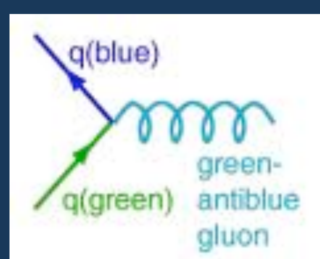
Baryon
(i.e. proton)

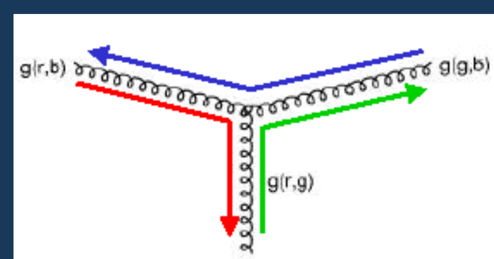


Meson (i.e. pion)

<u>Quantum Chromodynamics (QCD)</u> – theory of strong interactions

- *Quarks* are fundamental fields, interact via *gluon* exchange
- *Quarks* carry one of three color charges, and *gluons* carry two
- *Gluons* couple with *gluons* (3-*gluon* vertex)





ATLAS/CMS Detector Comparison

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels + strips TRD → particle identification B= 2T $\sigma/p_T \sim 5\text{x}10^{-4}\ p_T(\text{GeV}) \oplus 0.01$	Si pixels + strips No particle identification B= 4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\ p_T\,(\text{GeV}) \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7\%$ at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

Fabiola Gianotti's

Detector Performance Definitions

Concepts

Object Identification Efficiency:

- Probability to reconstruct a physics object in the detector and identify it as the real particle that originated the signature (e, γ, μ, τ, hadron, jet)

Object Fake Rate:

- Probability to reconstruct a physics object in the detector and identify it incorrectly as a real particle of a different type that the one that originated the signature

Object Isolation Efficiency:

- Isolation is a requirement for a physics object to be separated in space from others. Isolation Efficiency is the probability for an event with an isolated object to pass a given isolation requirement

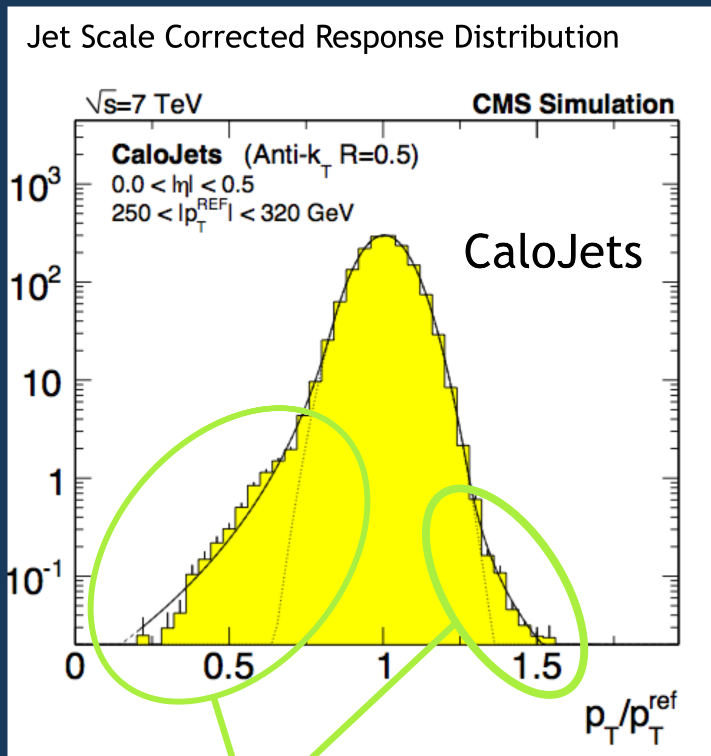
Object Response/Resolution:

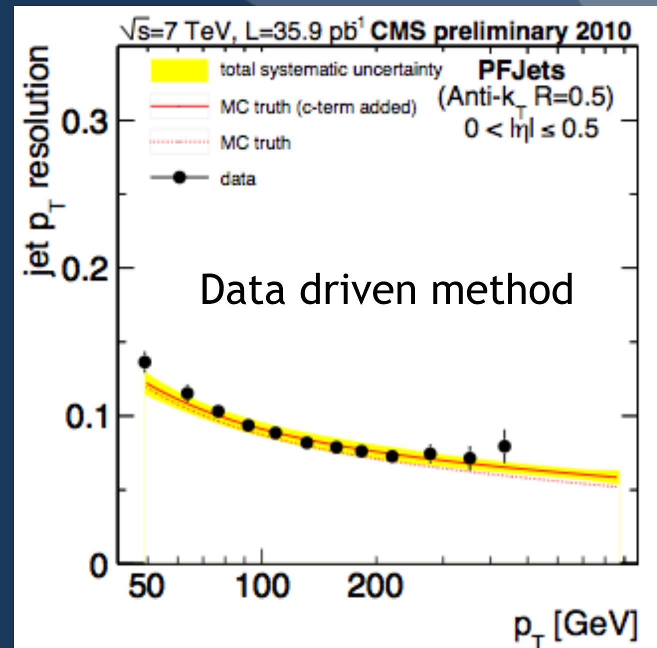
- Energy/momentum response is the fraction of energy/momentum reconstructed by the detector. Resolution is the variance of the response distribution

Angular Coverage & Hermeticity:

- Angular Coverage refers to the solid angle covered by the detector. A detector is Hermetic if no particle escapes beyond its boundaries

Jet Performance





Understanding tails critical for SUSY searches: events with fake large MET

Excellent MC modeling of jet relative p_T resolution: σ_{pT}/p_T

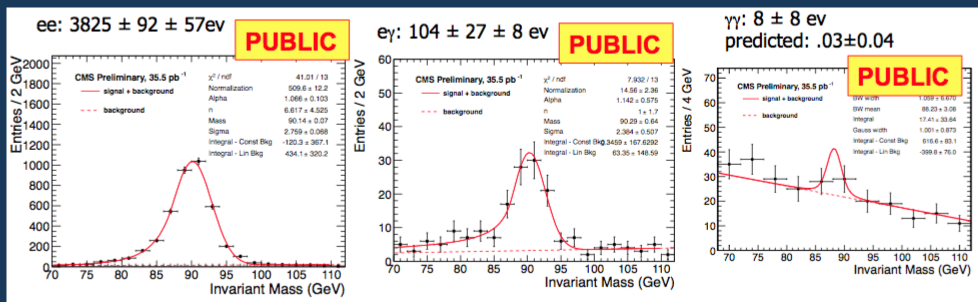
Resolution measured from data using p_T balance in dijet events

