



Early New Physics Reach: CMS

Oliver Buchmüller (CERN)

Flavour as a Window to New Physics at the LHC

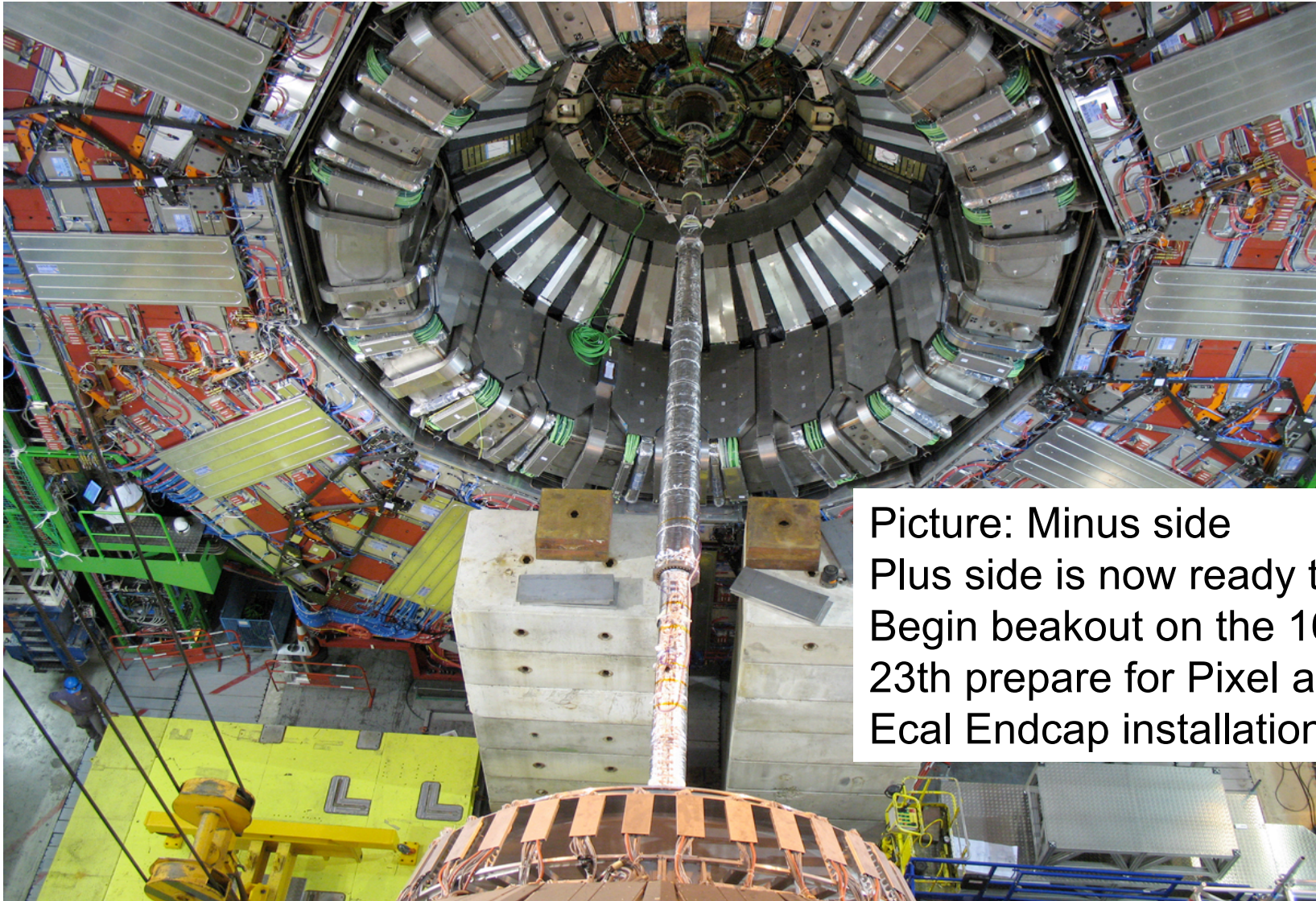
[Flavour/High-Q2 Interplay Focus Week]

- *Construction Status of CMS*
- *Physics Commissioning*
- *Early New Physics Reach of CMS*

Flavour/High-Q2 Interplay Focus Week 09/06/2008

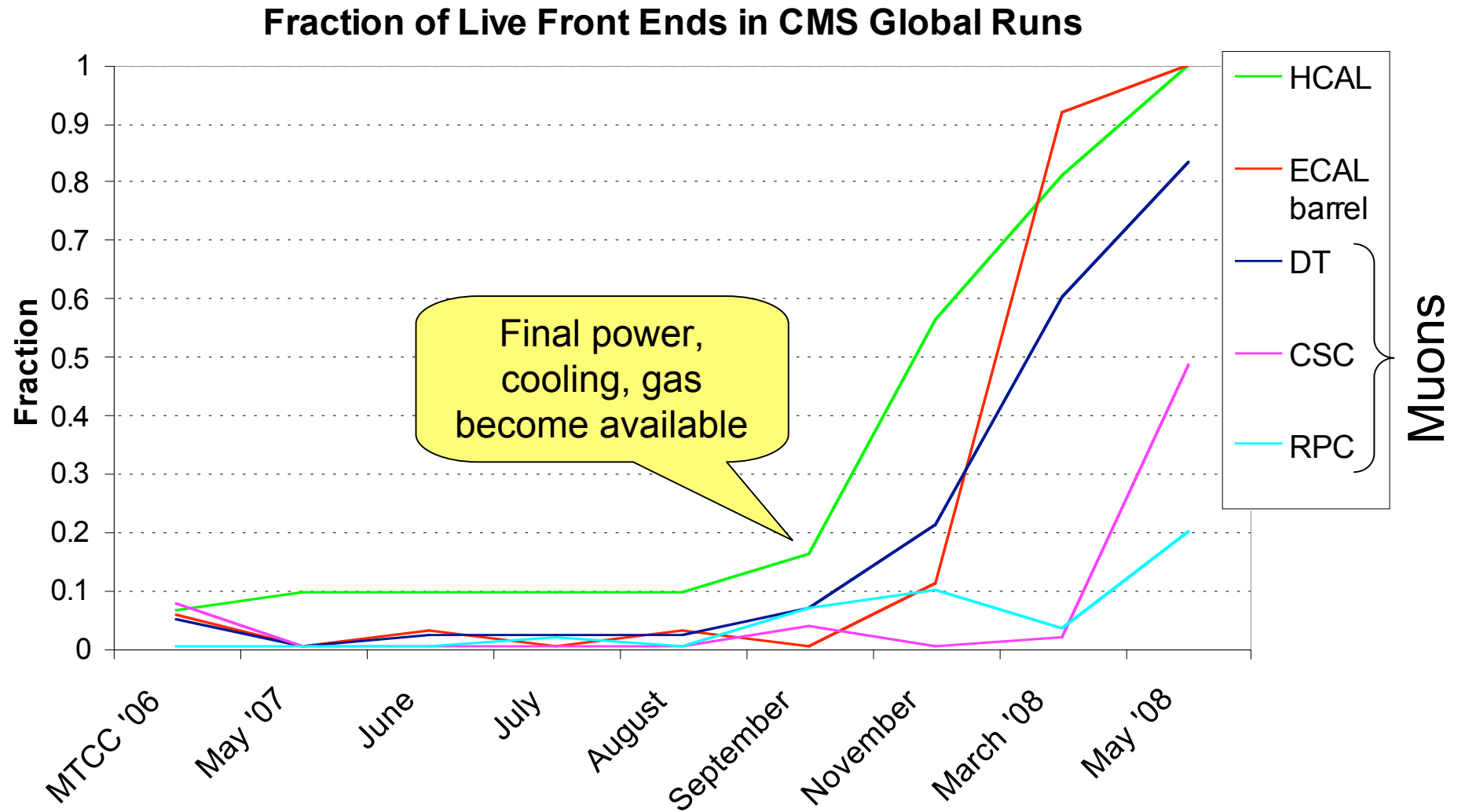
Status of the Experiment

CMS: Beam-pipe at both sides installed



Picture: Minus side
Plus side is now ready too.
Begin beakout on the 16th.
23th prepare for Pixel and
Ecal Endcap installation

Getting Ready: Scale of Global Operations



CMS Status: Summary

- Very good progress in global commissioning
- CMS closed by mid-July
 - Pixel detectors installed and at least one ECAL endcap installed
- Ready for full field magnet re-test underground
- Ready for LHC beam
- *Ready for physics at 10 TeV!*

Physics Commissioning with the first collision data

LHC Startup

Slide from Mike Lamont

- 1 to N to 43 to 156 bunches per beam
- N bunches displaced in one beam for LHCb
- Pushing gradually one or all of:
 - Bunches per beam
 - Squeeze
 - Bunch intensity

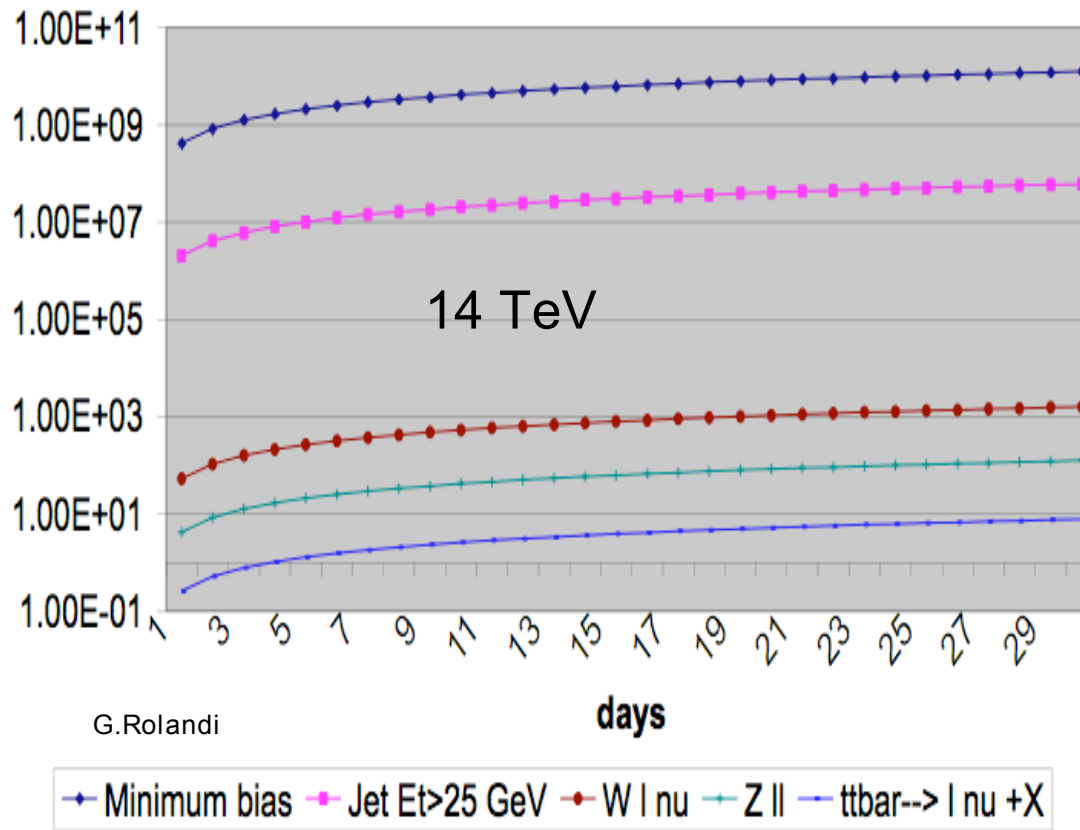
After initial commissioning phase 156x156 running of another month could yield
 $\sim 40\text{pb}^{-1}$ @ 10 TeV in 2008

IP 1 & 5

Bunches	β^*	I_b	Luminosity	Event rate
1 x 1	11	10^{10}	$\sim 10^{27}$	Low
43 x 43	11	3×10^{10}	6×10^{29}	0.05
43 x 43	4	3×10^{10}	1.7×10^{30}	0.21
43 x 43	2	4×10^{10}	6.1×10^{30}	0.76
156 x 156	4	4×10^{10}	1.1×10^{31}	0.38
156 x 156	4	9×10^{10}	5.6×10^{31}	1.9
156 x 156	2	9×10^{10}	1.1×10^{32}	3.9

Produced Events in the very First Days

30 days at 3×10^{29} with efficiency 20% = 0.15 pb⁻¹



Assumed Efficiencies
 $\epsilon(W) = 0.3$ $\epsilon(Z) = 0.5$ $\epsilon(ttbar) = 0.02$

Events after one Month

Min Bias : $\sim 10^{10}$

Jet_{Et>25}: $\sim 10^8$

$W \rightarrow \ell \nu$: $\sim 10^3$

$Z \rightarrow \ell \ell$: $\sim 10^2$

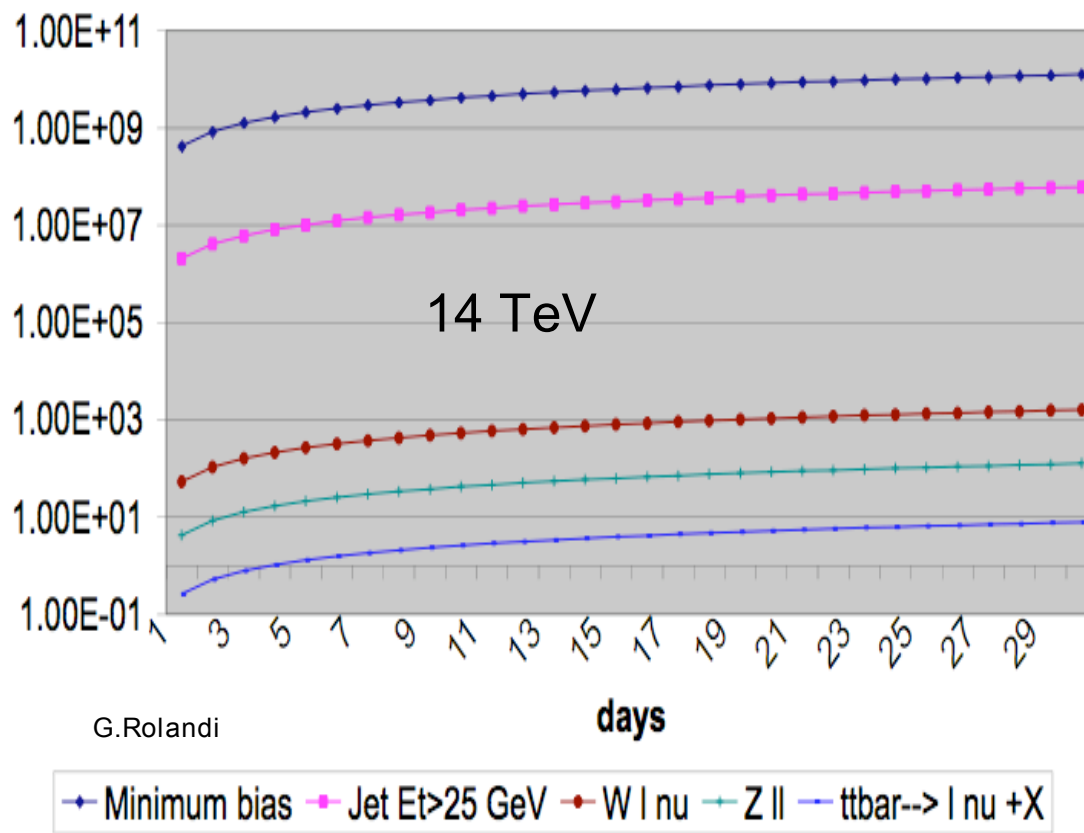
$tt \rightarrow \ell \nu + X$: $\sim 10^1$

14 TeV

First mainly used for general commissioning and detector alignment & calibration.

Produced Events in the very First Days

30 days at 3×10^{29} with efficiency 20% = 0.15 pb⁻¹



Production Rate: 10 vs.14 TeV:

- W/Z ~70%
- ttbar ~50%
- Higgs (200) ~50%

Assumed Efficiencies

$$\epsilon(W) = 0.3 \quad \epsilon(Z) = 0.5 \quad \epsilon(ttbar) = 0.02$$

Events after one Month

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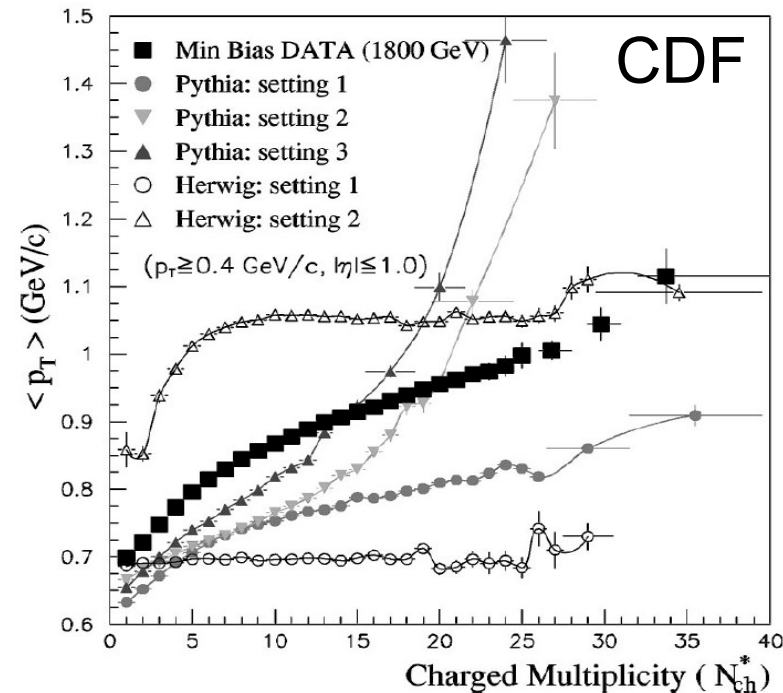
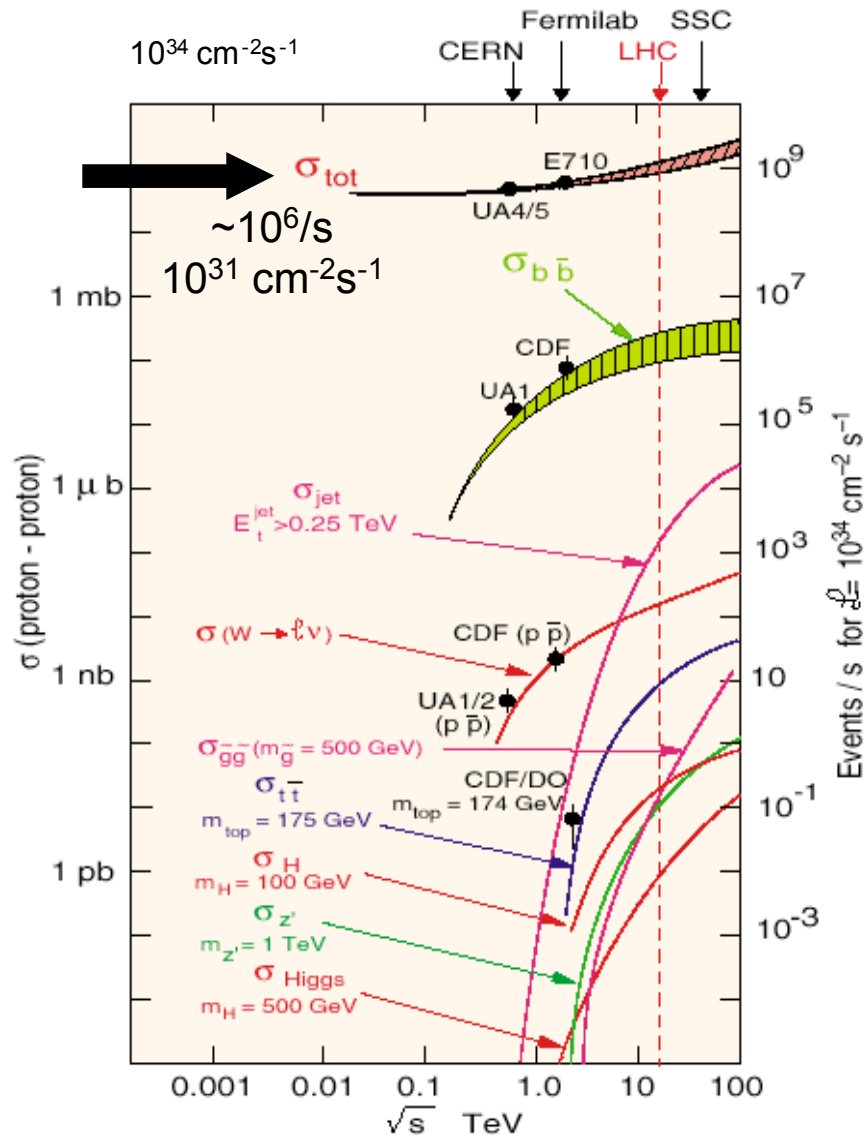
14 TeV

First mainly used for general commissioning and detector alignment & calibration.

