Collider probes of SUSY

Where do we go now with SUSY searches?

Rohini M. Godbole
Centre for High Energy Physics,
IISc, Bangalore, India

Happening at the Pre SUSY school at SUSY 2014, Manchester.

In this historic place!

I will spend the next few minutes and slides in putting these lectures in perspective

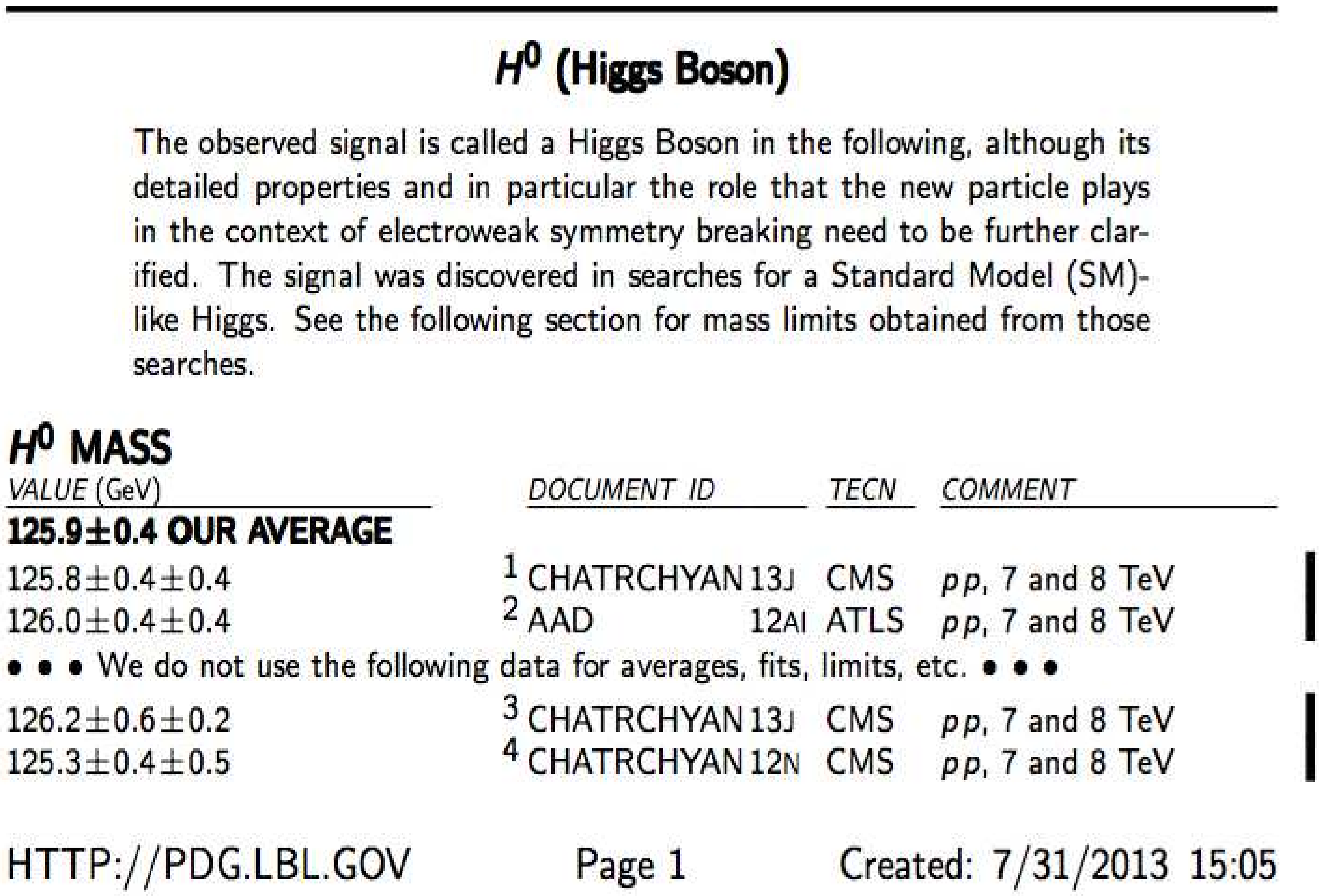
As it says on the web page:

These lectures will report on the current status of collider phenomenology and the state of the art of experimental techniques in the quest for SUSY, including jet-boosted techniques, primarily at the LHC, but also at other high-energy colliders.

What will they actually try to convey?

Recall that these lectures are happening in the backdrop of two equally ’ (future) historic ’ results: from two mega experiments, the LHC and PLANCK!

LHC: The biggest accelerator that has yet been built and the biggest collider experiment that was conducted by over 10,000 physicists, engineers from all over the world!