The Tag & Probe Method

Concept

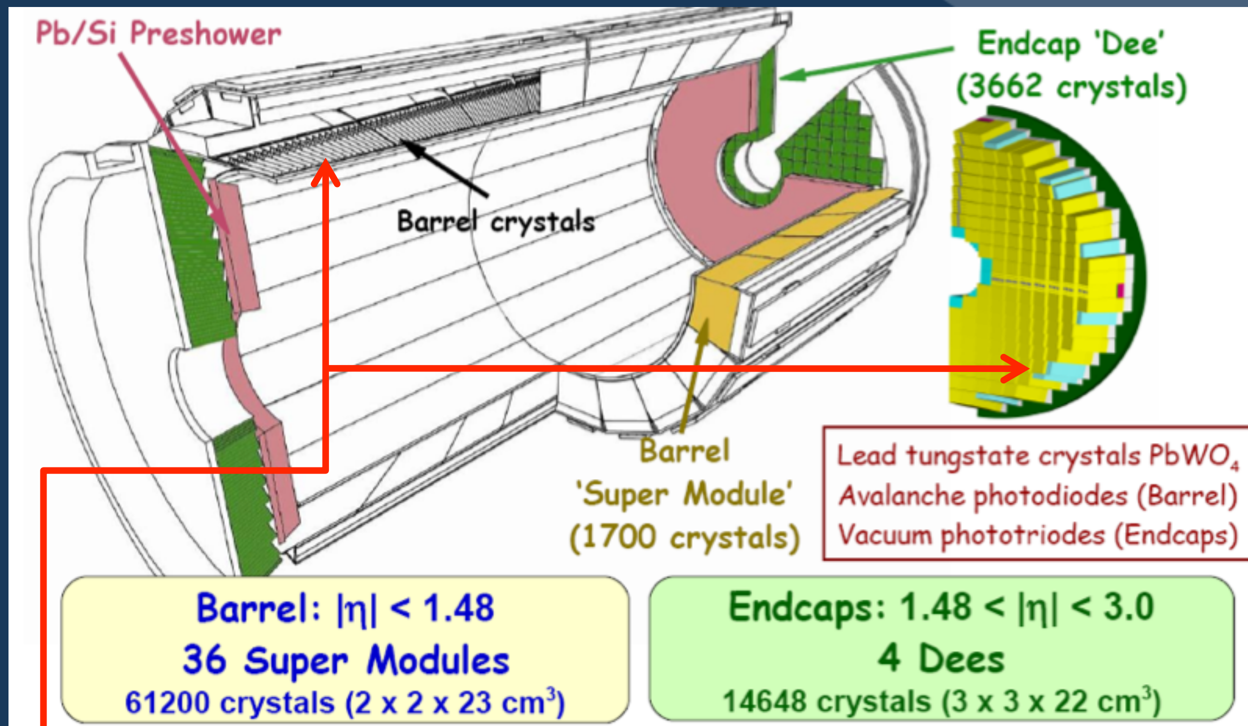
Data driven method to measure efficiencies and fake rates:

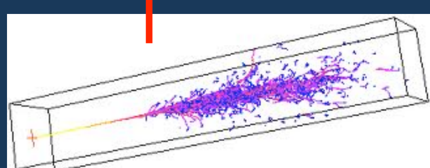
- Example: e->γ fake rate
  - ✓ Start with ee, eγ, γγ samples (e is tag object, γ is probe object)
  - ✓ After background subtraction, all events in peak are Z->ee
  - ✓ $f_{e\text{-}\gamma} = (N_{e\gamma} + 2N_{\gamma\gamma})/2N_{total}$



- Example: tau reco & ID efficiency
  - ✓ Select sample of Z->ττ with ττ->mτ$_{had}$ using cuts to suppress background but not the τ ID cuts
  - ✓ $f_{jet\text{-}\tau} = N_{pass}/(N_{pass} + N_{fail})$

γ/e in the CMS Detector



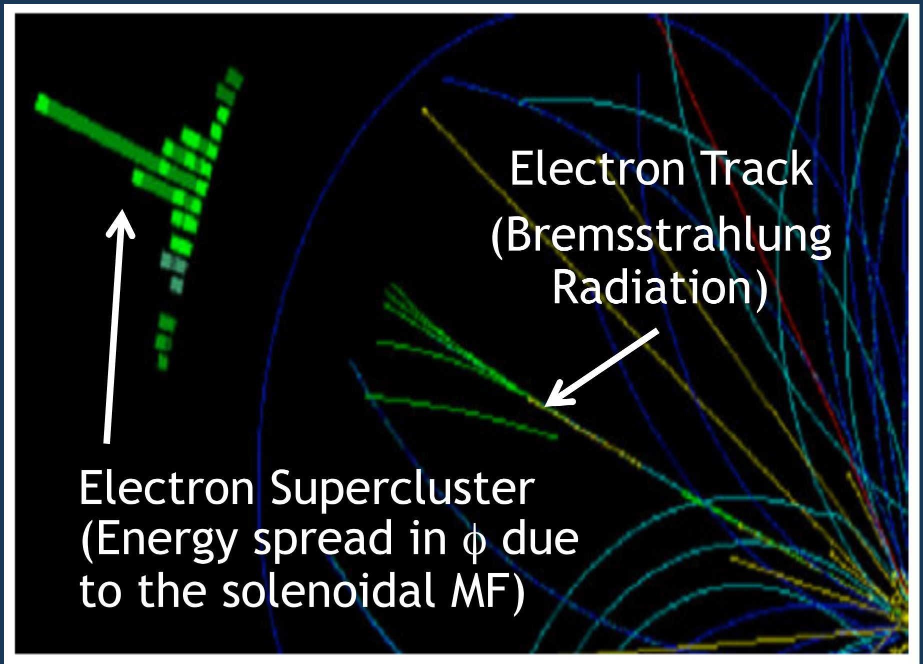


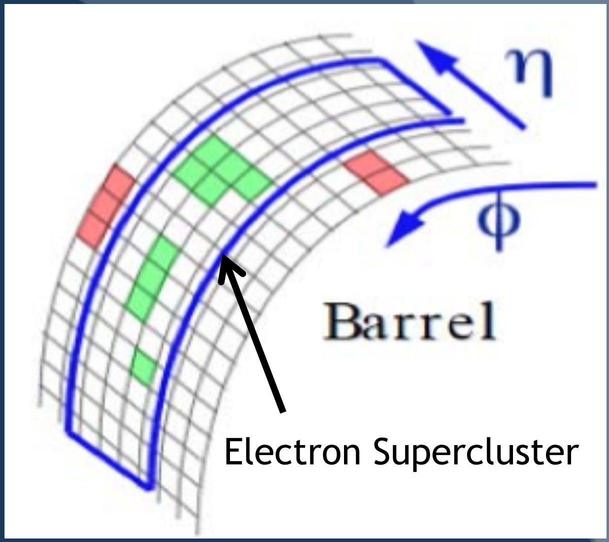
compact & high granularity:
radiation length = 0.89 cm
Moliere Radius = 2.2cm
⇒ good jet rejection