First Phase

“Why”: Measure Charged Particle Density

- W,Z, ttbar cross sections known to ~3 to 10%
- Large uncertainties in minimum bias $dN_{ch}/d\eta$ known to only ~50% (or worse)



Precise knowledge of $dN_{ch}/d\eta$ very important for MC tuning, understanding underlying event, pile-up etc

Second Phase

Re-discover the SM

- Reestablish the Standard Model
- Most SM cross sections are significantly higher than at the Tevatron
e.g. $\sigma_{t\bar{t}}(\text{LHC}) > 100 \times \sigma_{t\bar{t}}(\text{Tevatron})$
- Crucial for final Detector and Physics commissioning

THE path to new physics! 14 TeV

At Luminosity $10^{31} \text{cm}^{-2} \text{s}^{-1}$

$b\bar{b}$ production: $\rightarrow 10^3 \text{ Hz}$

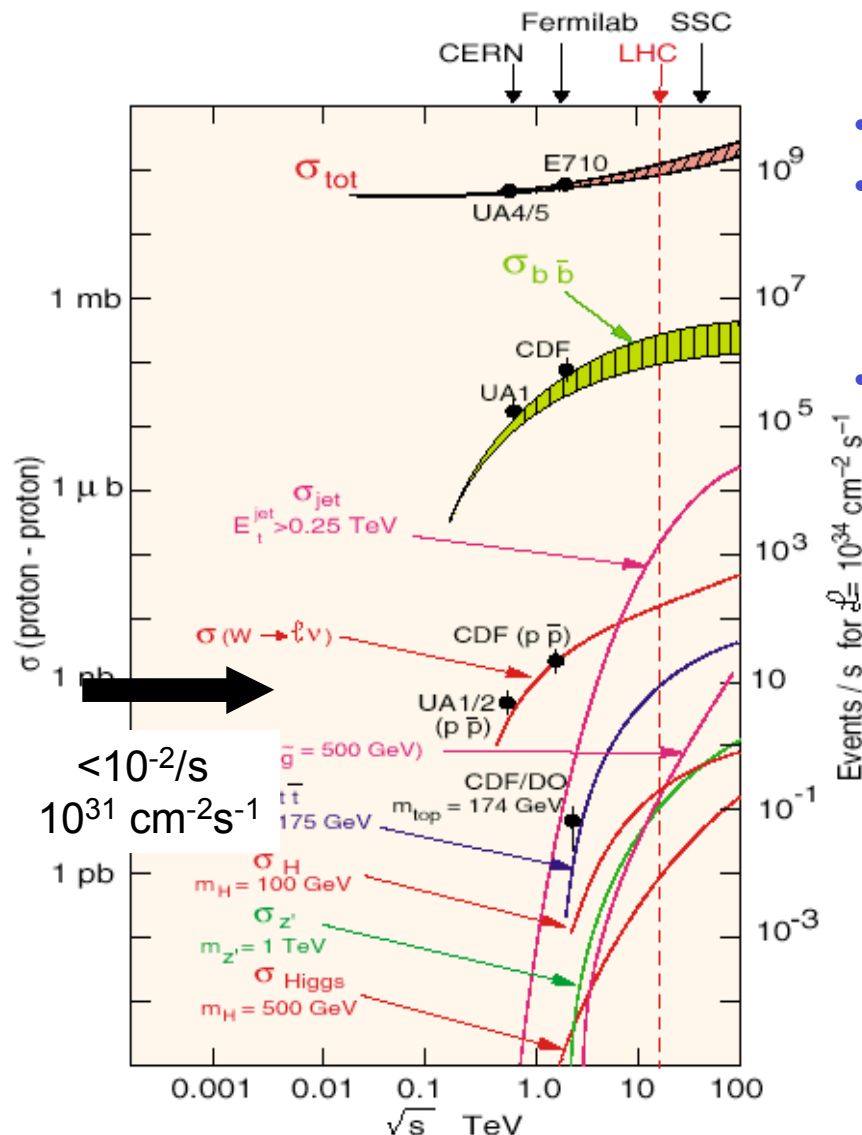
$W \rightarrow \ell \nu$: $\rightarrow 0.1 \text{ Hz}$

$Z \rightarrow \ell \ell$: $\rightarrow 0.01 \text{ Hz}$

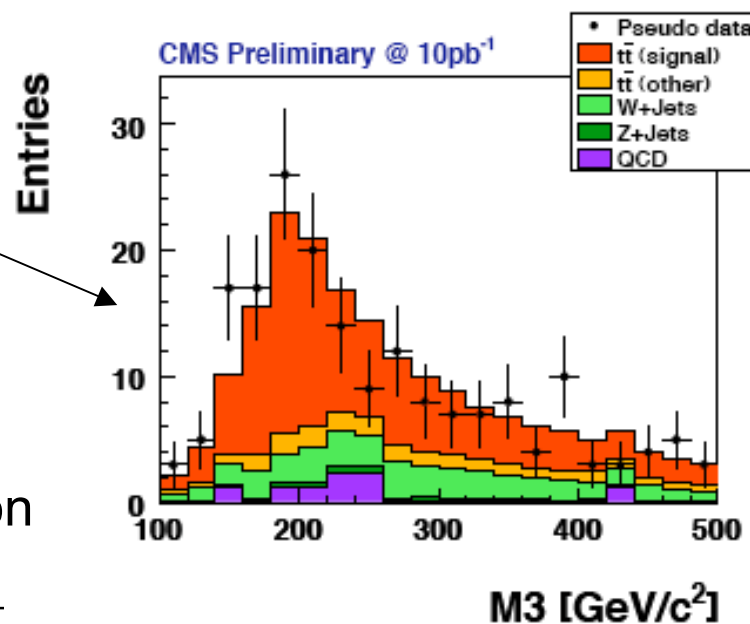
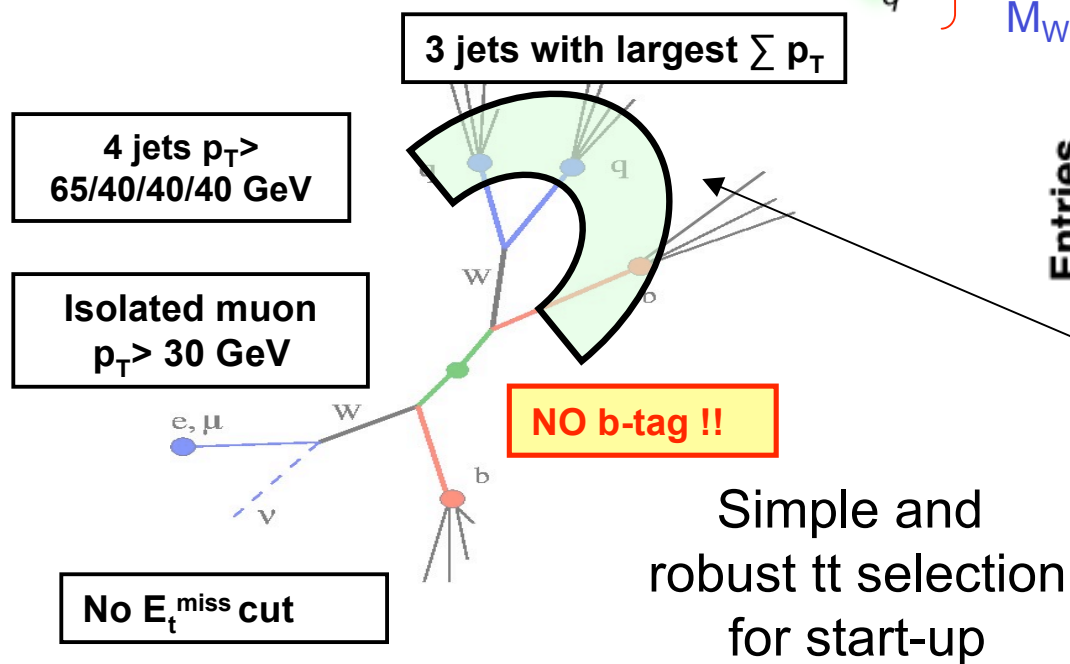
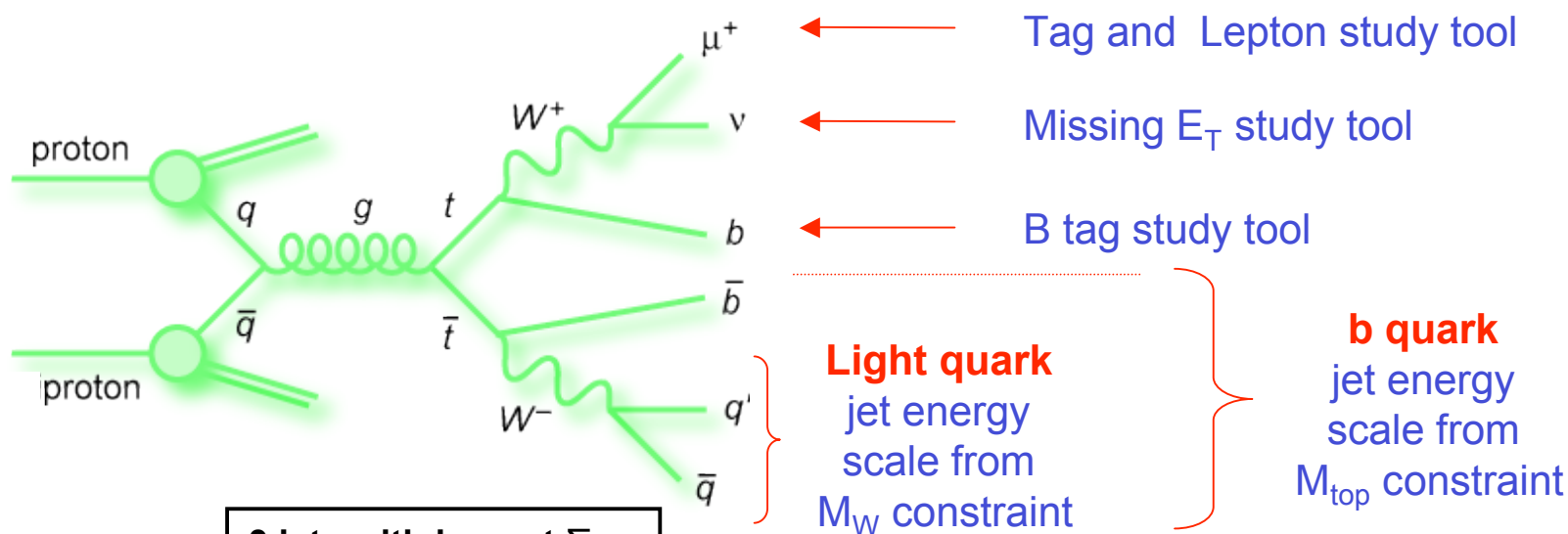
$t\bar{t}$ production: $\rightarrow 0.01 \text{ Hz}$

SM Higgs $\rightarrow 0.0001 \text{ Hz}$

At this stage the LHC becomes a real SM Factory!



Example: Top Events as a Tool



Early (New) Physics Reach of CMS

Focus mainly on the physics reach for a few pb^{-1} up to 1fb^{-1}

- *e.g. few hundred pb^{-1} expected for 2008/2009*
- *interplay between commissioning and physics will be significant*

A few Illustrative Examples

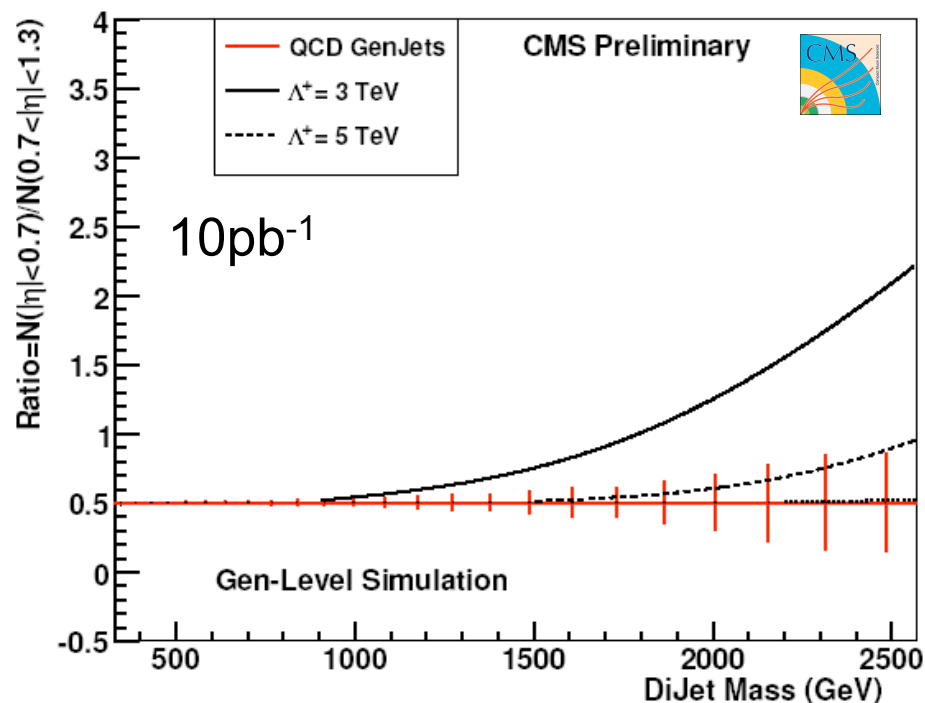
- *very early : Di-lepton and Di-jet signatures*
- *early : more “exotic” signatures*
- *early : low mass SUSY (“SUSY-like” - as a detailed example)*
- *(probably) later : SM-Higgs (backup)*

By far not an exhaustive list!

There are many more exciting (new) physics topic but no time to cover here!

New Physics Search with Di-jets

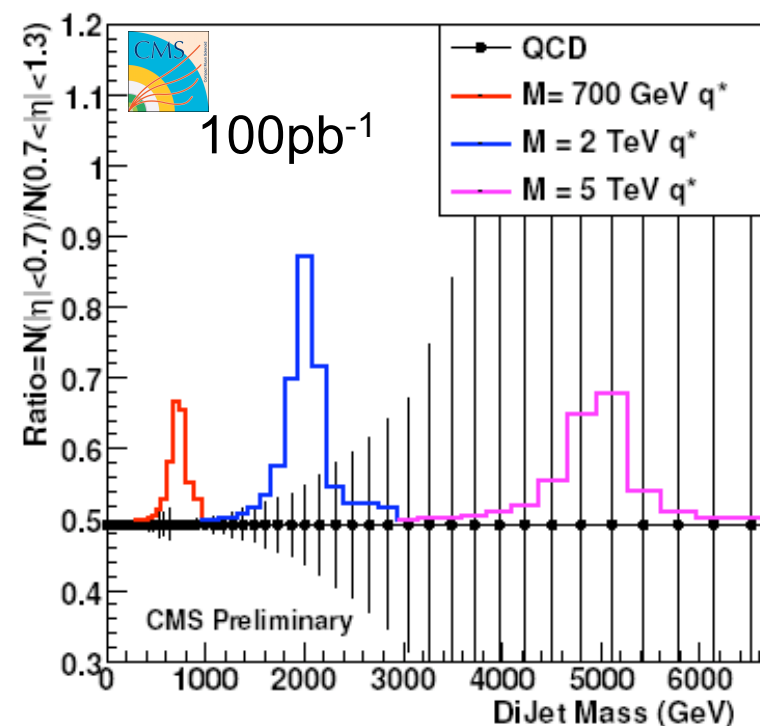
Contact Interaction



Small systematic due to use of ratio:
Di-jet Ratio = $N(|\eta| < 0.7) / N(0.7 < |\eta| < 1.3)$

	Excluded Λ (TeV)			Discovered Λ (TeV)		
	10 pb ⁻¹	100 pb ⁻¹	1 fb ⁻¹	10 pb ⁻¹	100 pb ⁻¹	1 fb ⁻¹
DØ and PTDR η cuts	< 3.8	< 6.8	< 12.2	< 2.8	< 4.9	< 9.1
Optimized η cuts	< 5.3	< 8.3	< 12.5	< 4.1	< 6.8	< 9.9

Exited Quarks

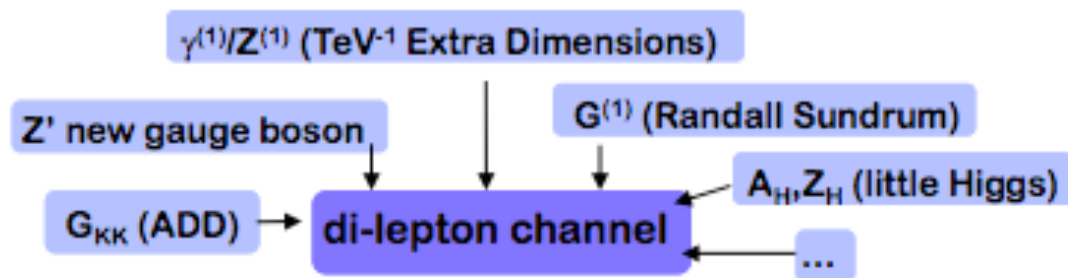


Significant
discovery potential:
e.g. up to $\Lambda \sim 10$ TeV
in 2008/2009

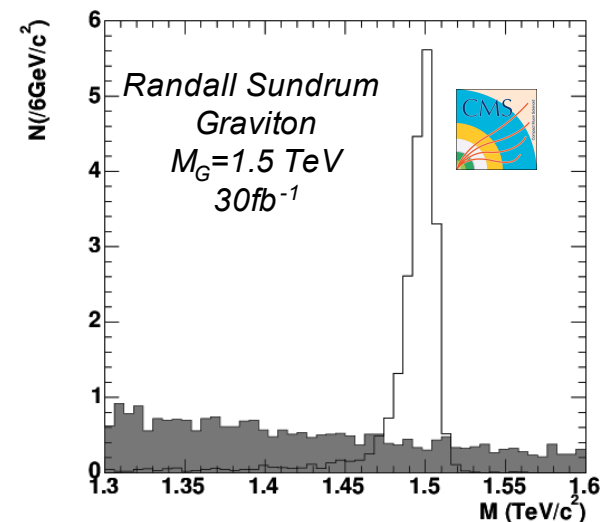
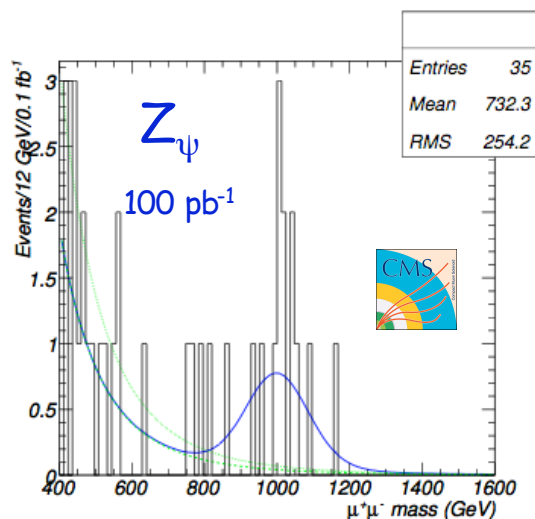
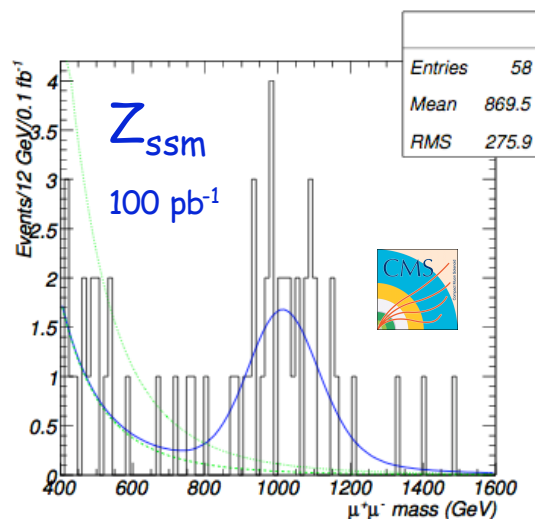
Di-lepton Resonances

Because of their clear signature di-lepton resonances have always been subject of new physics searches.