H^0 (Higgs Boson)

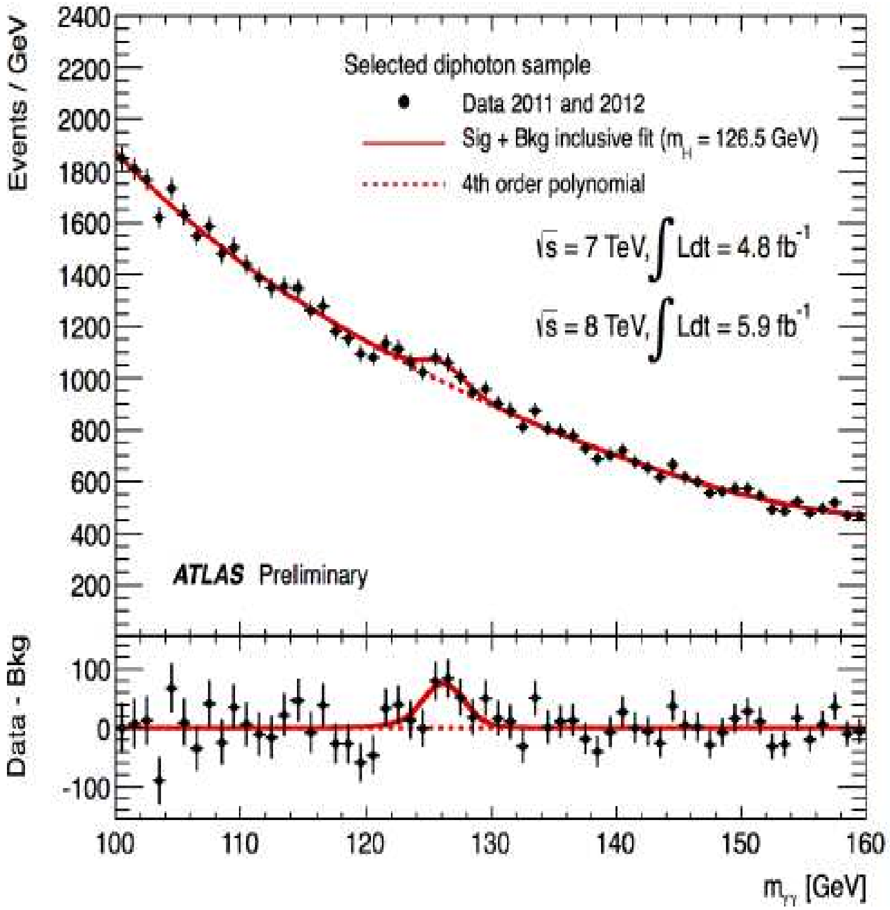
The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

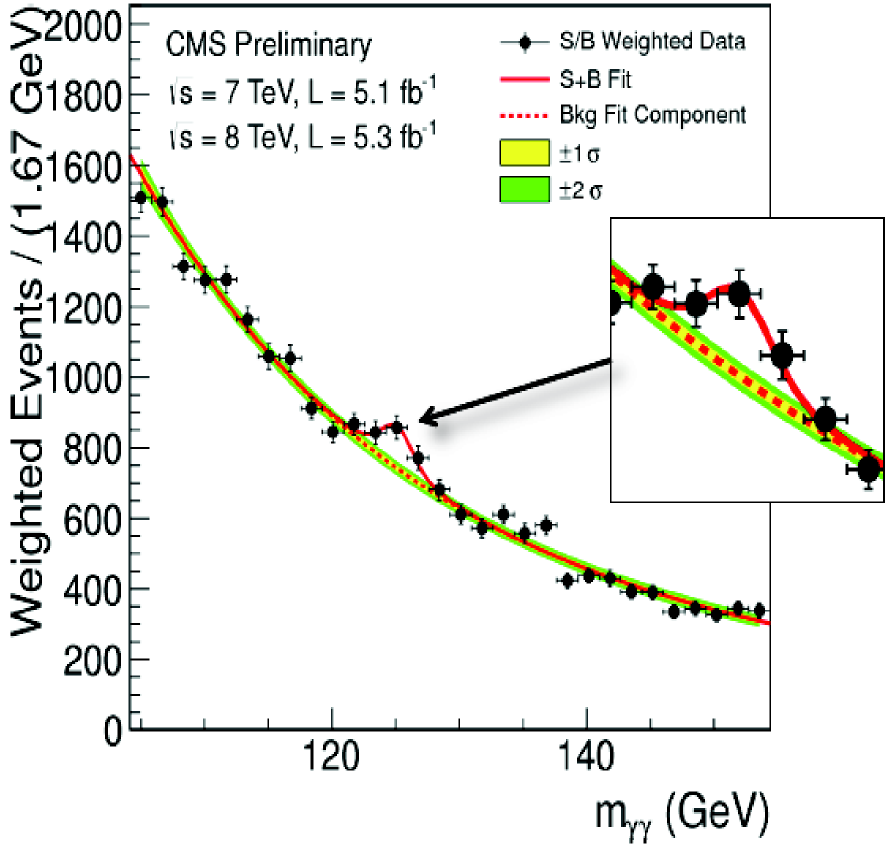
H^0 MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
125.9±0.4 OUR AVERAGE			
125.8±0.4±0.4	[1] CHATRCHYAN 13J	CMS	*pp*, 7 and 8 TeV
126.0±0.4±0.4	[2] AAD 12AI	ATLS	*pp*, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
126.2±0.6±0.2	[3] CHATRCHYAN 13J	CMS	*pp*, 7 and 8 TeV
125.3±0.4±0.5	[4] CHATRCHYAN 12N	CMS	*pp*, 7 and 8 TeV