26 rad. lengths
90% of shower contained in one crystal

e/γ resolution: <0.5%, E>120 GeV

γ/e Reconstruction & ID





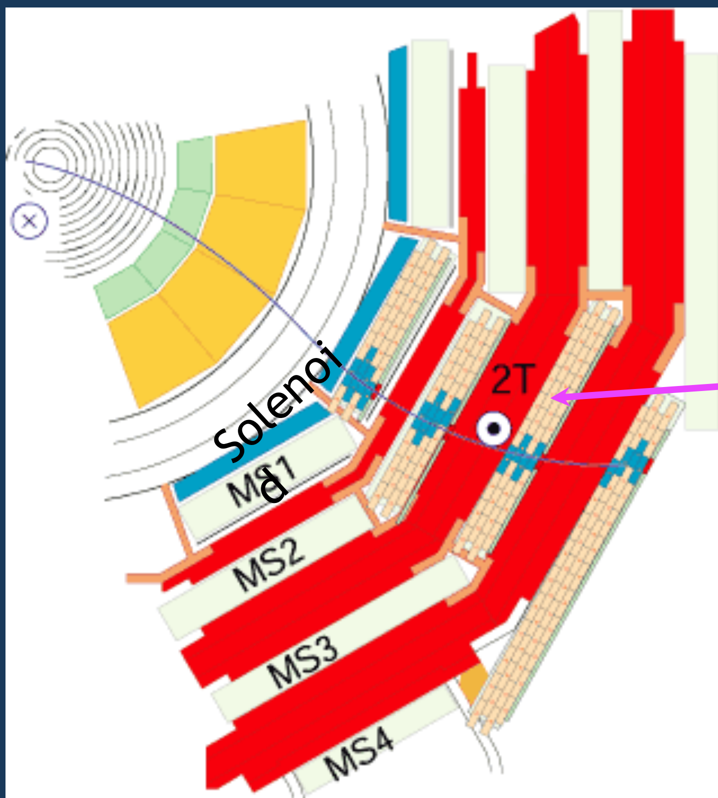
Supercluster defined in a narrow η strip extended in ϕ

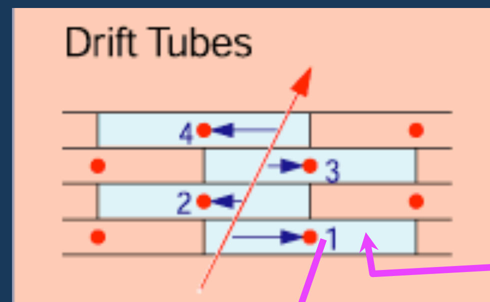
Calibrated supercluster passing isolation and shower shape criteria:

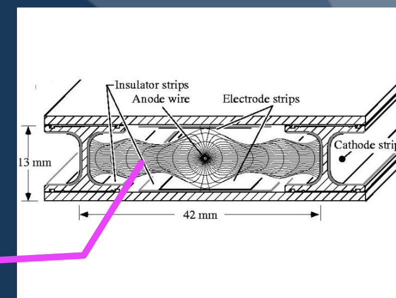
- Electron: if there are hits in pixel tracker consistent with tracks from the interaction point (IP)
- Photon: if there is no pixel match

e/γ efficiency > 96% γ purity: 30% (90%) for $p_{T\gamma}$=20 (200) GeV

Muons in the CMS Detector







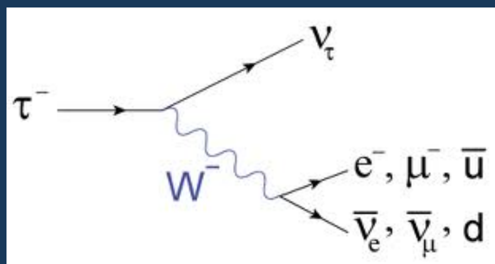
Drift Tubes (DT) outside solenoid and interleaved with iron "return yoke" plates:

- ✓ distance to wire
- ✓ position along the wire

Muons bend in powerful magnetic field:

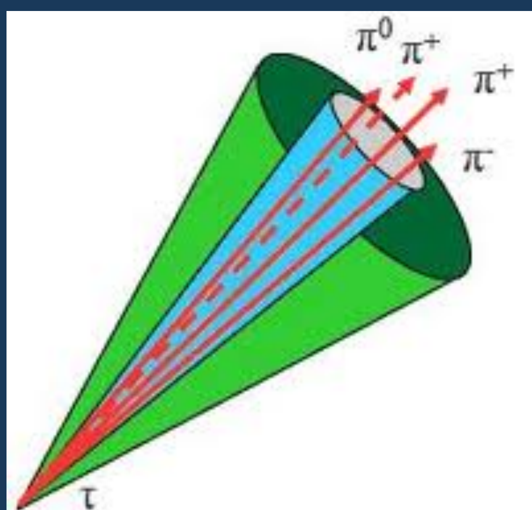
- ✓ Accurate p_T measurement

Tau Reconstruction & ID



Large mass (1.77 GeV) as compared to μ (106 MeV) and electron (0.5 MeV)

- Hadronic decay, t_{had}, 2/3 of times
- Leptonic decay, remaining branching ratio



Hadronic t decay

- Typically one or three charged mesons (p^+,p^-), up to 2 neutral mesons (p^0), and a n_t, with p^0 decaying to two g
- Collimated jet similar to QCD jet of q/g