At the LHC they are predicted to arise in many BSM models:

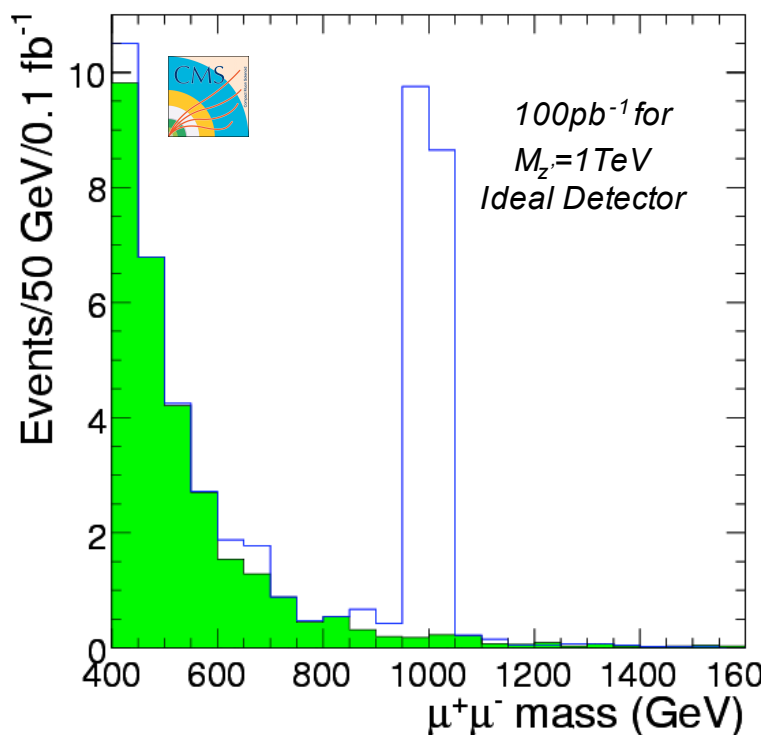


Clear signatures: $\mu^+\mu^-$ and e^+e^- final state

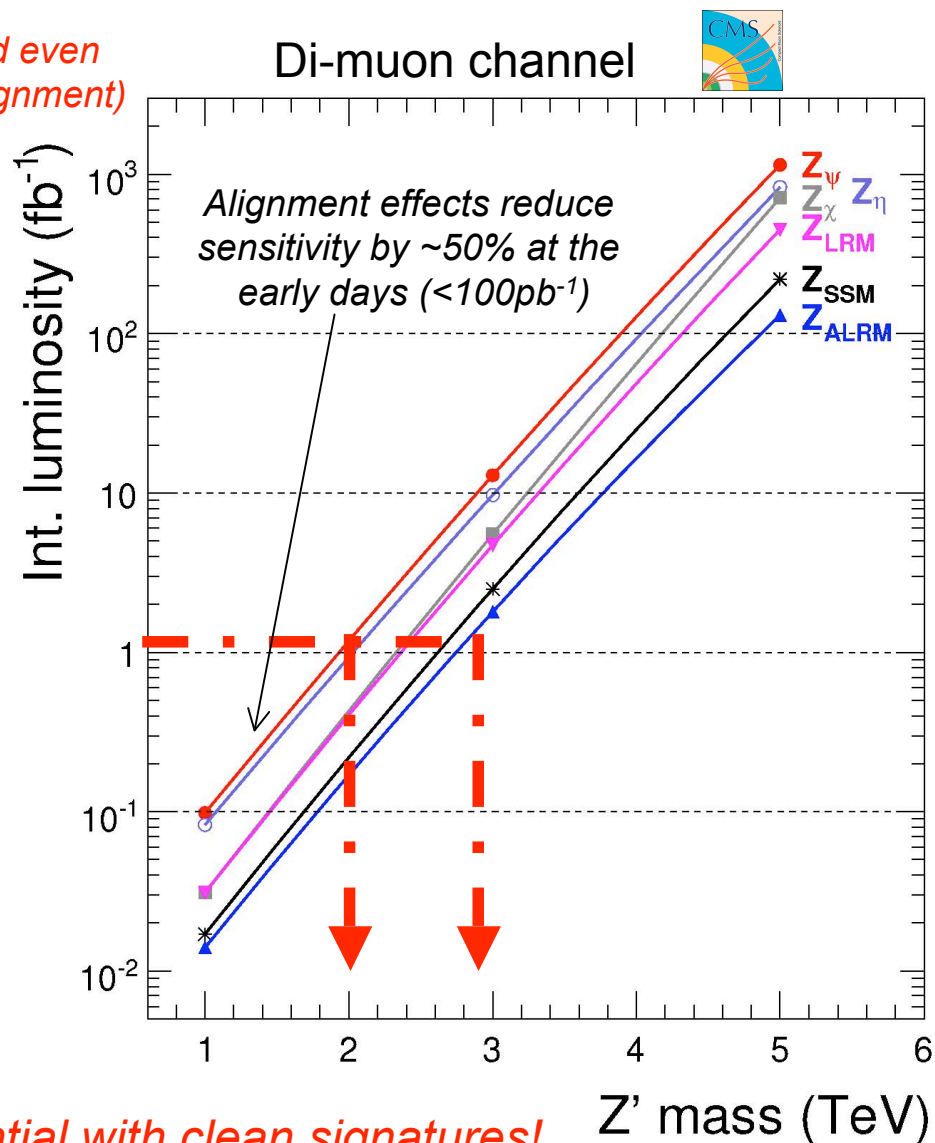


Di-lepton Resonances (Example Z')

Clear signature almost background free. Can be observed even when assuming realistic start-up conditions (e.g. mis-alignment)



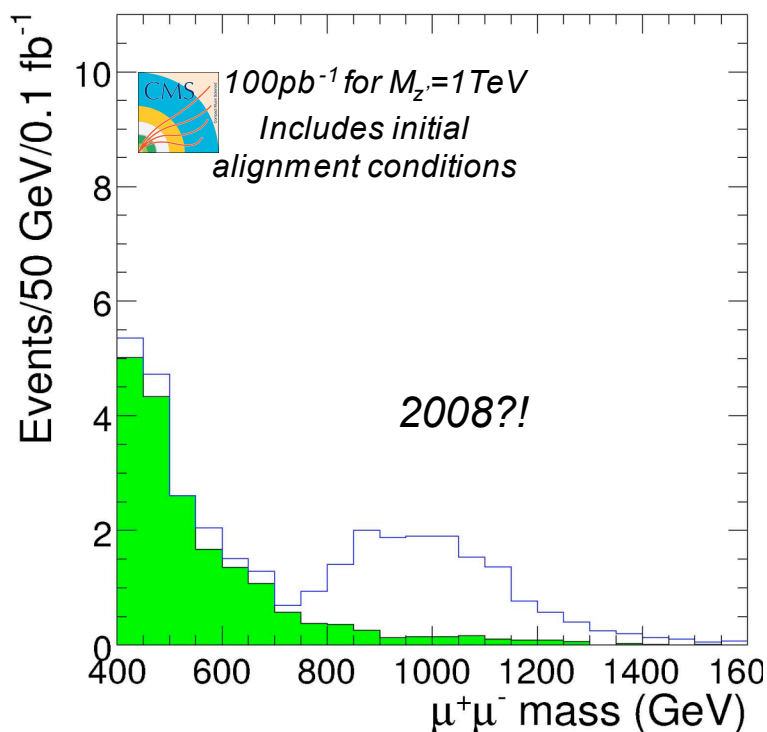
Main background: Drell-Yan:
Expect <1 event for $M > 1.5 \text{ TeV}$ in 1fb⁻¹



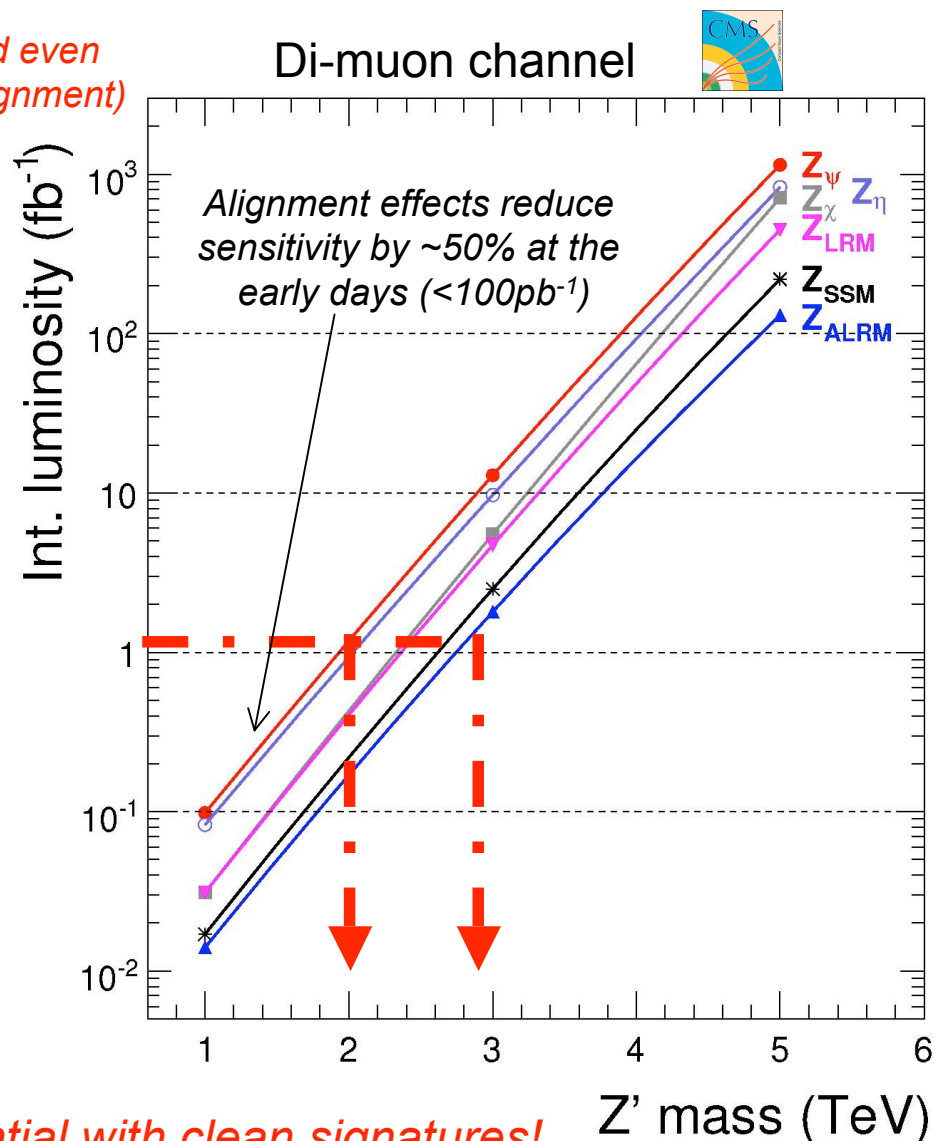
Very early discovery potential with clean signatures!

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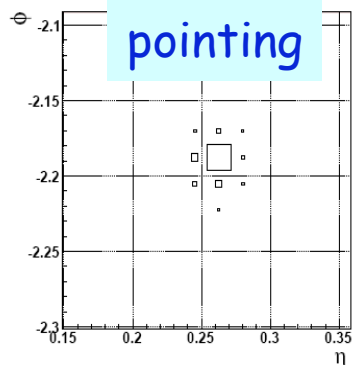


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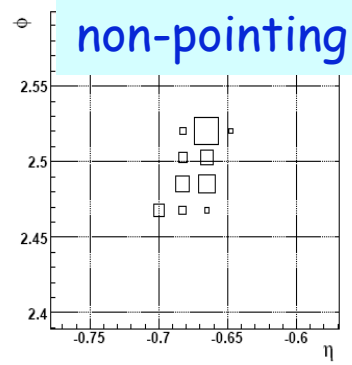
GMSB and R-Hadrons

Curtsey of A. De Roeck

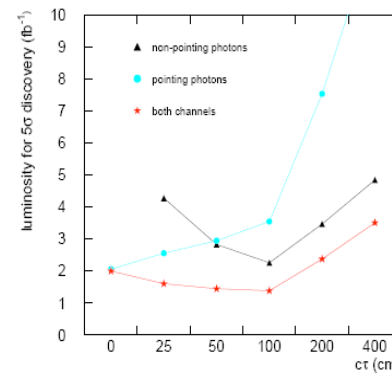
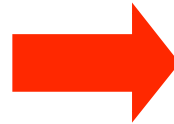
- GMSB: Non-pointing photons** GMSB parameters $N = 1$ $\tan \beta = 1$ $\text{sgn } \mu = 1$ $M_m = 2\Lambda$



pointing



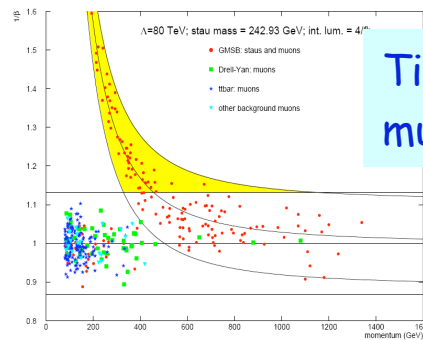
non-pointing



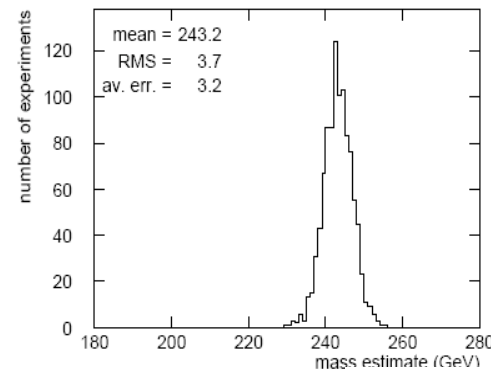
χ ct lifetime extraction with ~20% precision

- GMSB: long living staus**

GMSB parameters $N = 3$ $\tan \beta = 3$ $\text{sgn } \mu = 1$ $M_m = 2\Lambda$



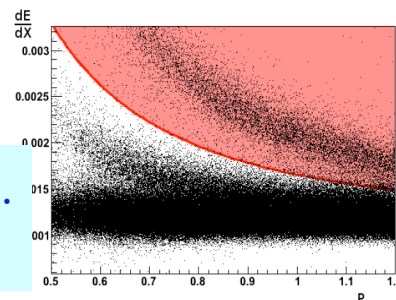
Timing (β) in muon detectors



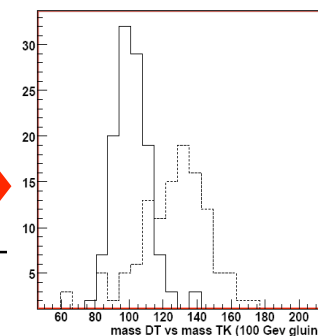
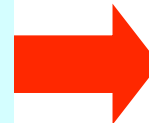
stau mass extraction with a few % precision

- R-hadrons**

trigger/mass meas. for region $\beta > 0.6$



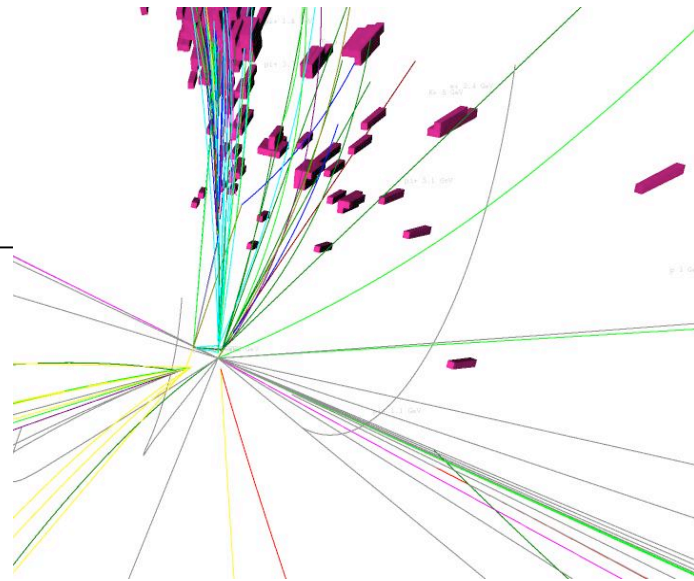
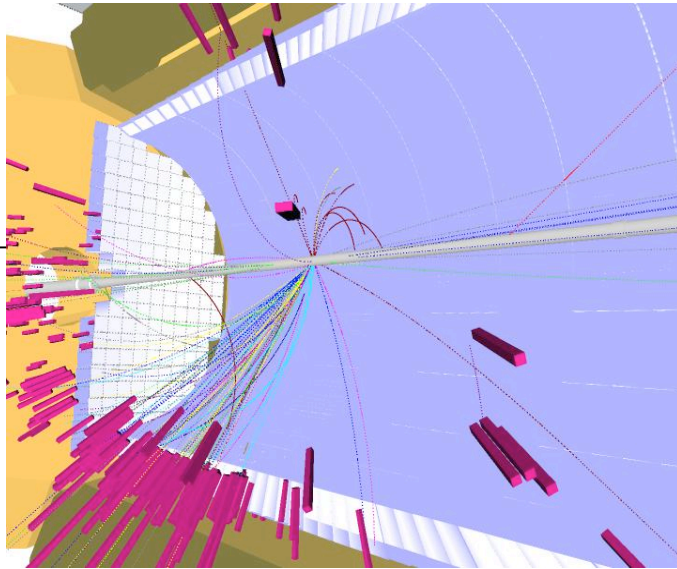
dE/dx in the tracker