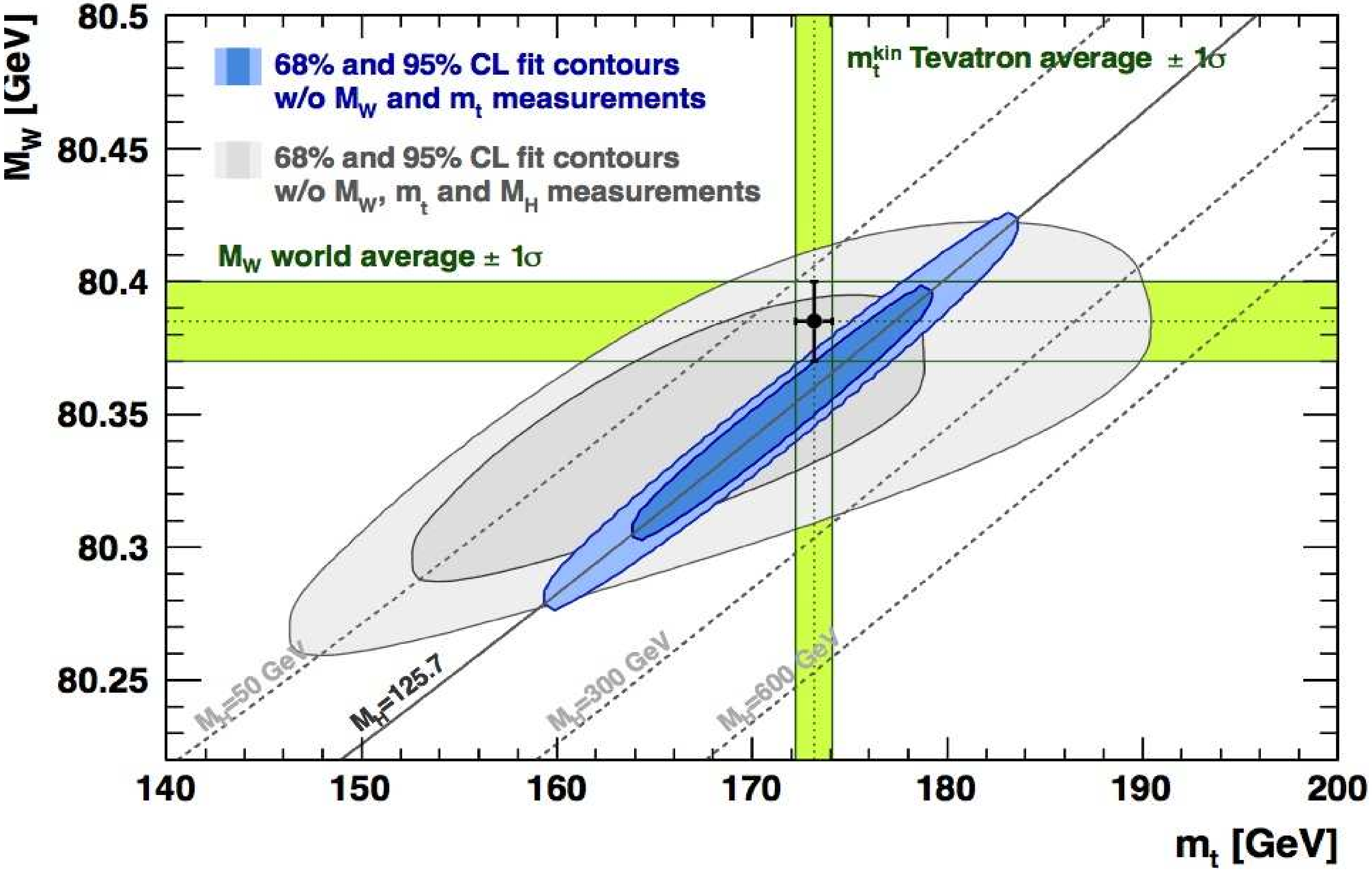
HTTP://PDG.LBL.GOV Page 1 Created: 7/31/2013 15:05

2013 Update of the PDG!





A **LIGHT** Higgs discovered and announced on July 4, 2012!