Reconstruction based on Pflow reco & ID of individual particles

τ efficiency: 25% (50%) for tight (loose) cuts

τ fake rate: 0.2% (1%) for tight (loose) cuts

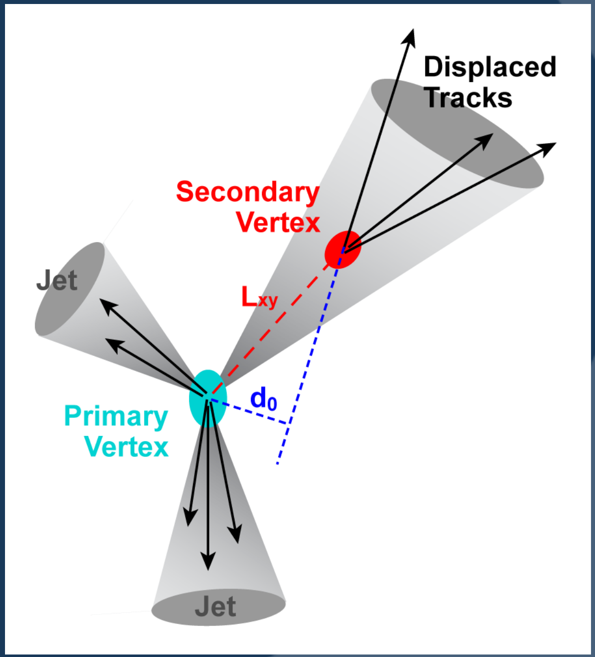
b-Jet Reconstruction

Hadron Colliders: outgoing b-partons evolve into jets

- M_b = 4.2 GeV
- Lifetime ~1.5 psec, 1.8 mm
- Weak decay into $\mu\nu_\mu$ + c-quarks ->μ (20%)

} Displaced decay vertex

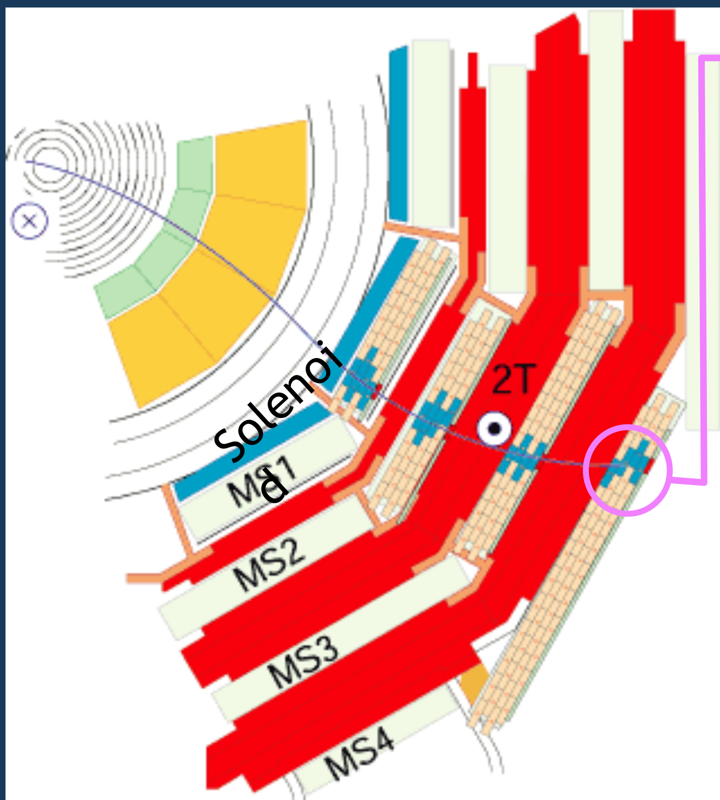
Look for displaced tracks & vertices in jets: b-tagging



b-tagging efficiencies in the (15-55%) range (tight-loose)

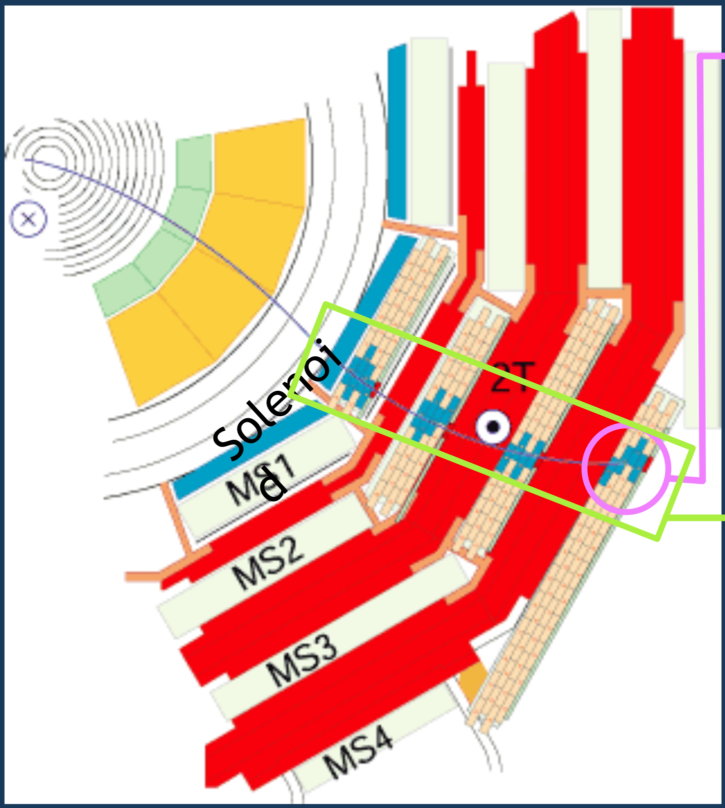
Light jet acceptance in the (0.1-10%) range (tight-loose)

Muon Reconstruction



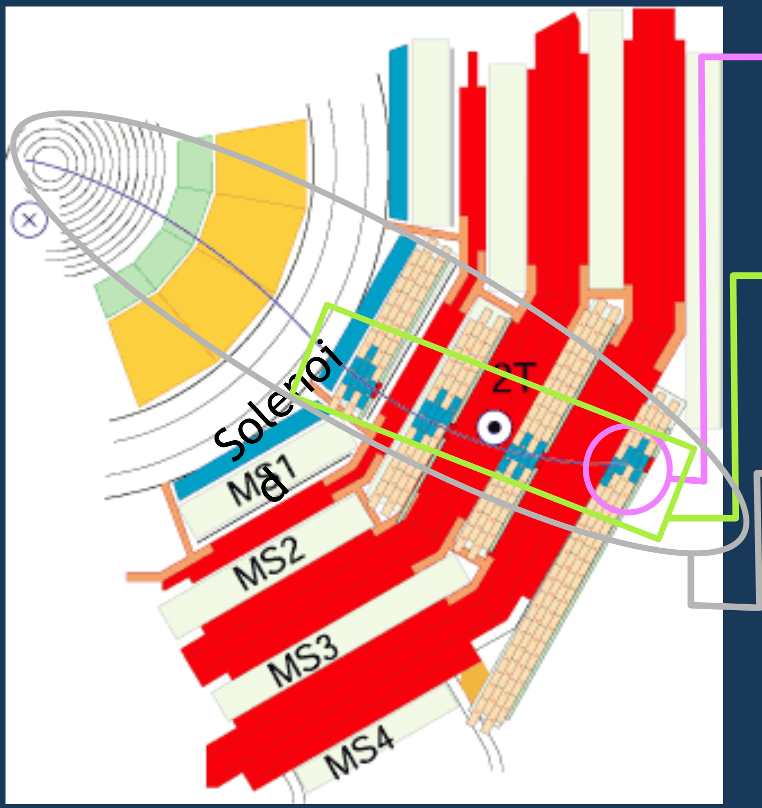
- Local Muon
  - ✓ Hits from subdetectors
  - ✓ Track Segments from hits