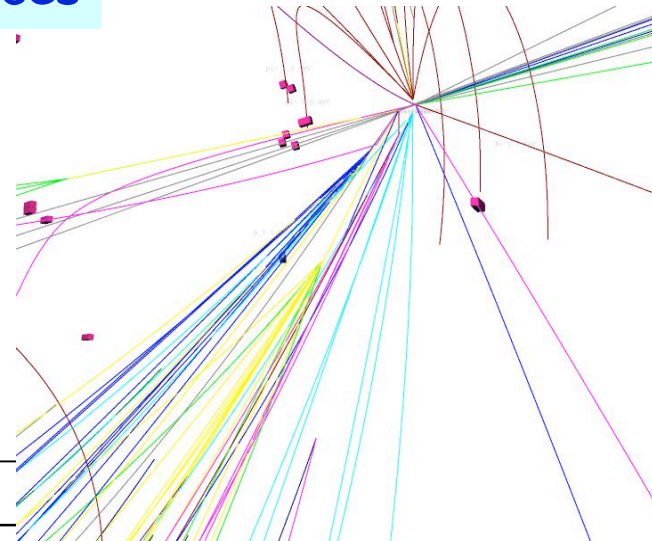
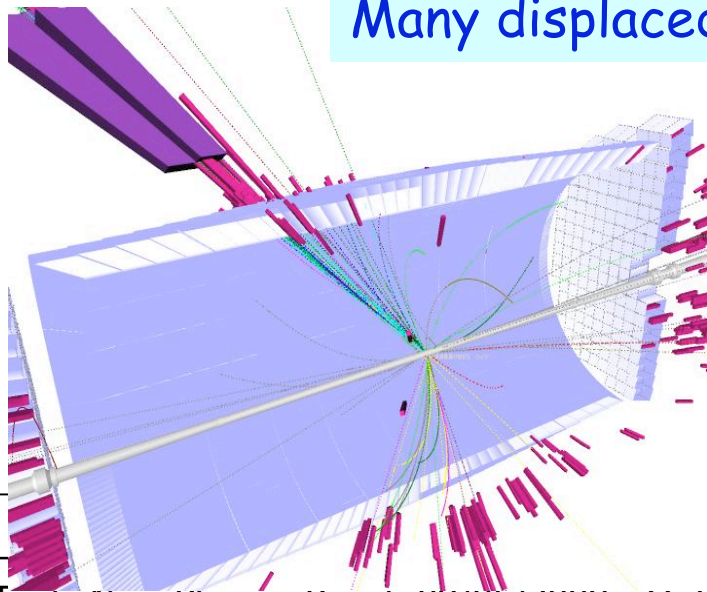
β -tracker β -muons

Hidden Valley Events

Curtsey of A. De Roeck



Many displaced vertices



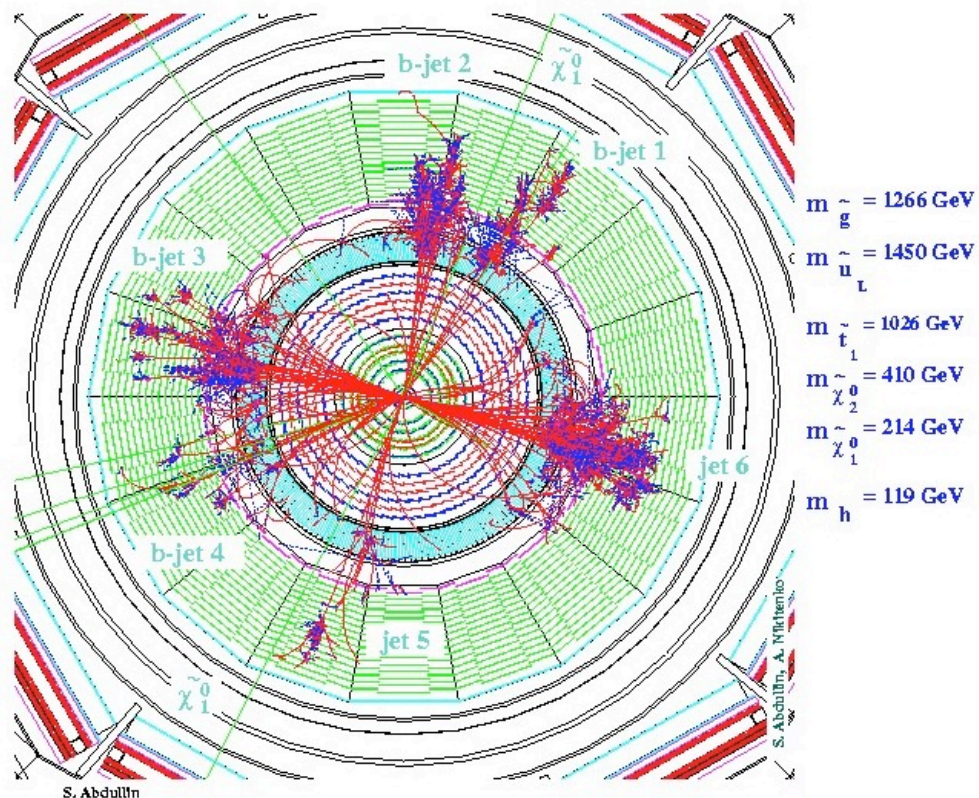
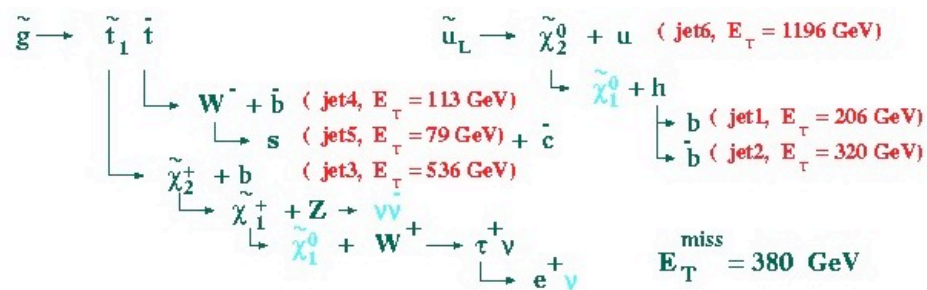
“SUSY-like” signatures at the LHC

What I call “SUSY-like”:

- Many hard Jets
- Large missing energy
 - 2 LSPs
 - Many neutrinos
- Many leptons
- In a word:
 - Spectacular!

$M_{sp}(\text{GeV})$	$\sigma \text{ (pb)}$	Evts/yr
500	100	$10^6\text{-}10^7$
1000	1	$10^4\text{-}10^5$
2000	0.01	$10^2\text{-}10^3$

For low masses the LHC
Would become a real
SUSY factory



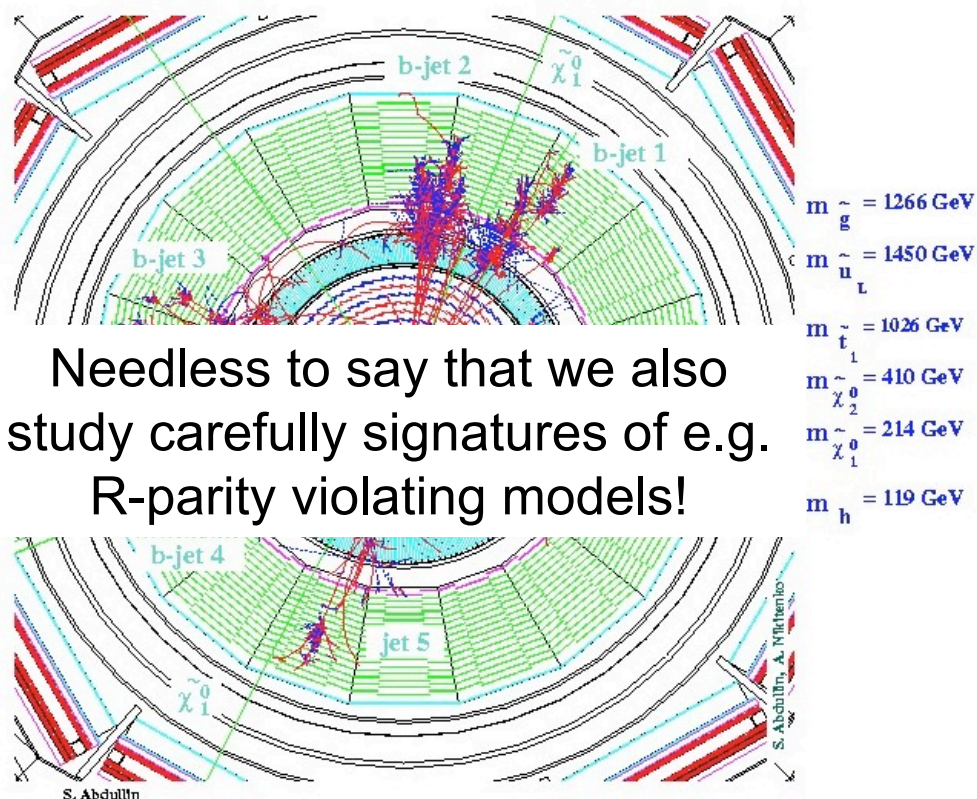
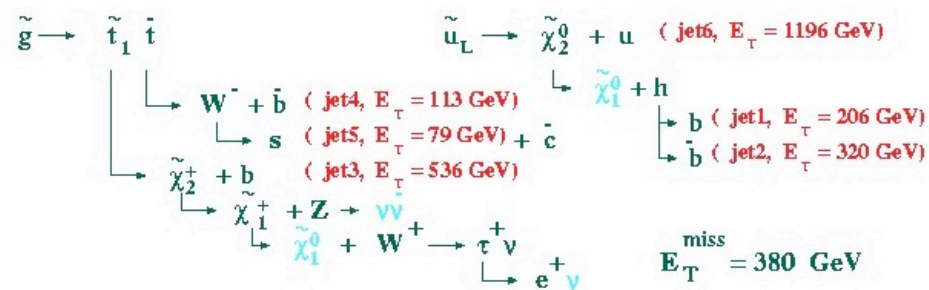
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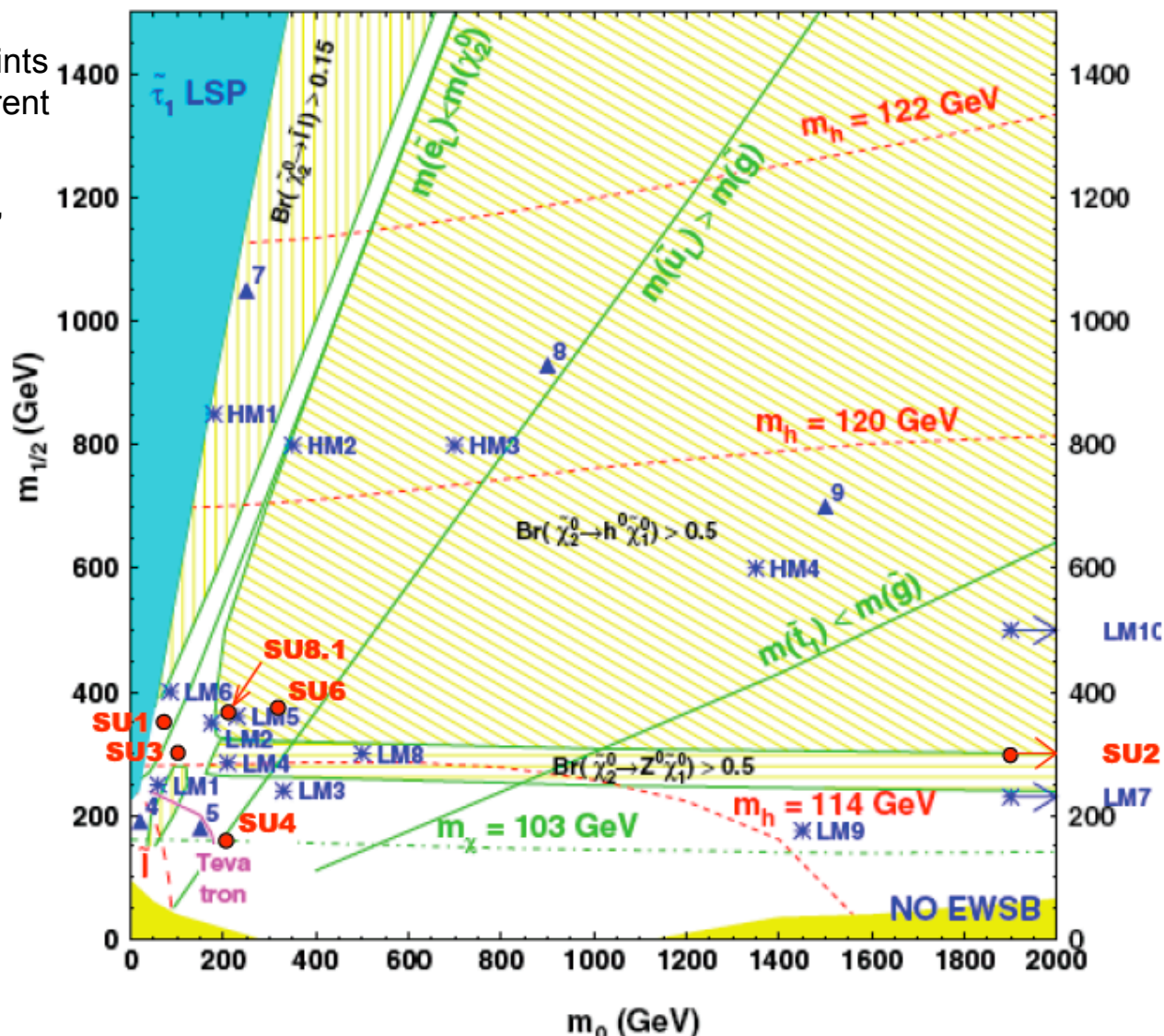
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How do we characterize “SUSY-like”

Establish benchmark points to study the various different Signatures.

Almost all “SUSY-like” BM points are defined in the CMSSM



LMx, HMx: CMS
SUX: ATLAS

“SUSY-like” Discovery Potential

CMS Reach for 1fb^{-1} (ATLAS similar)

Important signatures for the star Inclusive Search:

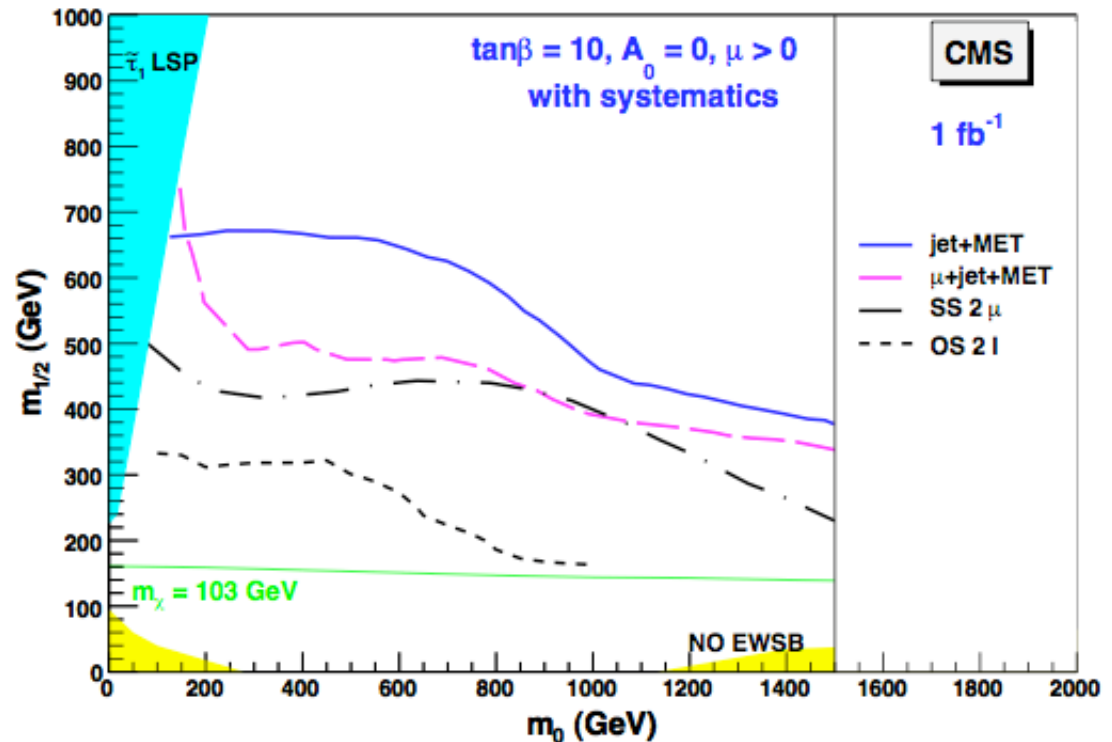
- **Jet+Missing E_t &**
 - 0 Lepton (e, μ)
 - 1 Lepton
 - 2 Leptons (same sign)
 - 2 Leptons (opposite sign)

Important SM Background:

- $t\bar{t}$
- W/Z + Jets
- QCD (multi-jets)
[difficult to simulate]

Background estimation:

- use control samples and side-band region to “measure” the background and/or tune your Monte Carlo.
→ mainly “data-driven”
(complemented with Monte Carlo)



Other important signatures like di-taus, $h \rightarrow b\bar{b}$, Z and top production have also been studied but not covered in this talk!

“Preferred” SUSY Parameter Space

* BUCHMULLER, CAVANAUGH, DE ROECK, HEINEMEYER, ISIDORI, PARADISI, RONGA, WEBER, WEIGLEIN.

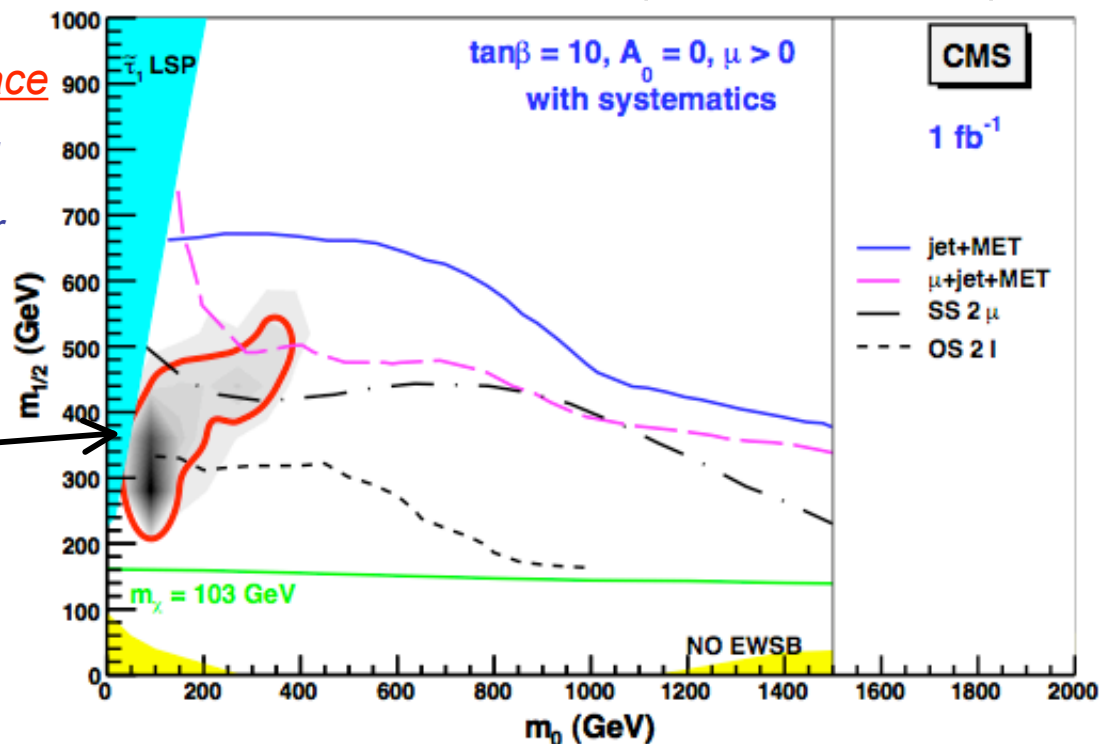
CMS Reach for 1fb^{-1} (ATLAS similar)

“Preferred” mSUGRA parameter space

Used indirect constraints from flavour, electroweak and cosmology physics to determine the mSUGRA parameter space compatible with these data.

Phys.Lett.B657:87-94,2007*
95% contour obtained from
a multi-parameter χ^2 fit to
important indirect constraints.
 $\chi^2/\text{NDF} = 17/14$ - good fit

NOTE: All mSUGRA parameters
are free in the fit!



If these “LHC weather forecasts” are correct, SUSY will emerge very early!