Muon Reconstruction & ID



- Local Muon
  - ✓ Hits from subdetectors
  - ✓ Track Segments from hits
- Standalone Muon
  - ✓ Combine track segments into a muon trajectory in muon system

Muon Reconstruction & ID



- Local Muon
  - ✓ Hits from subdetectors
  - ✓ Track Segments from hits
- Standalone Muon
  - ✓ Combine track segments into a muon trajectory in muon system
- Global Muon
  - ✓ Reconstruct Muon Tracker Track
  - ✓ Combine Standalone muon and Muon Tracker Track into a Global Muon (global fit)

Muon ID ➔ Global muon, with good PV match, isolation

$\sigma_{pT/pT}$ <1% at 10 GeV/c, ~8% at 500 GeV/c

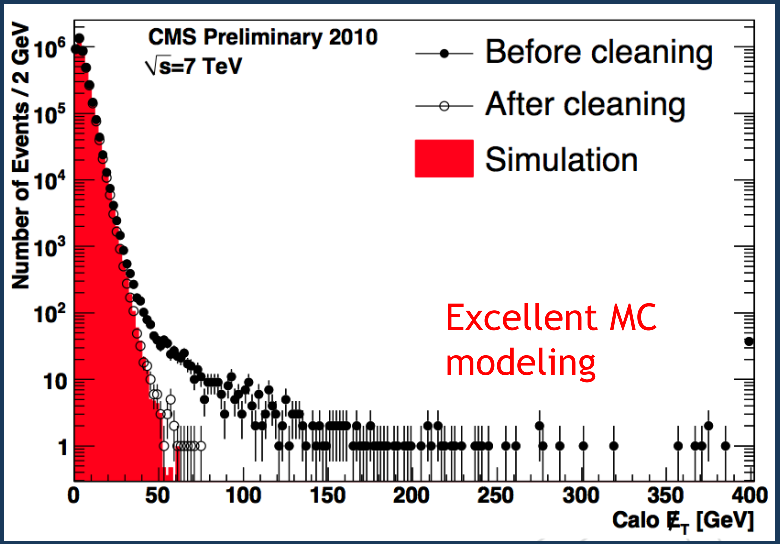
arXiv:0911.4994

MET Calculation

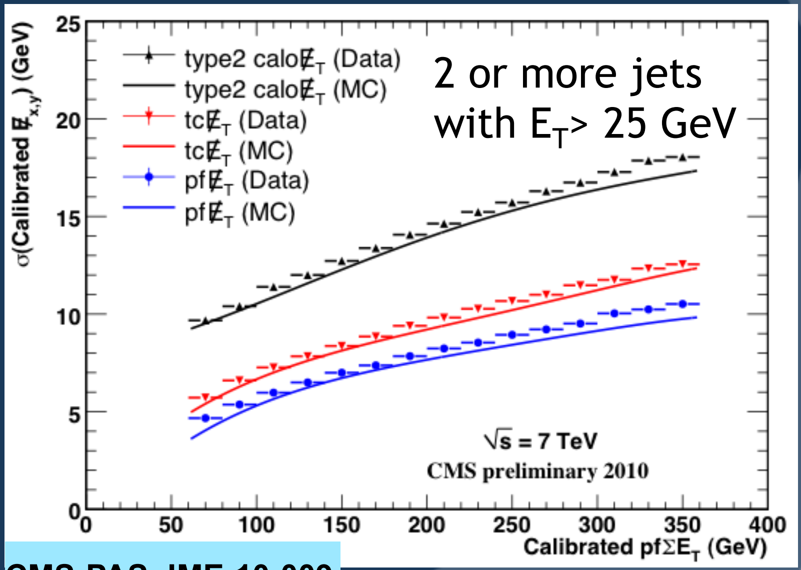
- Particle Flow MET (pfMET) is the transverse momentum vector sum over all PF particles: $\vec{\not{E}}_T = -\sum_{\text{particles}} (p_x \hat{\mathbf{i}} + p_y \hat{\mathbf{j}})$
- Calorimeter MET (CaloMET) is the transverse momentum vector sum over all calorimeter towers:

$$\vec{\not{E}}_T = -\sum_{n \; \text{CaloTowers}} (E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}}) = \not{E}_x \hat{\mathbf{i}} + \not{E}_y \hat{\mathbf{j}}$$

Corrected for jet E scale, μ/τ p_T, unclustered energy



Excellent MC modeling



2 or more jets with E_T> 25 GeV

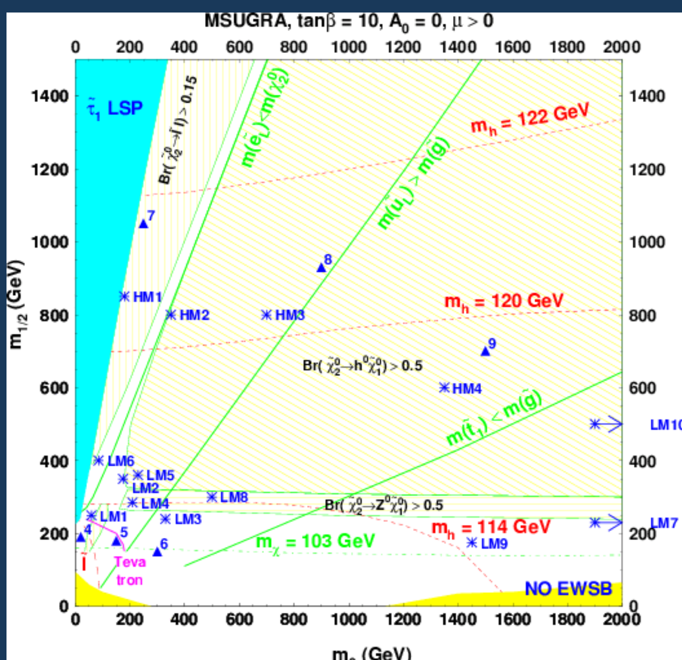
CMS-PAS-JME-10-009

CMSSM Benchmark Points

Experiments use benchmark points as aid for comparative assessment

Define a grid of points in parameter space for setting exclusion limits

($m_{1/2}$ & m_0 scanned in 10 GeV steps for tan β=3, 10, 50 using LO generators and NLO k-factors using PROSPINO. Events then passed through detector simulation)



CMS Physics TDR, Vol.II, CERN/LHCC 06-021

- Low Mass points (LM1 to LM10), above TeV reach, target early LHC searches
- High Mass points (HM1 to HM4) defined for ultimate CMS reach

LM1(LMB):

m_0=60 (400) GeV, $m_{1/2}$=250 (200) GeV, A_0=0, tan β=10 (50), sign(μ) > 0

m_{squark}=559 GeV and m_{gluino}=611 GeV

MHT All Hadronic Search

Search regions:

- High-MHT: Baseline + HT>800 GeV, MHT>500 GeV
  (DM candidate - good bkgd rejection)
- High-HT: Baseline + HT>800 GeV
  (heavy particle - long cascade, high multiplicity)
- Medium HT & MHT: Baseline + HT>800 GeV, MHT>500 GeV

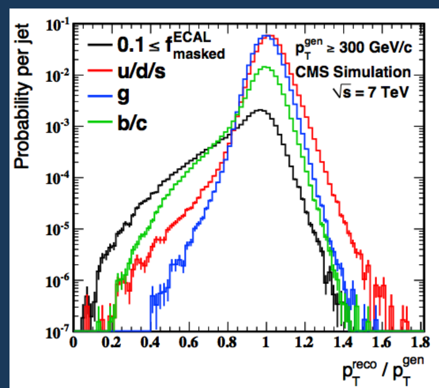
Physics generators not accurate enough (QCD multijets, W/Z+jets) → Background predictions extracted from data

Data Driven Methods for background predictions

Concept

- Use “control data samples” or “control regions in data”
- Control sample/region: signal depleted sample/region from which to infer the bkgd in the signal region by use of event properties, physics laws, etc
- Signal: area of phase space where the signal is enhanced = search region (good s/b)

QCD Background: smearing effect

+ 

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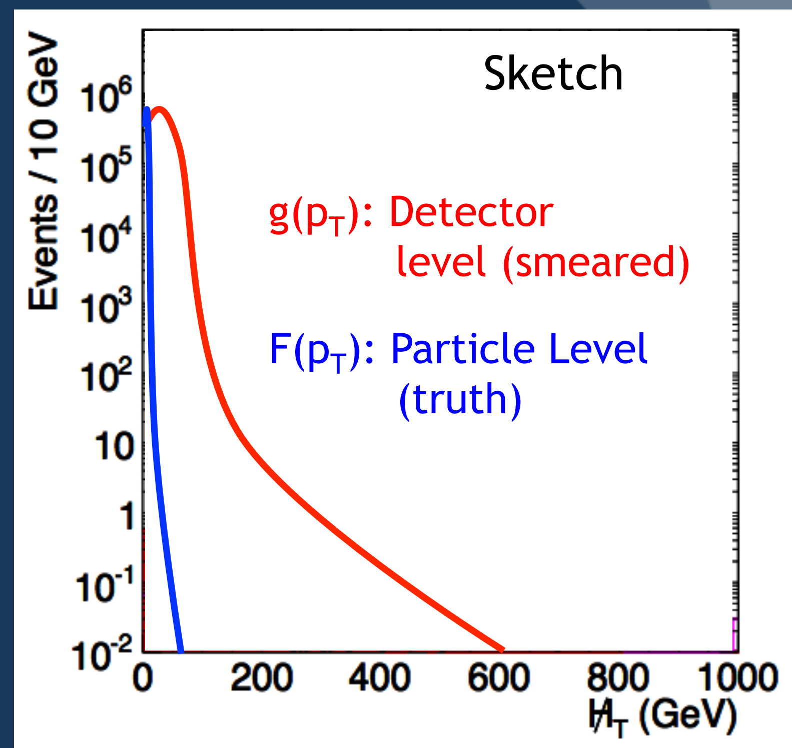
=

True distribution "smeared" due to the finite detector energy resolution

$$g^{smeared}(p_T^{meas}) = \int_0^{\infty} F^{true}(p_T^{true})\,R(p_T^{meas}, p_T^{true})\,dp_T^{true}$$



Jets that fluctuate to high/low response create spurious MHT tail

QCD Background: R+S Method

- Rebalance

  Jet particle level p_T restored from detector level inclusive multi-jet data sample by maximum likelihood using:

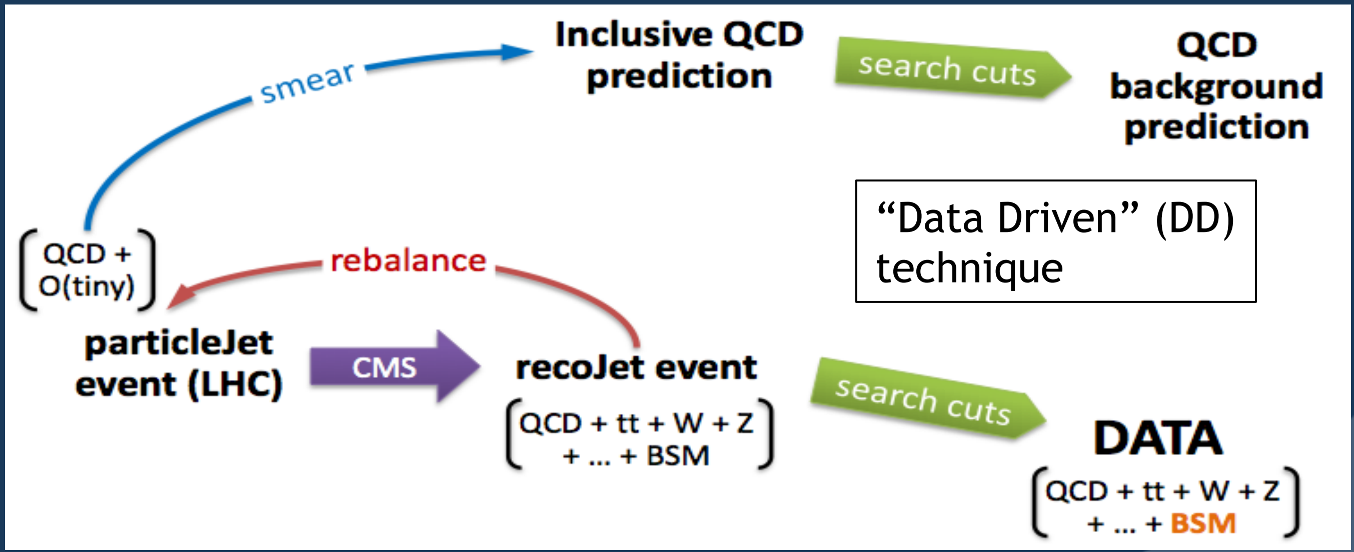
  ✓ Measured jet p_T response probability density functions