For sure these tools will be very useful
to solve the “inverse problem”:
→ Interpretation of discoveries

Example of similar analyses:

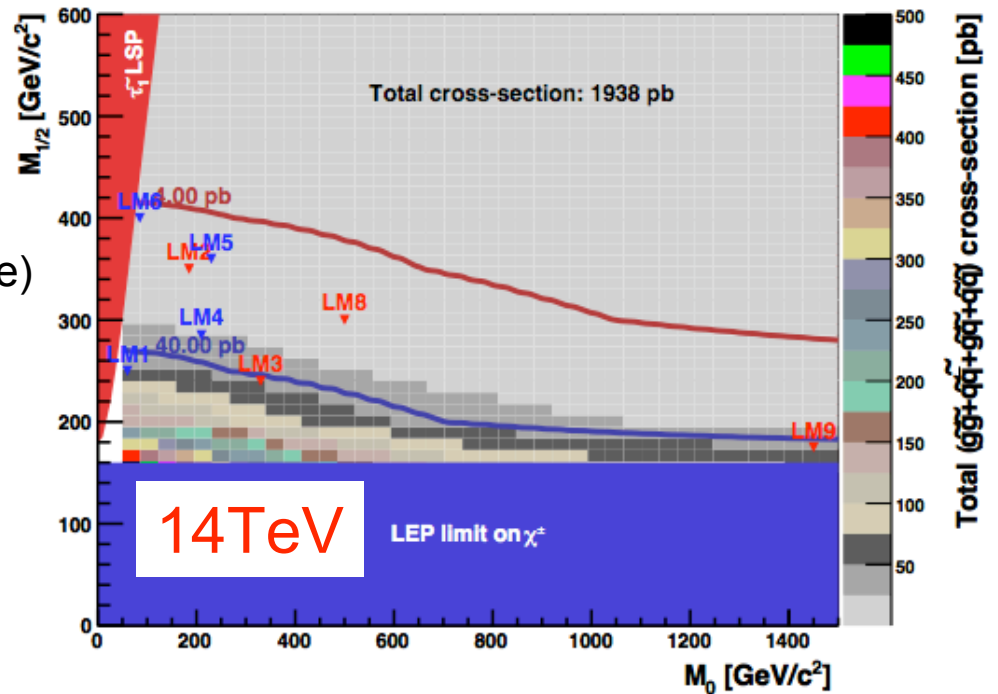
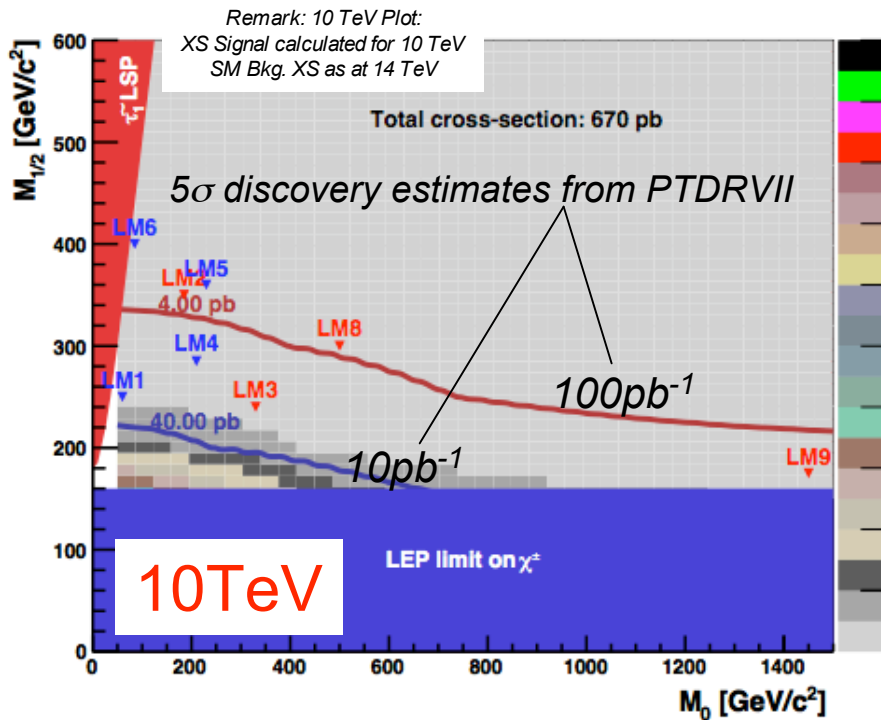
- Ellis, Heinemeyer, Olive, Weber, Weiglein - hep-ph/0706.0652
- Allanach, Lester, Weber - hep-ph/0705.0487
- Trotta, Austri, Roszkowski - hep-ph/0609126
- ... there are more!

SUSY (CMSSM) Reach: 14TeV vs. 10TeV

Comparison of SUSY production XS for 14TeV and 10TeV.

For 10TeV the reach is reduced but:

- 10 to 100pb⁻¹ start to cover our low mass (LM) SUSY points (i.e. interesting phase space) [assumes reasonably well understood data - of course]



10pb⁻¹(blue) and 100pb⁻¹(red) 5 σ discovery lines are based on PTDRVII studies (simple scaling!).

For illustration only!

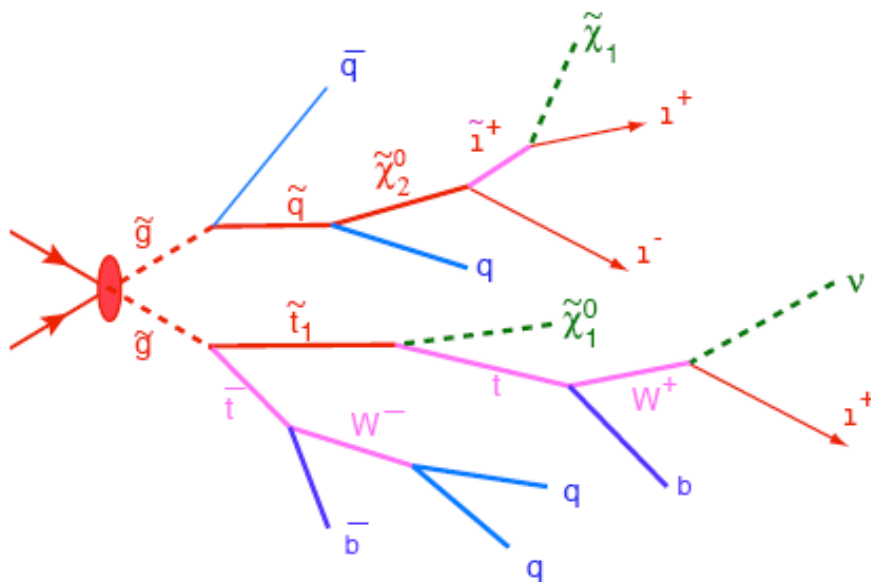
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- Focus on generic “model independent” signatures (RP-conserving)
 - missing energy, multi-jets, leptons...
 - need to confirm discovery through multiple signatures



Missing Energy:

- from LSP

Multi-Jet:

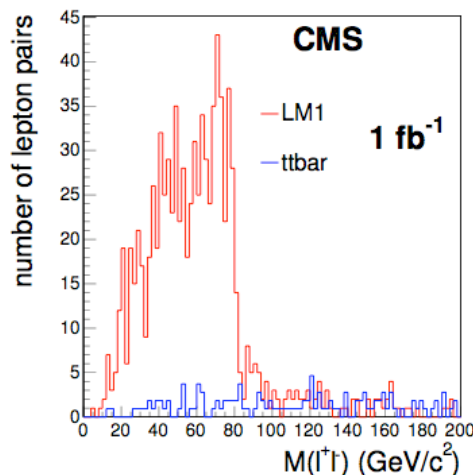
- from cascade decay (gaugino)

Multi-Leptons:

- from decay of charginos/neutranions

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- Extract constraints on SUSY properties from kinematics/decay chain reconstruction (assuming positive signal established)
 - Available observables are: sparticle masses, production cross section, decay chain properties (BR's, angular distributions, etc)



$$M_{\ell\ell}^{\max} = M(\tilde{\chi}_2^0) \sqrt{1 - \frac{M^2(\tilde{\ell}_R)}{M^2(\tilde{\chi}_2^0)}} \sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{\ell}_R)}}$$

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 - Predict additional signatures to be observed (likely iterative procedure)
 - Demonstrate the fundamental SUSY properties (e.g. particle \Leftrightarrow sparticle relations)

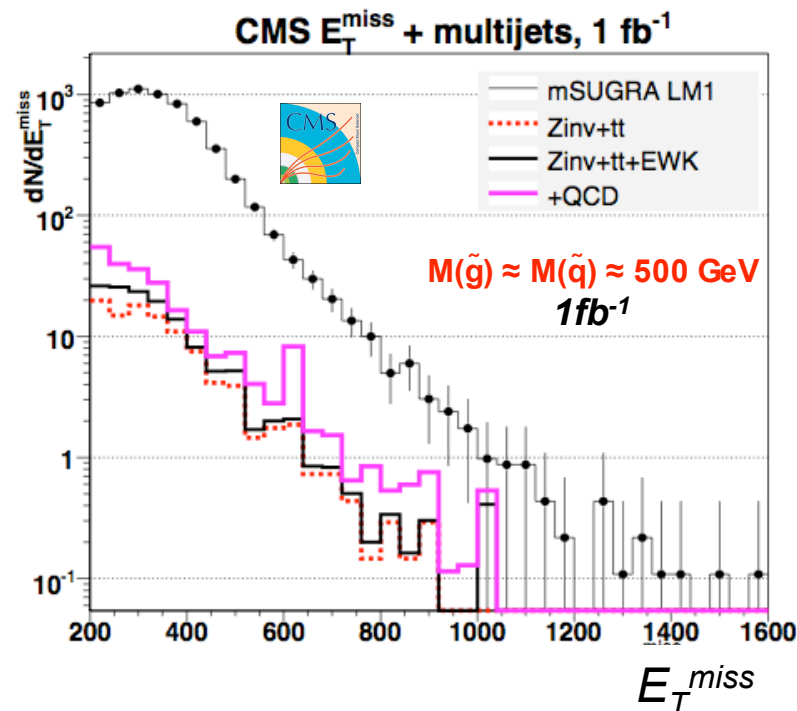
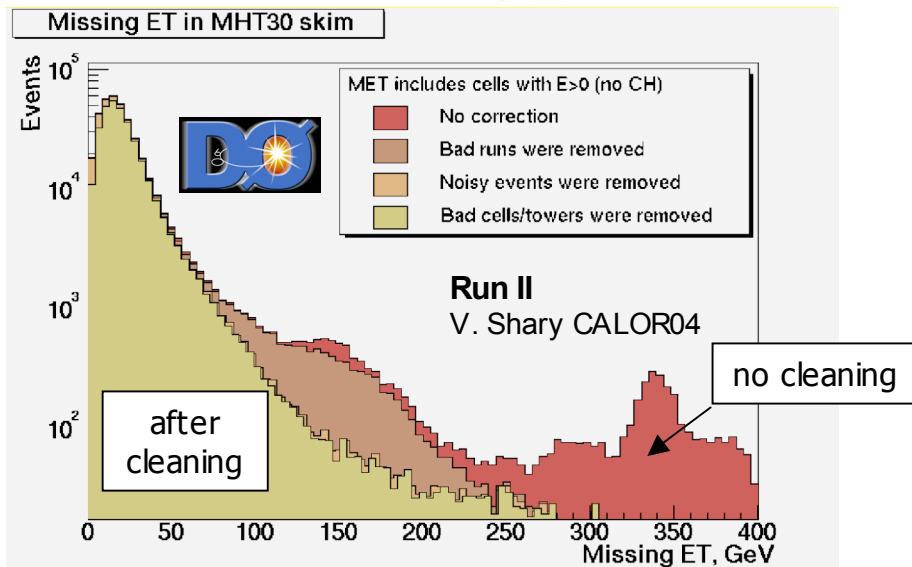
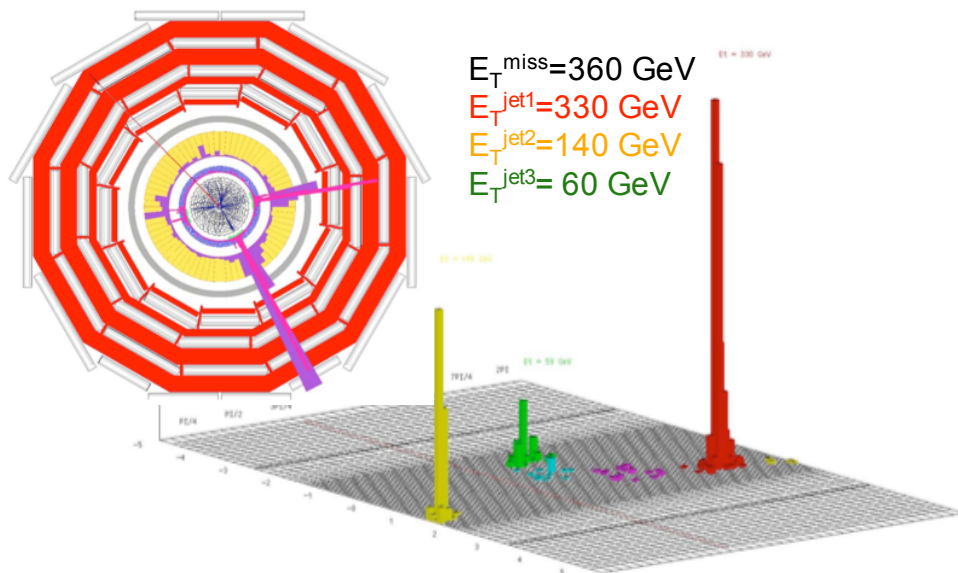
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Establish (or exclude) “SUSY-like” signatures

Jets + E_T^{miss} - Inclusive Search



Big discovery potential

But requires a very good detector understanding:

Analysis Strategy:

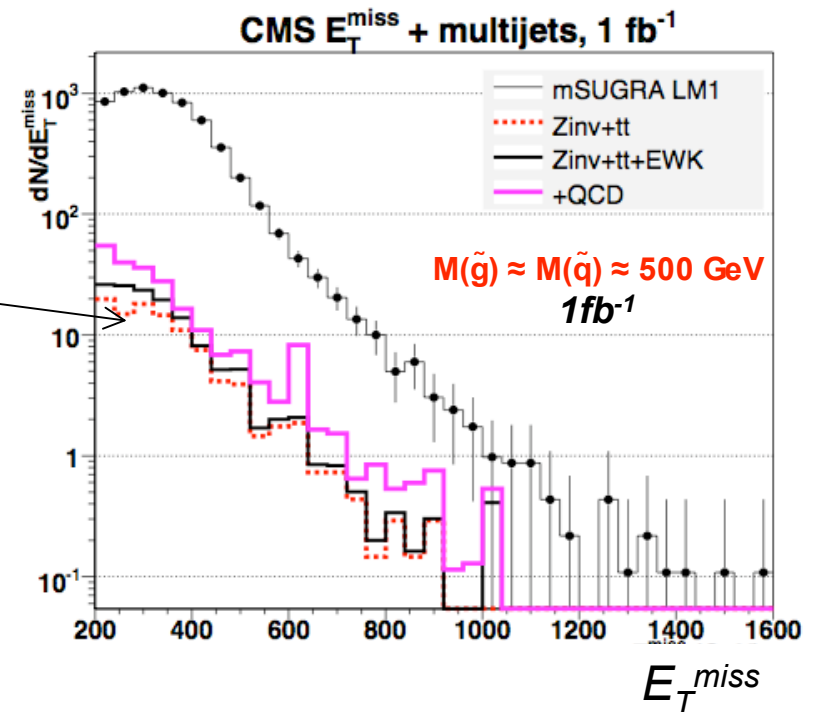
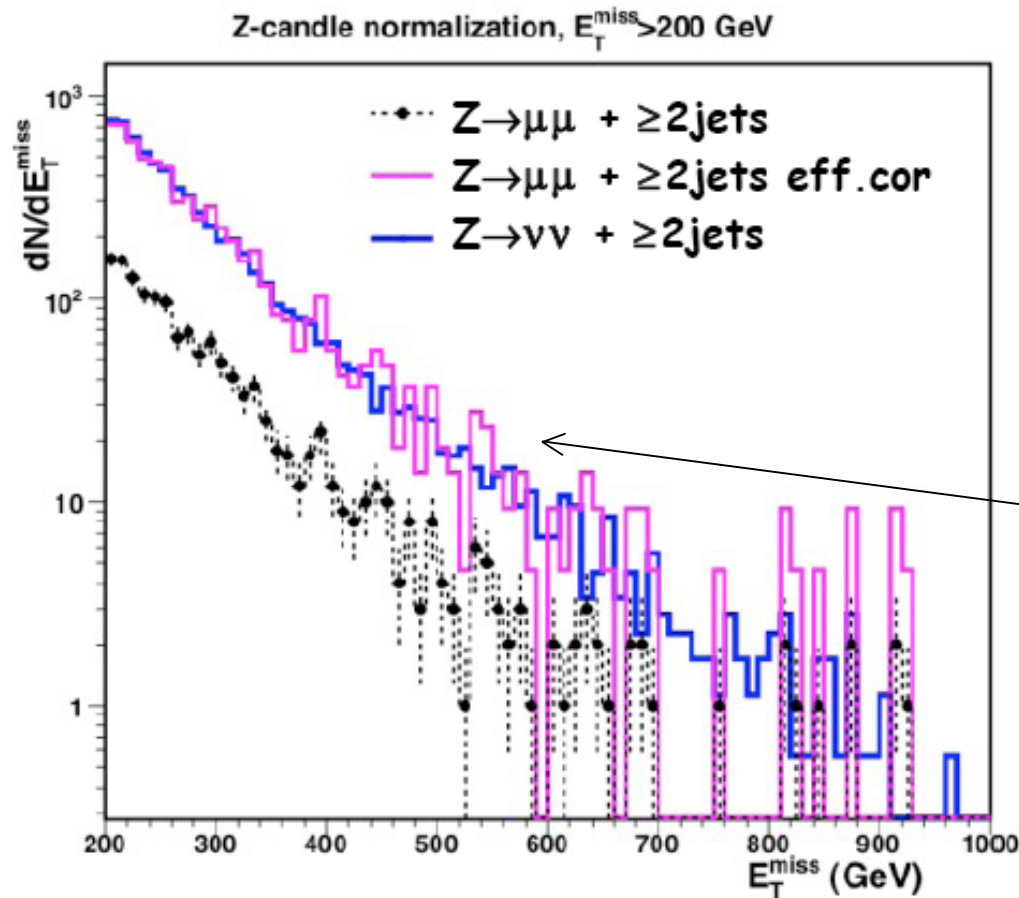
- Be brave
- Fight background and noise
- Use data control samples

Data Driven Background Estimations

The simplest example: $Z \rightarrow \nu\nu + \text{jets}$
[irreducible backg. Jets+ E_T^{miss} search]

Estimate this background
from $Z \rightarrow \mu\mu + \text{jets}$

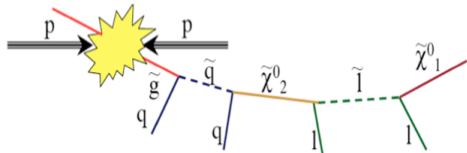
Need to correct for:
Muon efficiency \rightarrow from data
Muon acceptance \rightarrow from MC



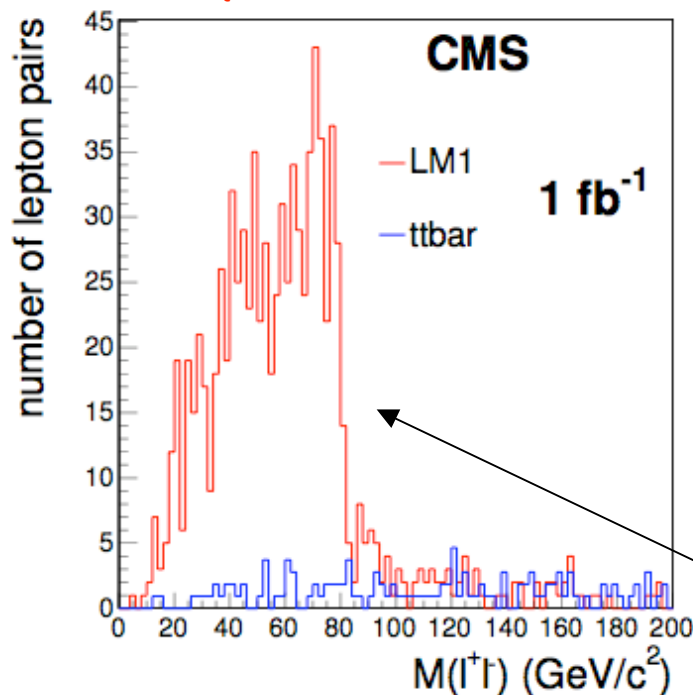
Di-Leptons & First Kinematic Measurements

...and if we are a bit lucky we might see spectacular signals already at the early days!

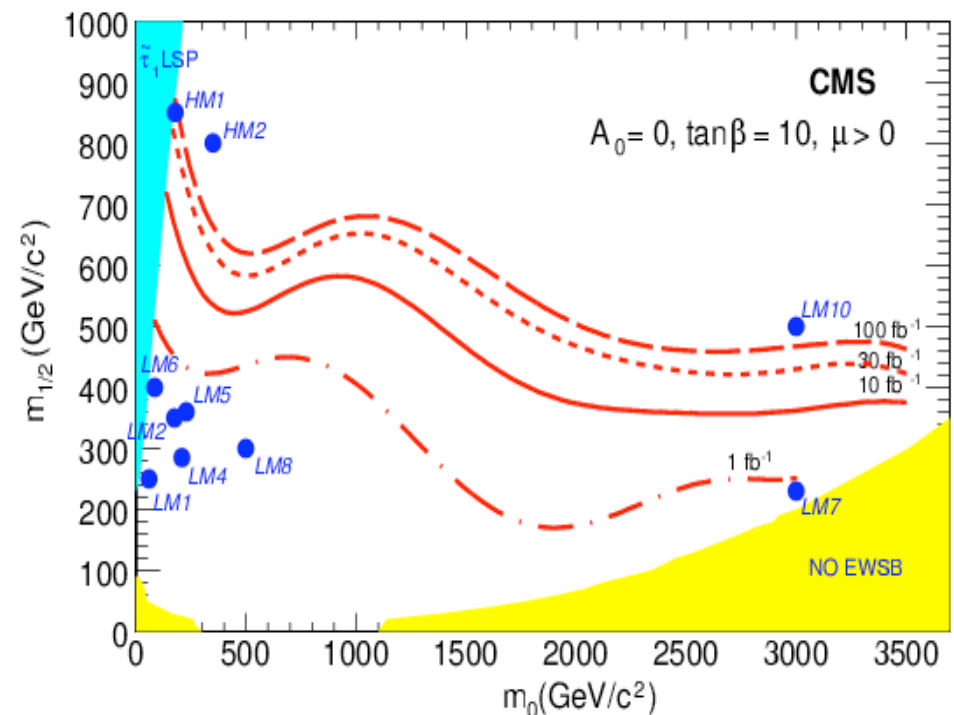
Look for generic signatures of cascade decays:



Jets + E_t^{miss} + SFOS di-leptons

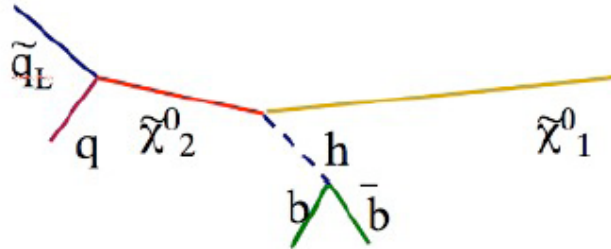


Jets + E_t^{miss} + SS di-muons

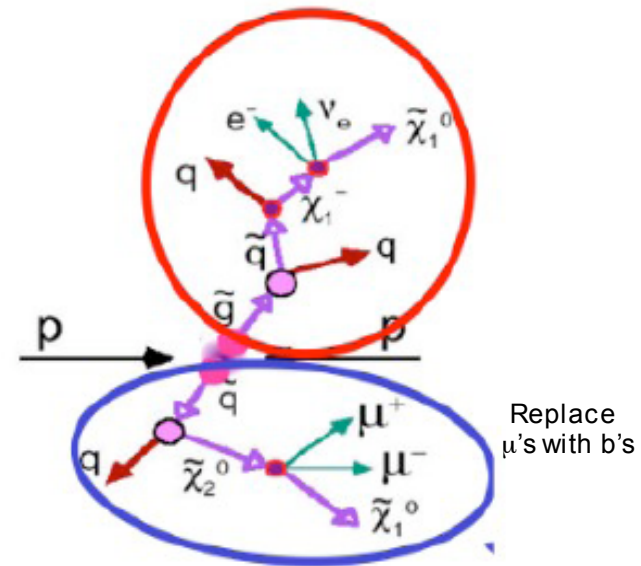
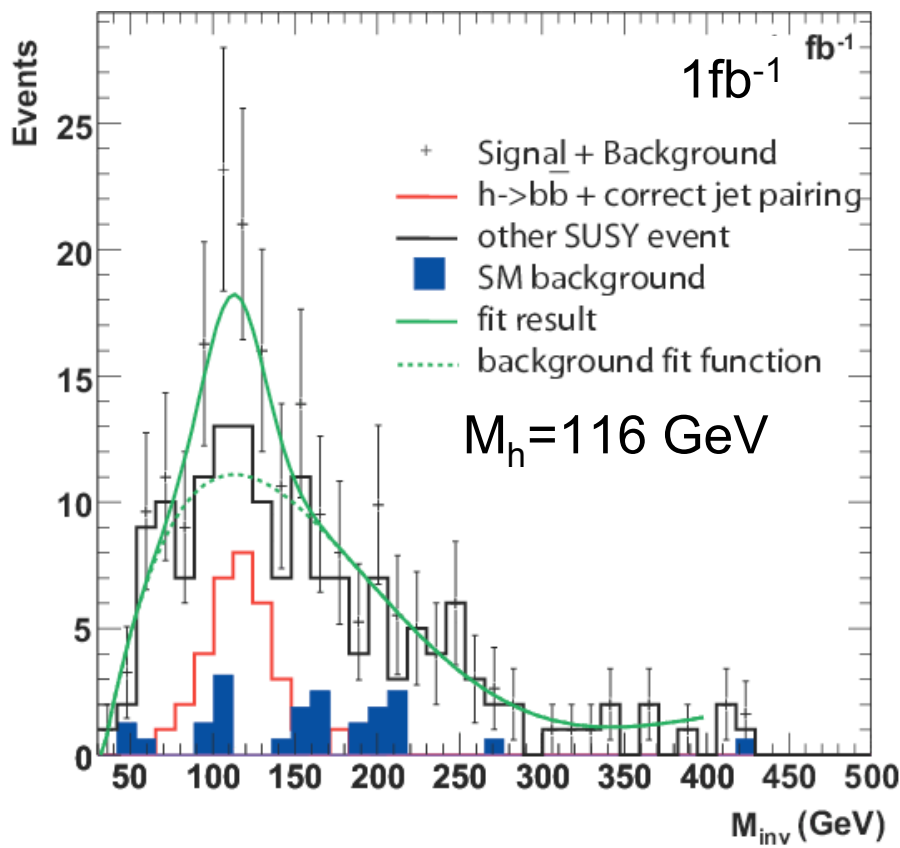


Extract: $M_{\ell\ell}^{max} = M(\tilde{\chi}_2^0) \sqrt{1 - \frac{M^2(\tilde{\ell}_R)}{M^2(\tilde{\chi}_2^0)}} \sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{\ell}_R)}}$
from a fit to the “edge distribution”.

“Low Mass M_h ” in SUSY Decays



Depending on the SUSY parameter space the $h \rightarrow b\bar{b}$ production is possible



- Separate cascade decay chain in two hemispheres and require two b's in one.
- 5σ Signal ($M_h = 115$ GeV) already with $\sim 2\text{fb}^{-1}$

Could be the first sign of a light higgs
but b-tagging is crucial!

Summary

- CMS is on track for first collisions in 2008
 - Challenge: commissioning of machine and detectors of unprecedented complexity, technology and performance
- CMS(& ATLAS) will discover (or exclude) the Higgs by ~ 2010
 - Electro Weak Symmetry Breaking
 - Large phase space can already be excluded with only $\sim 1\text{fb}^{-1}$
- CMS(& ATLAS) will discover low energy SUSY (if it exists)
 - Could be easy; could also take more time and ingenuity before we can claim a discovery
 - First signals might emerge already in the first data (even at 10 TeV)
 - 1-2 TeV can be covered already with $\sim 10\text{fb}^{-1}$
- We will cover a new physics scale of 1-3 TeV
 - Many new physics models; Black hole, Extra Dimensions, Little Higgs, Split Susy, New Bosons, Technicolour, etc ...

Flavour/High-Q2 Interplay

A few (private) comments from an experimentalist ...

- **Highest Priorities:** “Early” Running:
 - understand detector, measure SM processes, *(hopefully) establish a significant deviation from the SM - good things can come early!*
- **Today:** Develop Search Strategies including Data Driven Background Methods and Trigger
 - Try to cover NP model phase space using “representative signature models” (e.g. CMSSM for “Dark Matter Searches”). Indeed, these training models are usually flavour blind!
- **Important Question:** Are we missing important NP signatures?
 - Is the flavour blindness of our traditional training models a real concern for discovery?

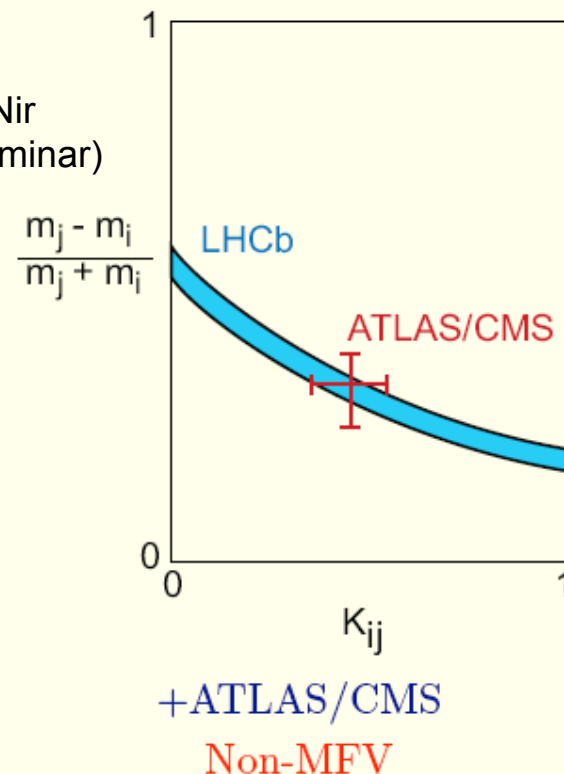
Flavour/High-Q2 Interplay

What comes after the discovery

ATLAS/CMS will, hopefully, observe NP at $\Lambda_{\text{NP}} \lesssim \text{TeV}$ and...

- Measure new flavor parameters
- Teach us about how the NP flavor puzzle is (not) solved
- Probe NP at $\Lambda_{\text{NP}} \gg \text{TeV}$
- Provide hints about the solution to the SM flavor puzzle

Yossi Nir
(CERN seminar)



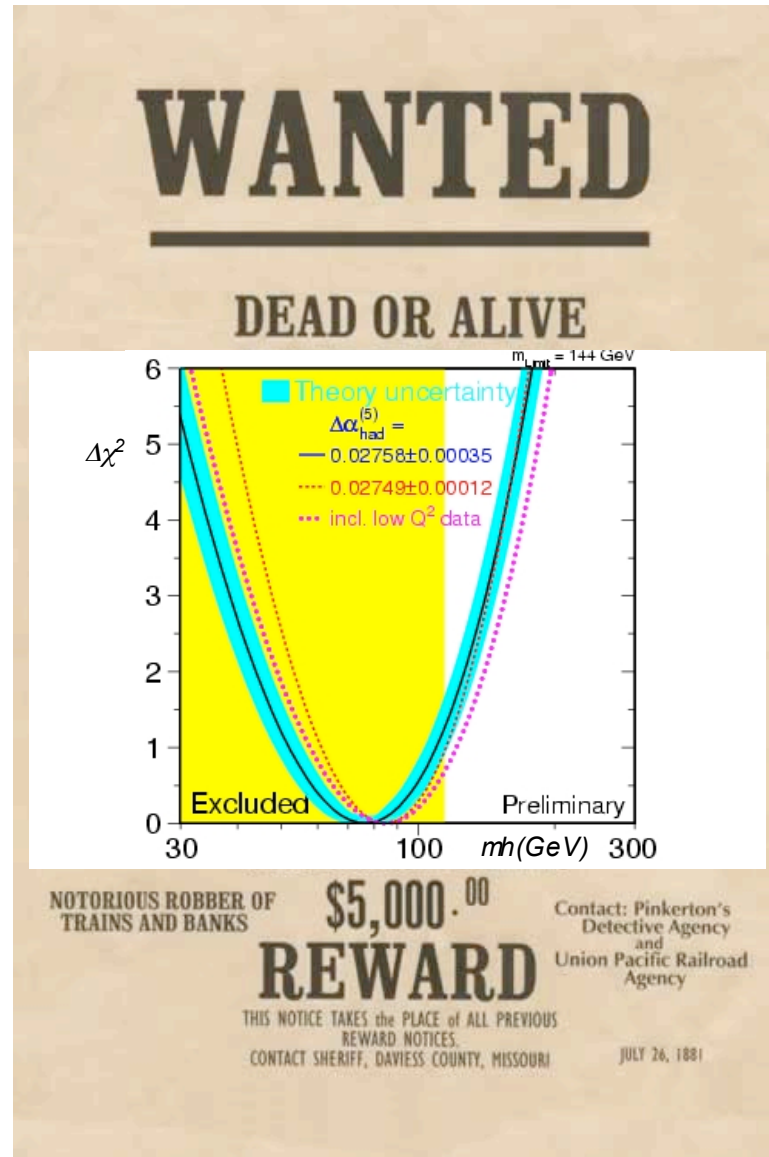
Point Take!

“Flavour” will play a crucial role in the interpretation of LHC discoveries. Clearly, we need to include “Flavour” more into our High-Q2 search & interpretation strategies!

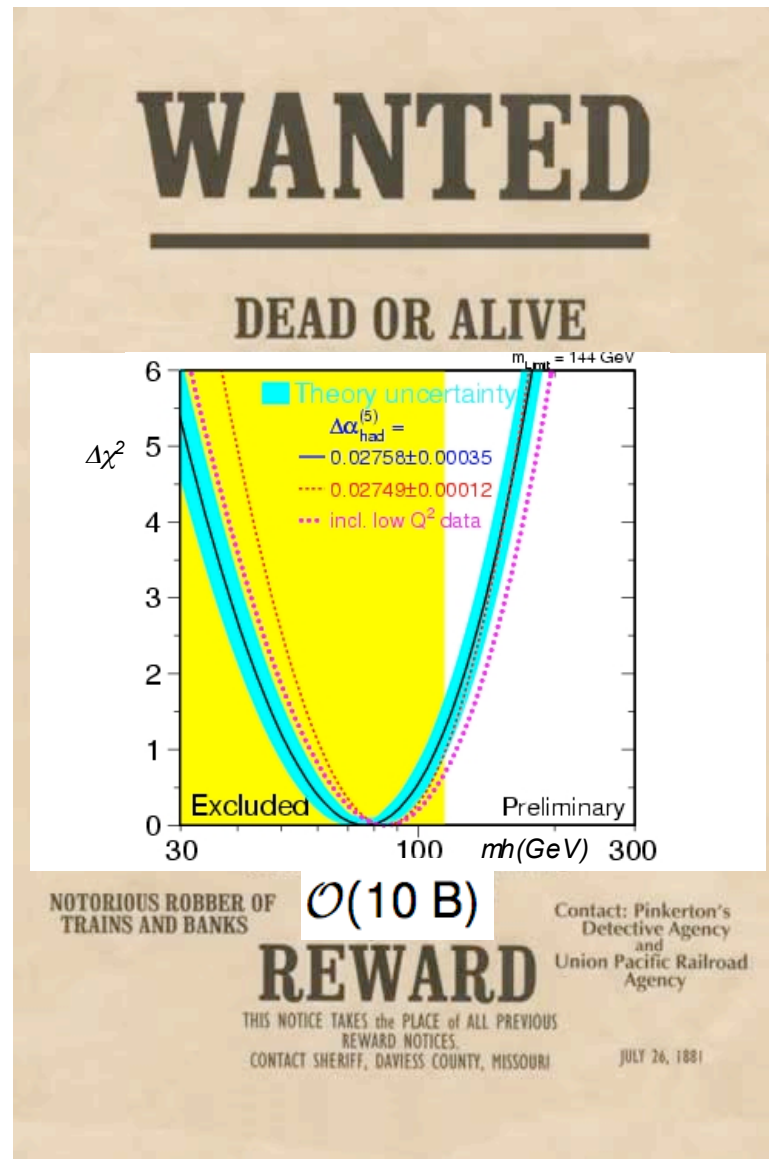
What would be the best approach for this?