  ✓ Transverse momentum conservation $\sum_{i=1}^{n} \vec{p}_{T,i}^{\,true} + \vec{p}_{T,soft}^{\,true} = 0$

  ✓ Events with real MET are turned to QCD multi-jet events automatically

- Smear

  Rebalanced distribution is smeared by the measured jet pT resolution functions including the tails



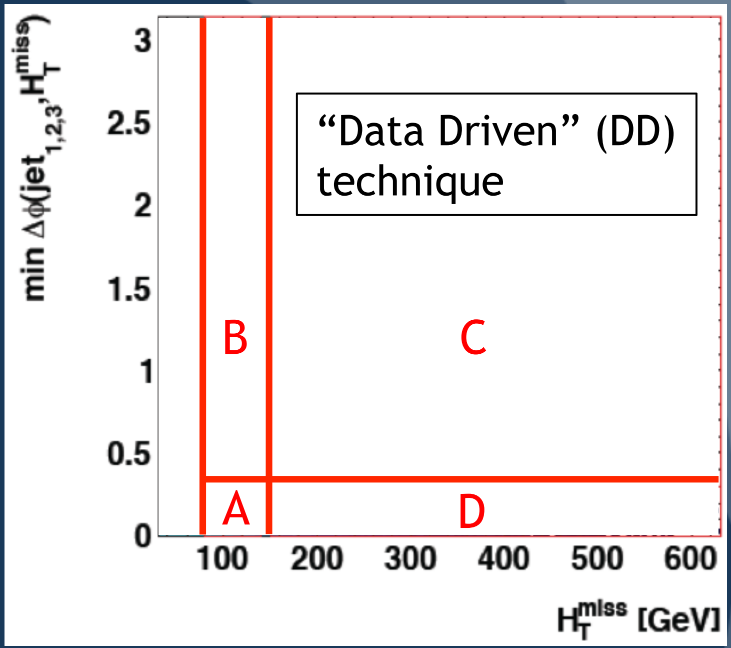
QCD Background: factorization

- A, B, D are background dominated regions
- C is the signal region

min $\Delta\phi$ (jet,MHT)>0.3, MHT>150 GeV

If variables uncorrelated:

$$N_C = N_B / N_A * N_D$$



If variables are correlated and $r(MHT)=N_B/N_A$ is understood :

$$N_C = r(MHT) * N_D$$

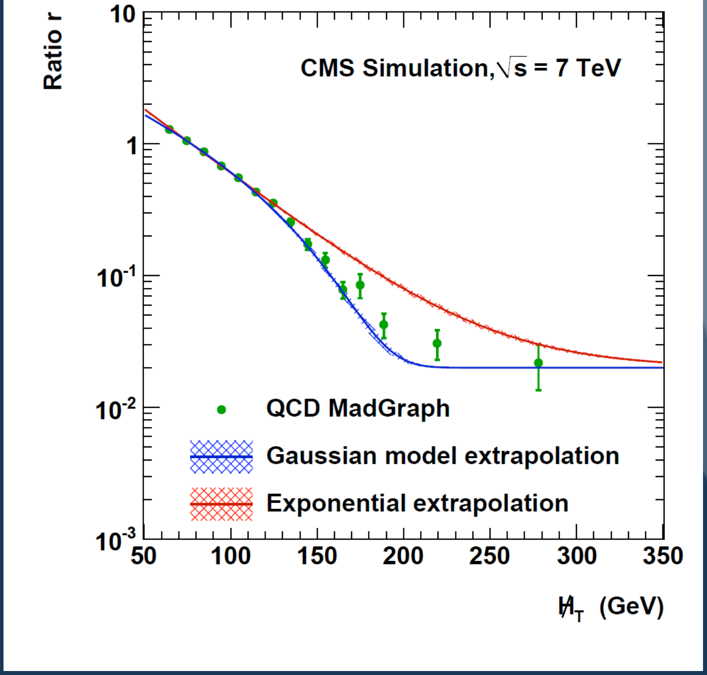
with r(MHT) extrapolated to the signal region

QCD Background: factorization

- A, B, D are background dominated regions
- C is the signal region

min $\Delta\phi$ (jet,MHT)>0.3, MHT>150 GeV

ABCD or factorization method widely used to predict different backgrounds in many analyses



If variables are correlated and $r(MHT)=N_B/N_A$ is understood :

$$N_C = r(MHT) * N_D$$

with r(MHT) extrapolated to the signal region

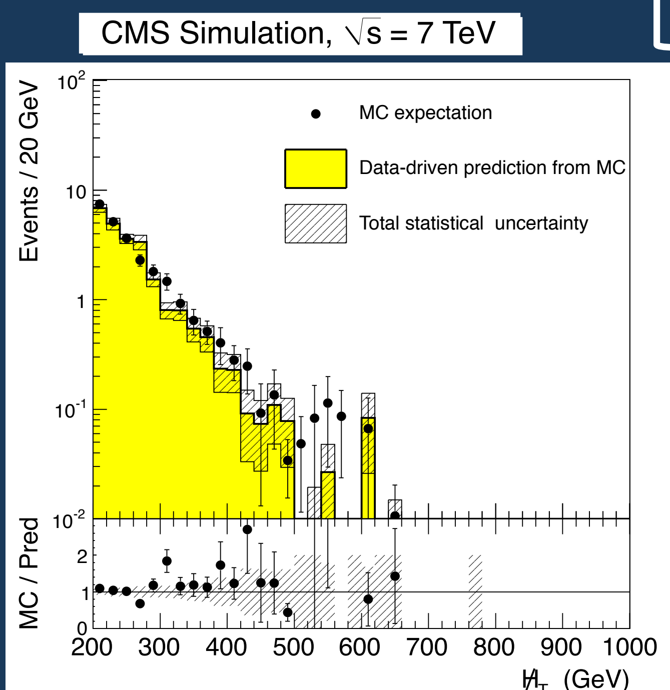
W/top Background: lost lepton

Lepton veto not fully efficient rejecting W/top background. Lepton is "lost" and the event not rejected if:

- ✓ Not reconstructed
- ✓ Not Isolated
- ✓ Out of detector acceptance

Pythia prediction for events with lost leptons passing lepton veto

36 pb^{-1}	ttbar		W+jets	
Baseline selection	**electron**	**muon**	**electron**	**muon**
Not reconstructed	1.5	0.4	0.4	0.1
Not isolated	3.2	3.8	0.6	0.6
Out of acceptance	5.5	4.8	2.1	1.9
total	10.2	9.0	3.1	2.6



Invert lepton veto technique on μ+jets control sample

(97% of events are ttbar or W+jets)

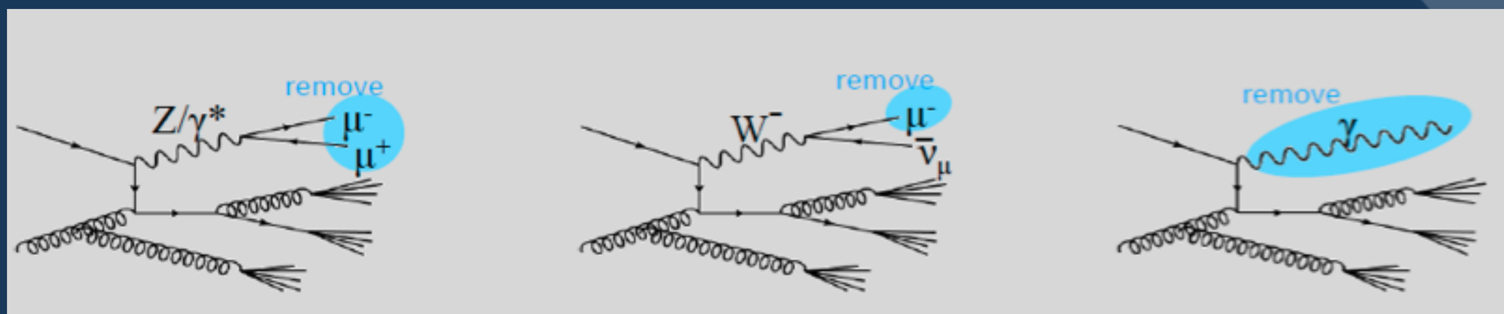
and scale the # of events in the signal region by:

$$\frac{1}{\varepsilon_{iso}} \frac{1-\varepsilon_{id}}{\varepsilon_{id}}$$

Z(νν) Background

Three independent <u>data driven methods</u> are explored based on Boson substitution with MET

Z(ll)+jets | W(lν)+jets | γ+jets



Z(ll)+jets
- Same kinematics
- Trivial Br correction
  $Br(Z \to \mu\bar{\mu})/Br(Z \to \nu\bar{\nu}) = 1/6$
- Lower stats than γ/W+jets

W(lν)+jets
- Similar kinematics
- Large backgrounds
- More stats than Z(νν) and 2.5 more than Z(μμ)

γ+jets
- Similar kinematics as Z+jets at high p_T and MHT
- Large and complex theory corrections
- High statistics

γ+jets prediction is used for the limit,
Z/W+jets are cross checks

Statistical Tests for Limits

CMS uses the Modified Frequentist Procedure (CL_s)

- ✓ Avoids excluding or discovering signals, that the analysis is not really sensitive to.
- ✓ Reduce dependency on uncertainty from background

CMS also uses Bayesian Framework (flat prior for the signal)

- ✓ Frequentist probability is the limit of a frequency
- ✓ Bayesian probability is a subjective degree of believe (The prior is the probability of a theory)

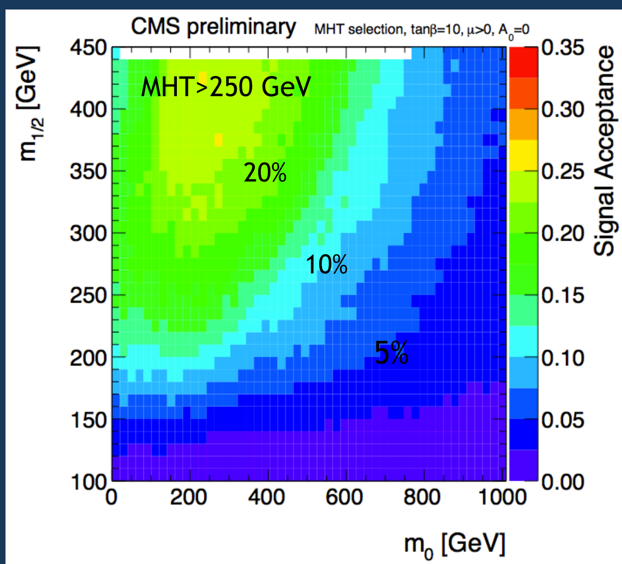
ATLAS uses Power Constraints Limits (PCL)

- ✓ Tends to give better (higher) limits for downward fluctuations in data
- ✓ ATLAS also used CL_s to allow comparison with CMS

Signal Acceptance/Efficiency

The expected number of signal events for a given model and event selection is estimated from simulated signal samples (generation + detector simulation)

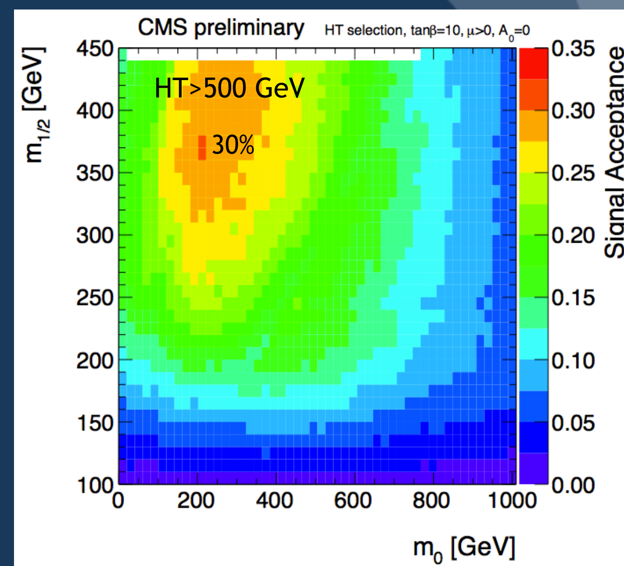
- Experimental and theoretical uncertainties from event selection, reconstruction, calibration
- Theoretical uncertainties related to event generation
- Overall luminosity uncertainty



Signal A_{cc} x E_{ff}

Acceptance (Acc): fraction of events passing the topology & kinematics requirement

Efficiency (Eff): Fraction of "accepted" events that were triggered, reconstructed, identified



Signal Uncertainties:

JEC and JER (8%), lepton veto/trigger efficiency (1%), dead Ecal filter inefficiency (1.5%), luminosity (4%), $\mu_{R,F}$ in NLO signal calculation (16%), PDFs (3%)