Backup

SM-like Higgs Boson



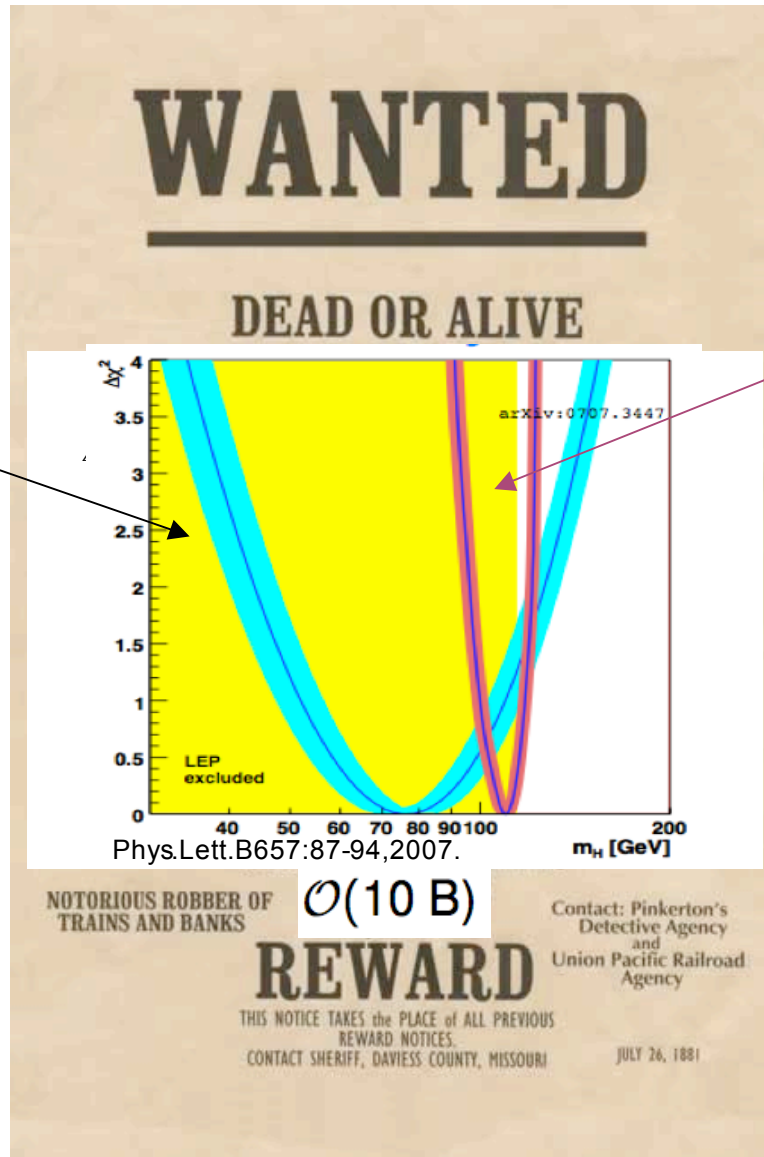
SM-like Higgs Boson



SM-like Higgs Boson

Higgs in the SM

Higgs in the CMSSM



Important Higgs Channels

- $H \rightarrow ZZ^* \rightarrow 4l$
 - $H \rightarrow WW^* \rightarrow lnl n$
- } “early” discovery channels
measure Higgs properties (mass, width, xsec)
already with 30 fb^{-1} !!
- $H \rightarrow WW^* \rightarrow jjln / lnl n$ in VBF
 - $H \rightarrow t t$ in VBF
- } significance $> 5(3)$ with 30 fb^{-1}
but good comprehension of detector needed
(jet, MET, t in lept. and hadr. decay)
- $H \rightarrow gg$ very difficult analysis with still quite unpredictable background
 - $ttH \rightarrow ttbb$ at least 60 fb^{-1} (many jets also with low p_T ($< 30 \text{ GeV}$) \rightarrow bad reso/eff)
 - other channels (mainly **associated production**) can help
EXCLUDING Higgs (e.g. $WH \rightarrow WWW^* \rightarrow Wlnln$)

channel	XS	studied M_H
$H \rightarrow ZZ^* \rightarrow 4l$	5-100 fb	130-500 GeV
$H \rightarrow WW^* \rightarrow lnl n$	0.5-2.5 pb	120-200 GeV
VBF {	$H \rightarrow WW^* \rightarrow jjln$	200-900 fb
	$H \rightarrow WW^* \rightarrow lnl n$	120-250 GeV
	$H \rightarrow t t$	120-200 GeV
		50-150 fb
$H \rightarrow gg$	50-100 fb	115-145 GeV
		115-150 GeV

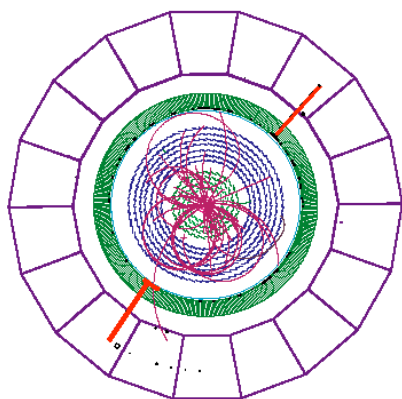
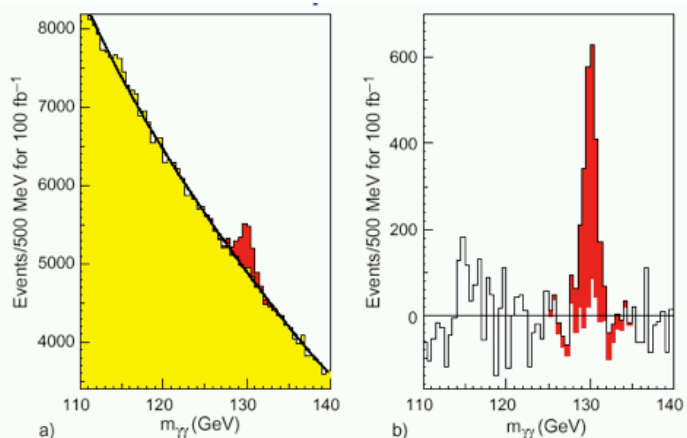
□ Analysis focusing on

- improvement of the reconstruction
- backgr. and syst. from data

Higgs Mass below 200 GeV

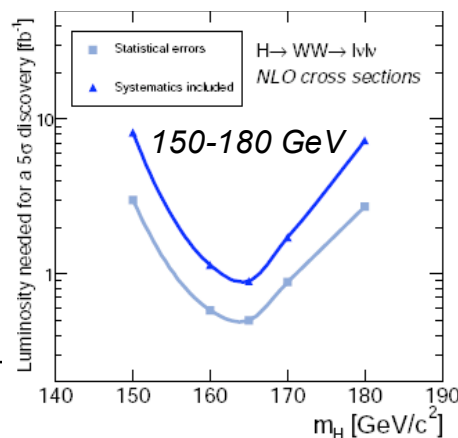
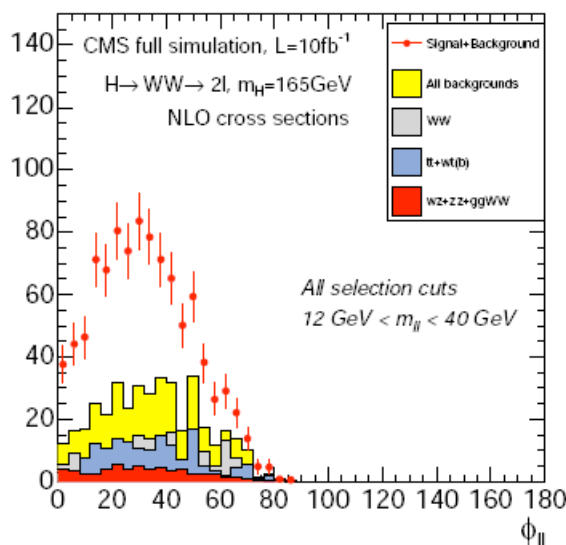
Low $M_H < 140$ GeV

$$H \rightarrow \gamma\gamma$$



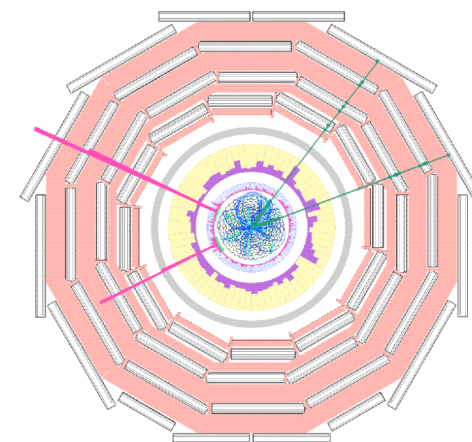
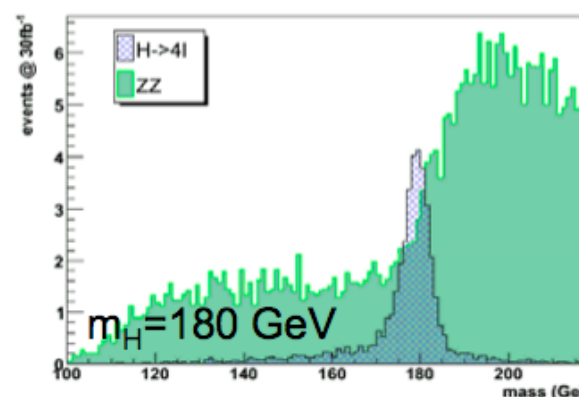
$2M_W < M_h < 2M_Z$

$$H \rightarrow WW^{(*)} \rightarrow 2l$$

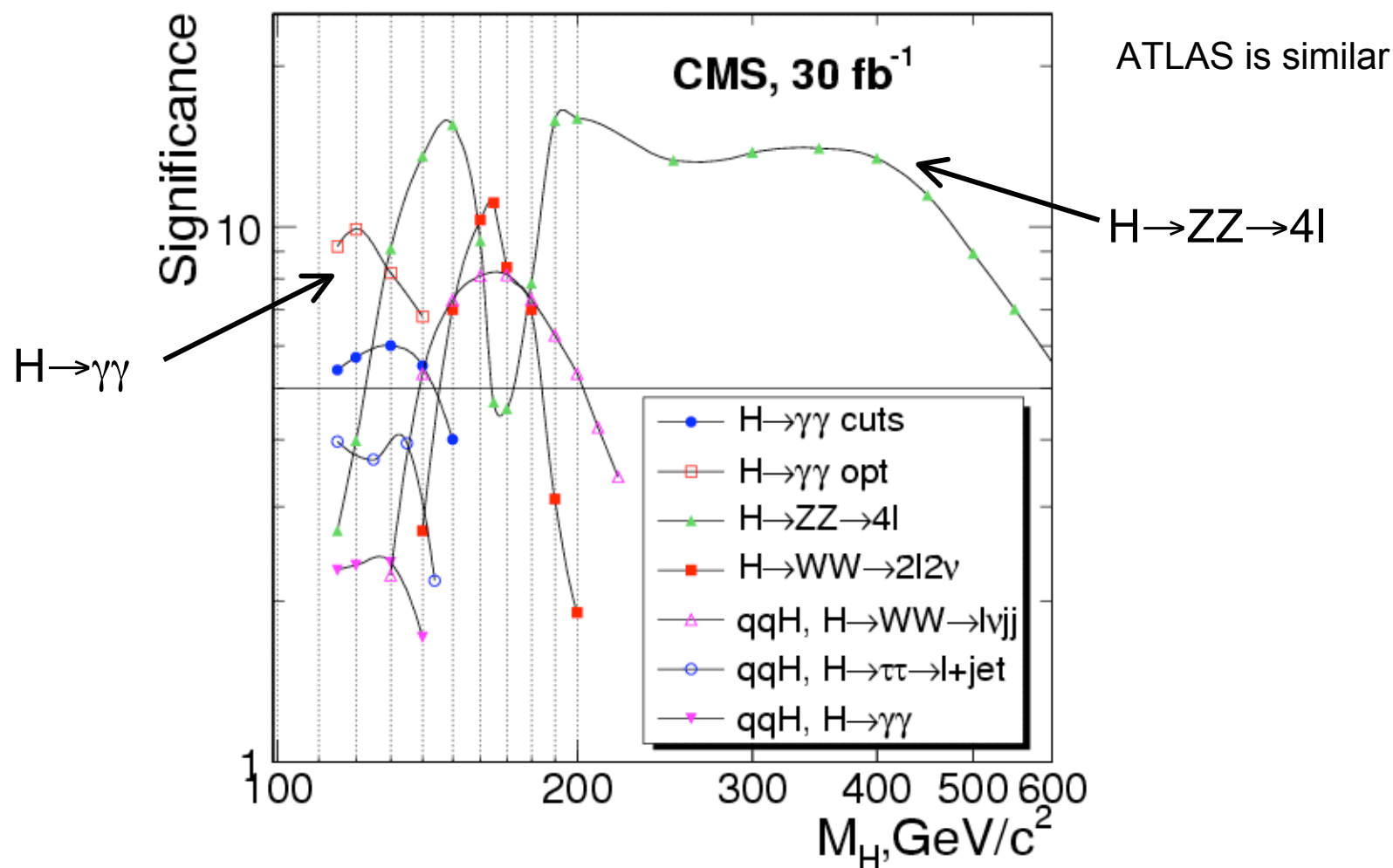


$130 < M_H < \sim 600$ GeV

$$H \rightarrow ZZ^{(*)} \rightarrow 4l$$



CMS: Higgs Discovery Potential



Bottom line: We will find the Higgs (or exclude it)!

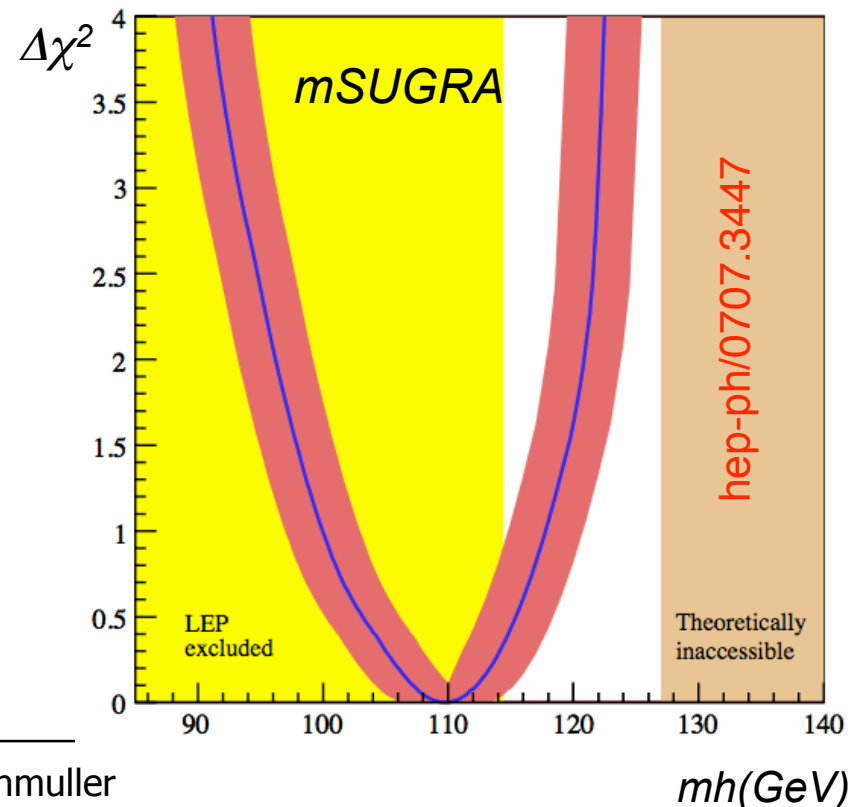
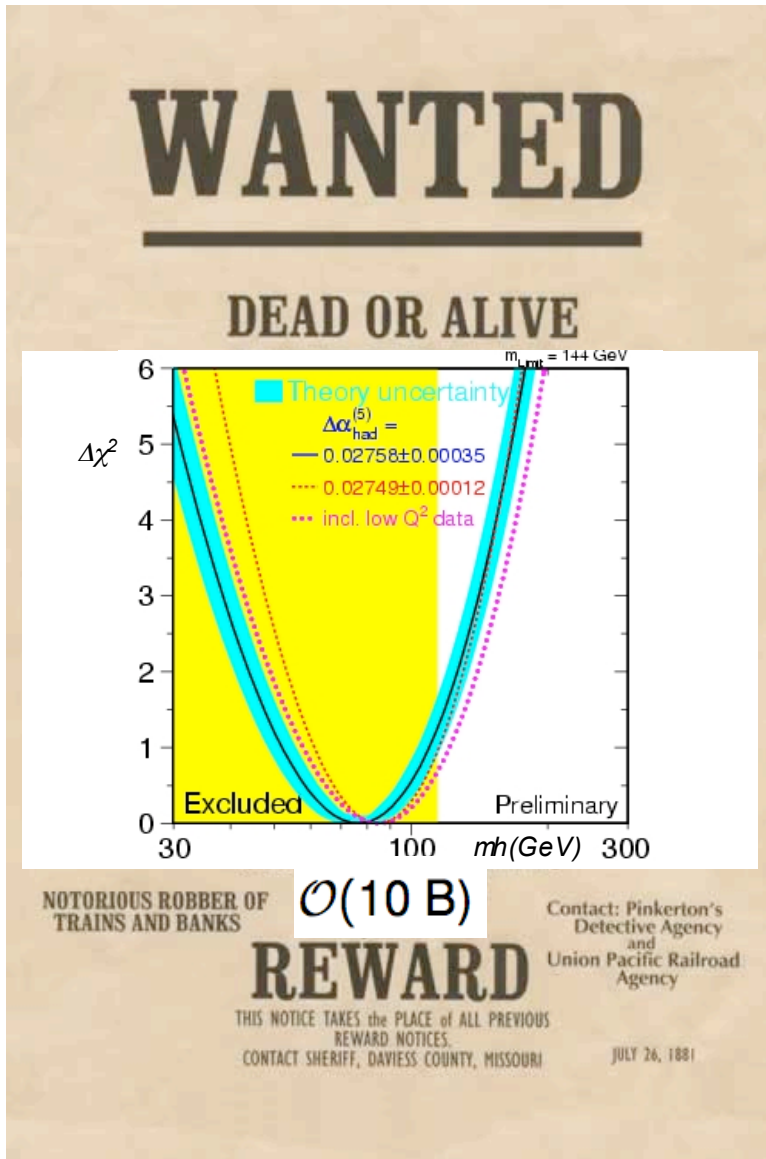
SM-like Higgs Boson

Precision electroweak data tightly constrain the allowed region of m_h in the SM.

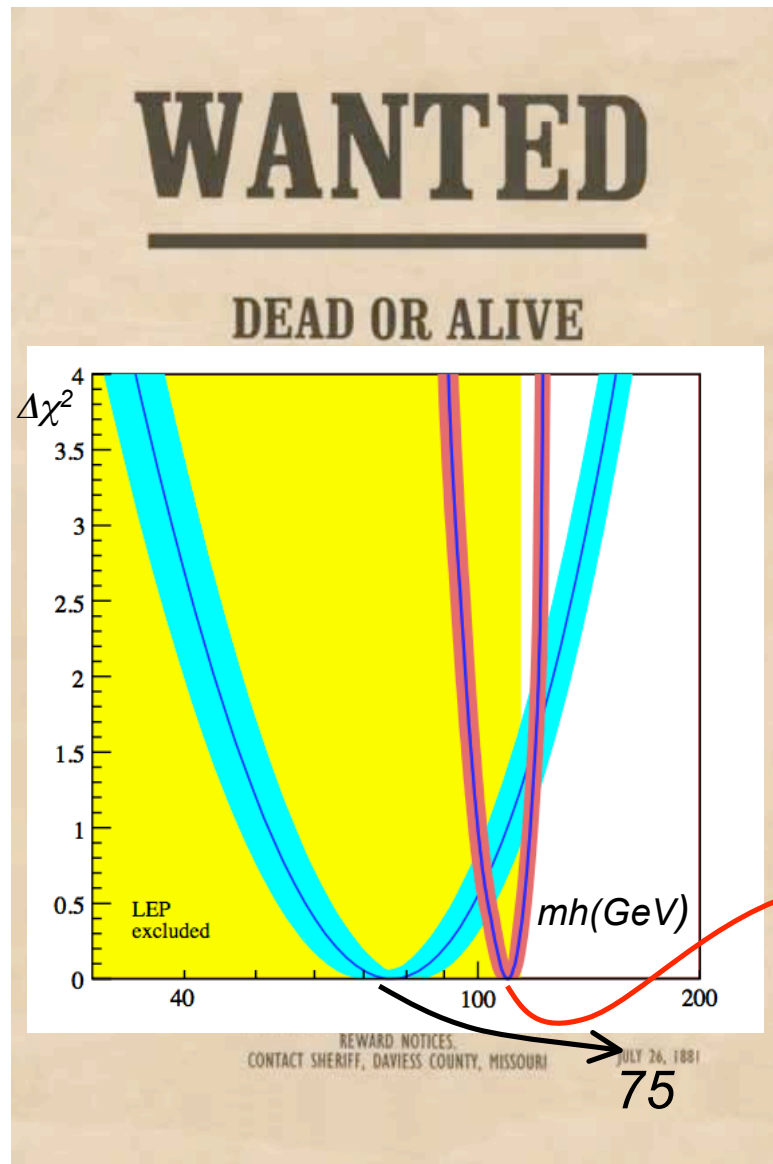
Yet, also other important models like *mSUGRA* are constrained by these data:

mSUGRA fit to flavour, electroweak and cosmology data:

$$m_h(mSUGRA) = 110^{+8}_{-10} \text{ (exp)} \pm 3 \text{ (theo)} \text{ GeV}$$



SM-like Higgs Boson

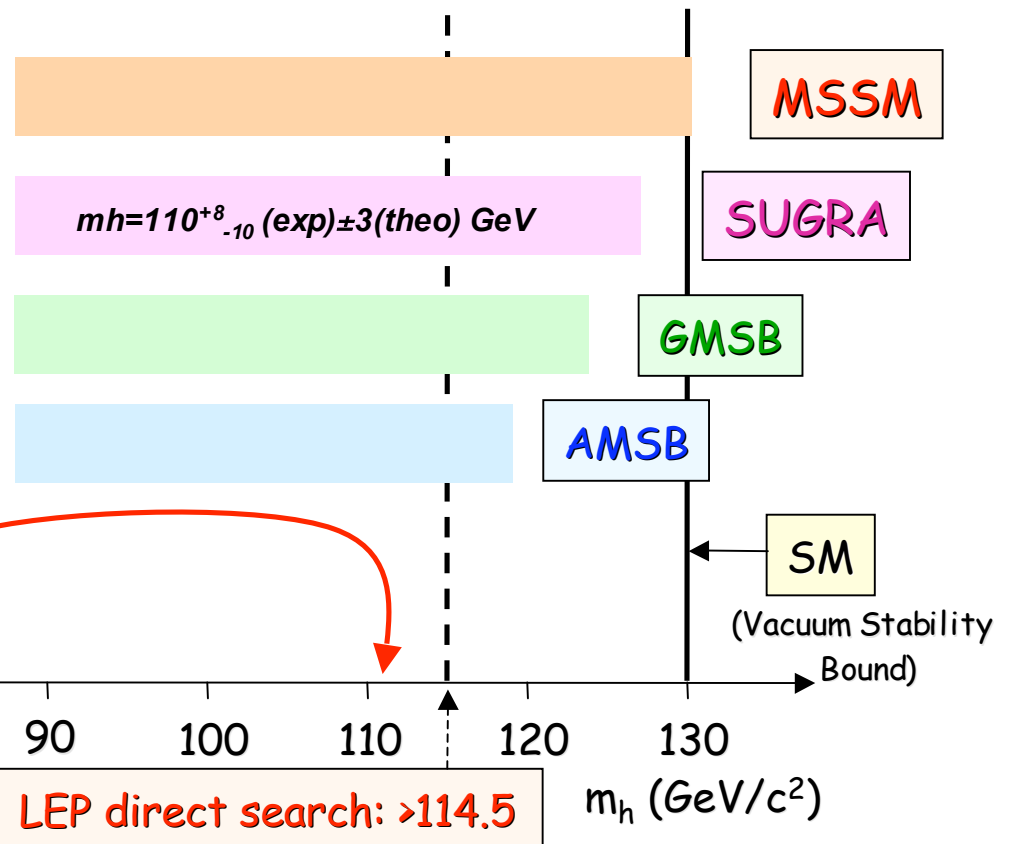


SM: Constrained Phase Space

$$m_h(\text{SM}) = 76^{+33}_{-24} \text{ GeV}$$

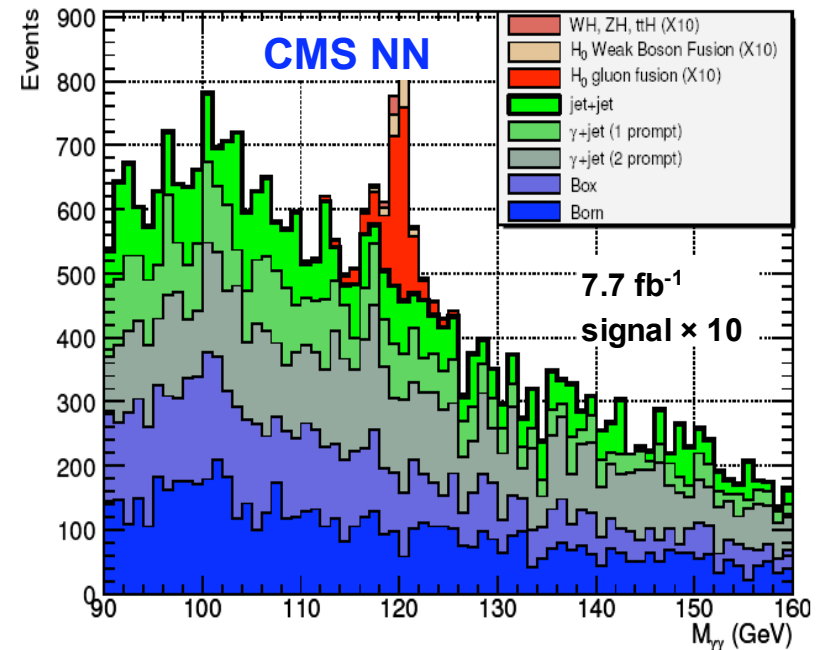
$$m_h(\text{SM}) < 144 \text{ GeV @ 95\% CL}$$

SUSY: Accessible Phase Space

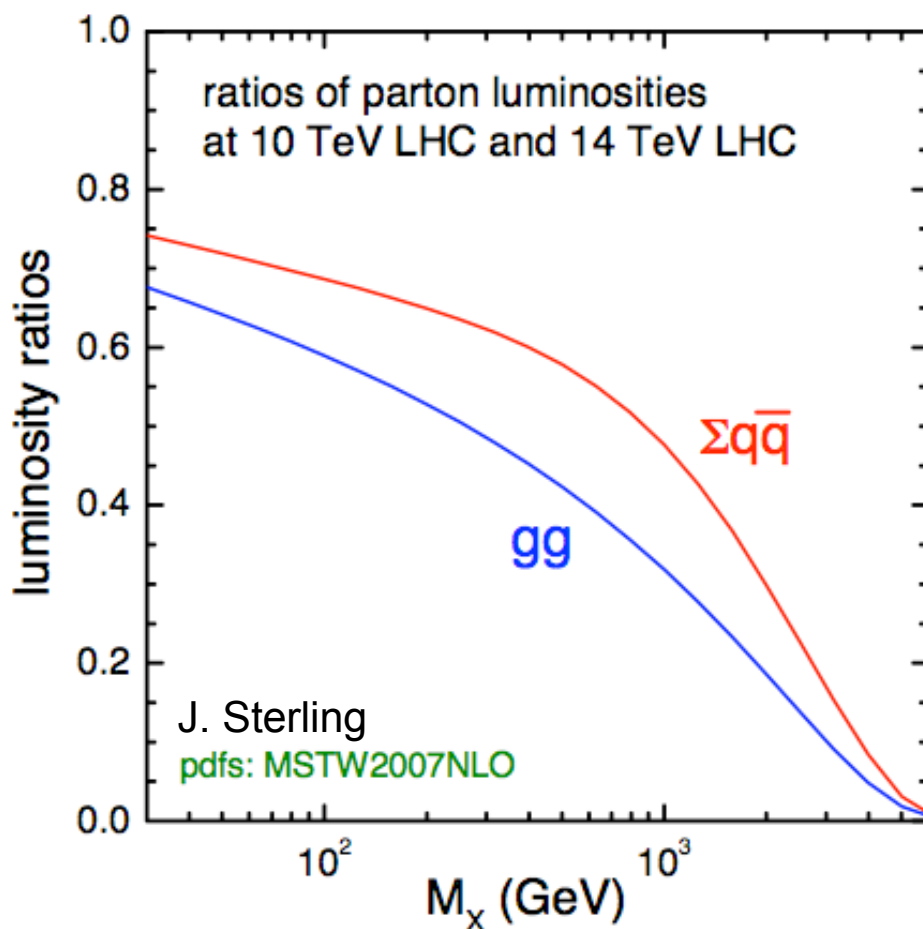


$H \rightarrow \gamma\gamma$

- **Photon conversions** are important, due to material balance in inner detectors
 - **42%** in the barrel, **59.5%** in the endcap
- **Energy Resolution**
 - **0.3%** in the barrel, **1%** in the endcap
- **Associated production** allows to improve s/b ratio. Both ATLAS and CMS are studying several channels
- **“Advanced” analyses** (NN, Likelihood, categories) allow to improve results with low statistics



Production Rates: 14 TeV vs. 10 TeV



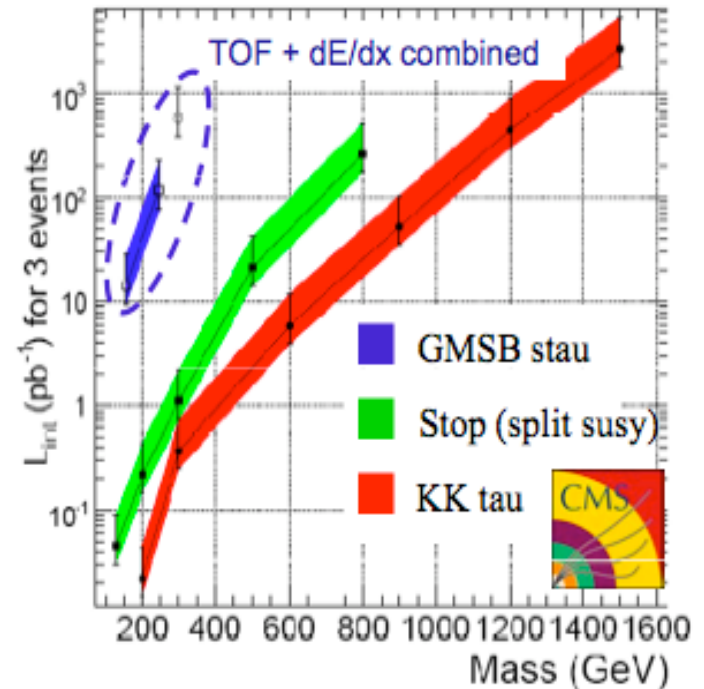
Production Rate wrt 14 TeV:

- W/Z ~70%
- ttbar ~50%
- Higgs (200) ~50%

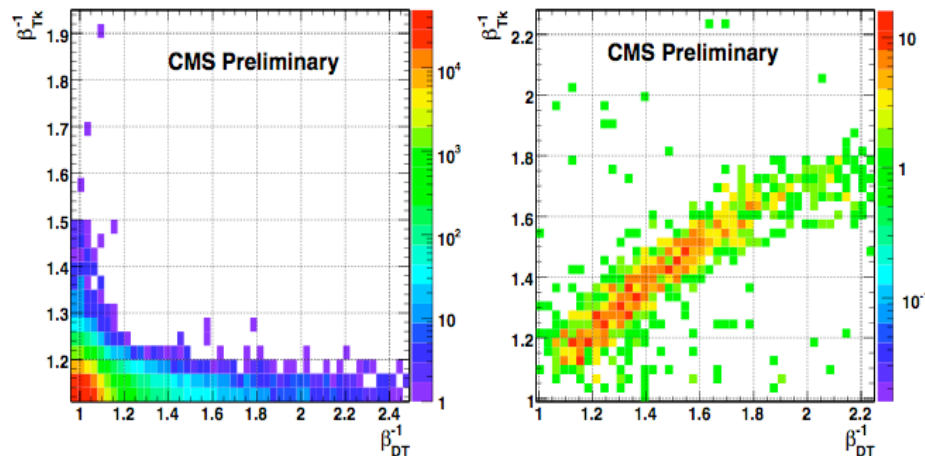
Heavy Stable Charged Particles

Data Sample	Cross section (pb)	HSCP in $ \eta < 2.4$ (%)	HSCP in $ \eta < 0.9$ (%)
$\tilde{\tau}_1$ (156 GeV)	1.19	97.6	72.6
$\tilde{\tau}_1$ (247 GeV)	0.097	97.5	70.9
KK tau (300 GeV)	0.020	84.7	40.9
\tilde{g} (200 GeV)	2.2×10^3	89.7	47.4
\tilde{g} (300 GeV)	100	91.7	50.0
\tilde{g} (600 GeV)	5.00	93.7	55.5
\tilde{g} (900 GeV)	0.46	92.6	57.7
\tilde{g} (1200 GeV)	61×10^{-3}	91.4	53.9
\tilde{g} (1500 GeV)	10×10^{-3}	90.4	55.8
\tilde{t}_1 (130 GeV)	1.11×10^3	87.8	43.1
\tilde{t}_1 (200 GeV)	1.77×10^2	90.9	47.3
\tilde{t}_1 (300 GeV)	27.4	92.8	50.4
\tilde{t}_1 (500 GeV)	1.27	95.3	54.7
\tilde{t}_1 (800 GeV)	7.81×10^{-2}	96.9	61.9

New extended HCSP study



Curtsey of A. De Roeck



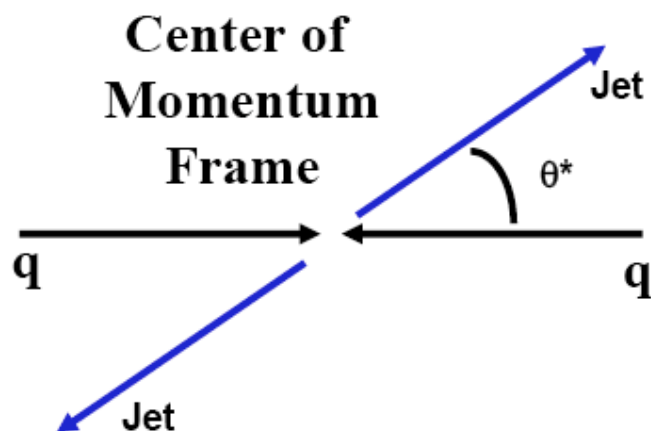
New Physics Discovery Potential (early days)

Model	Mass reach	Luminosity (fb ⁻¹)	Early Systematic Challenges
Contact Interaction	$\Lambda < 2.8 \text{ TeV}$	0.01	Jet Eff., Energy Scale
Z'			Alignment
ALRM	$M \sim 1 \text{ TeV}$	0.01	
SSM	$M \sim 1 \text{ TeV}$	0.02	
LRM	$M \sim 1 \text{ TeV}$	0.03	
E6, SO(10)	$M \sim 1 \text{ TeV}$	0.03 – 0.1	
Excited Quark	$M \sim 0.7 - 3.6 \text{ TeV}$	0.1	Jet Energy Scale
Axigluon or Coloureon	$M \sim 0.7 - 3.5 \text{ TeV}$	0.1	Jet Energy Scale
E6 diquarks	$M \sim 0.7 - 4.0 \text{ TeV}$	0.1	Jet Energy Scale
Technirho	$M \sim 0.7 - 2.4 \text{ TeV}$	0.1	Jet Energy Scale
ADD Virtual G_{KK}	$M_D \sim 4.3 - 3 \text{ TeV}, n = 3-6$ $M_D \sim 5 - 4 \text{ TeV}, n = 3-6$	0.1 1	Alignment
ADD Direct G_{KK}	$M_D \sim 1.5-1.0 \text{ TeV}, n = 3-6$	0.1	MET, Jet/photon Scale
SUSY	$M \sim 1.5 - 1.8 \text{ TeV}$	1	MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backgrounds
Jet+MET+0 lepton	$M \sim 0.5 \text{ TeV}$	0.01	
Jet+MET+1 lepton	$M \sim 0.5 \text{ TeV}$	0.1	
Jet+MET+2 leptons	$M \sim 0.5 \text{ TeV}$	0.1	
mUED	$M \sim 0.3 \text{ TeV}$ $M \sim 0.6 \text{ TeV}$	0.01 1	ibid
RS1			
di-jets	$M_{G1} \sim 0.7 - 0.8 \text{ TeV}, c=0.1$	0.1	Jet Energy Scale
di-muons	$M_{G1} \sim 0.8 - 2.3 \text{ TeV}, c=0.01-0.1$	1	Alignment

Not an exhaustive list!!

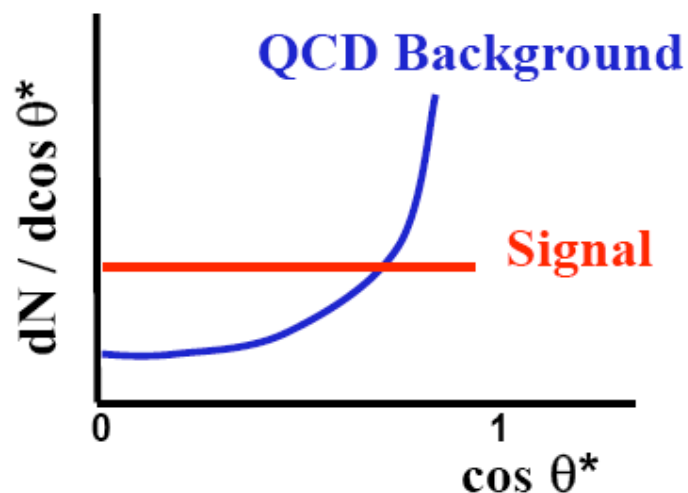


Contact Interactions in Angular Distributions



Contact interaction is often **more isotropic** than QCD

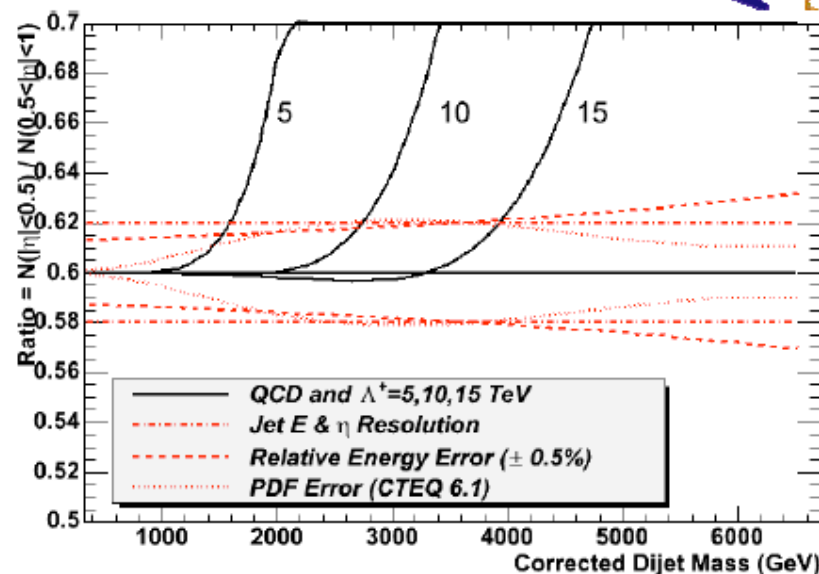
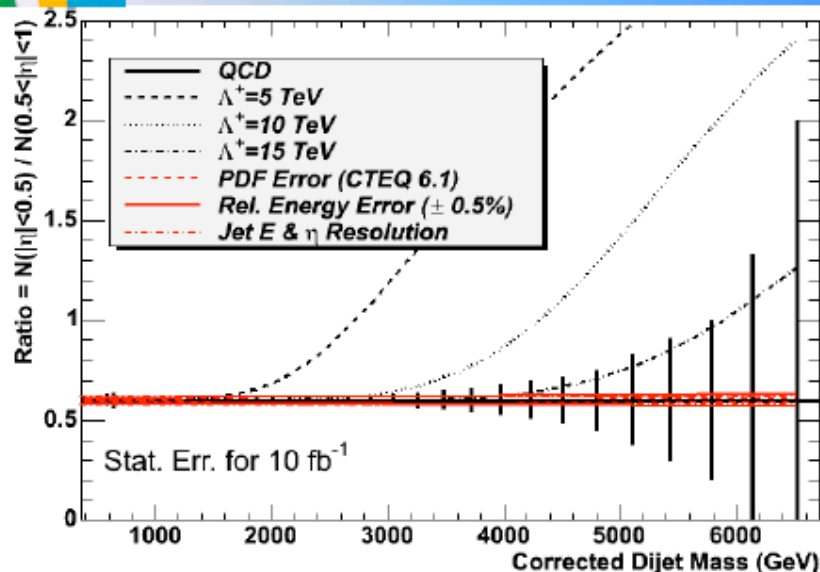
Angular distribution has much **smaller systematic uncertainties** than cross section vs. dijet mass



Effects emerge at **high mass**



CMS: Dijet Ratio Systematic Uncertainties



Absolute Jet Energy Scale

No effect on QCD dijet ratio: flat vs. dijet mass
Causes 5% uncertainty in Λ

Relative Energy Scale

Energy scale in $|\eta| < 0.5$ vs. $0.5 < |\eta| < 1$
Estimate $\pm 0.5\%$ is achievable in Barrel
Changes ratio between ± 0.01 and ± 0.03

Resolution

No change to the ratio when changing resolution
Systematics bounded by MC statistics: 0.02

Parton Distributions

CTEQ6.1 uncertainties
Systematics on ratio less than 0.02