SM rocks! **LOOP Level**!

BUT

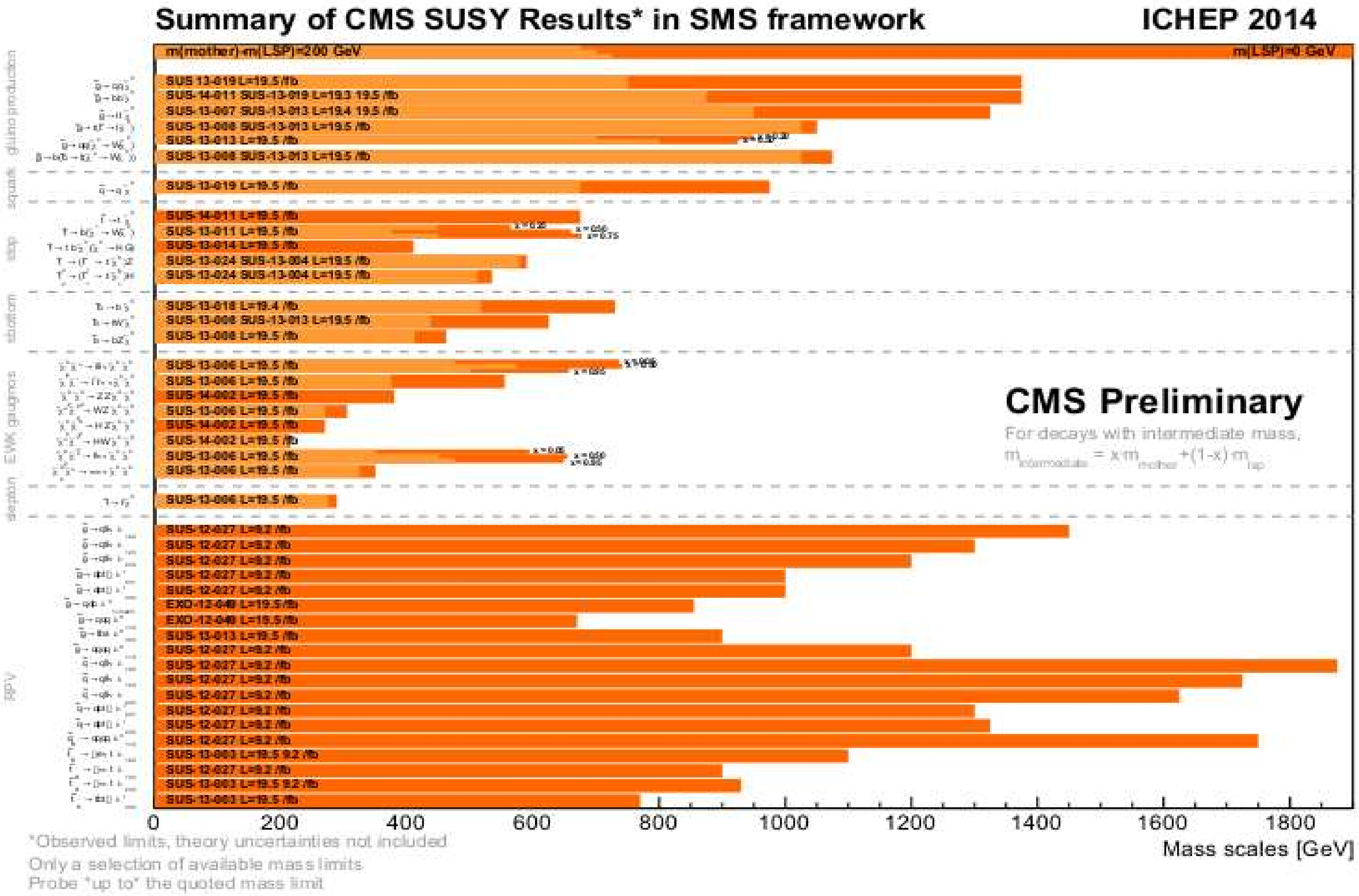
NO **other** new physics!

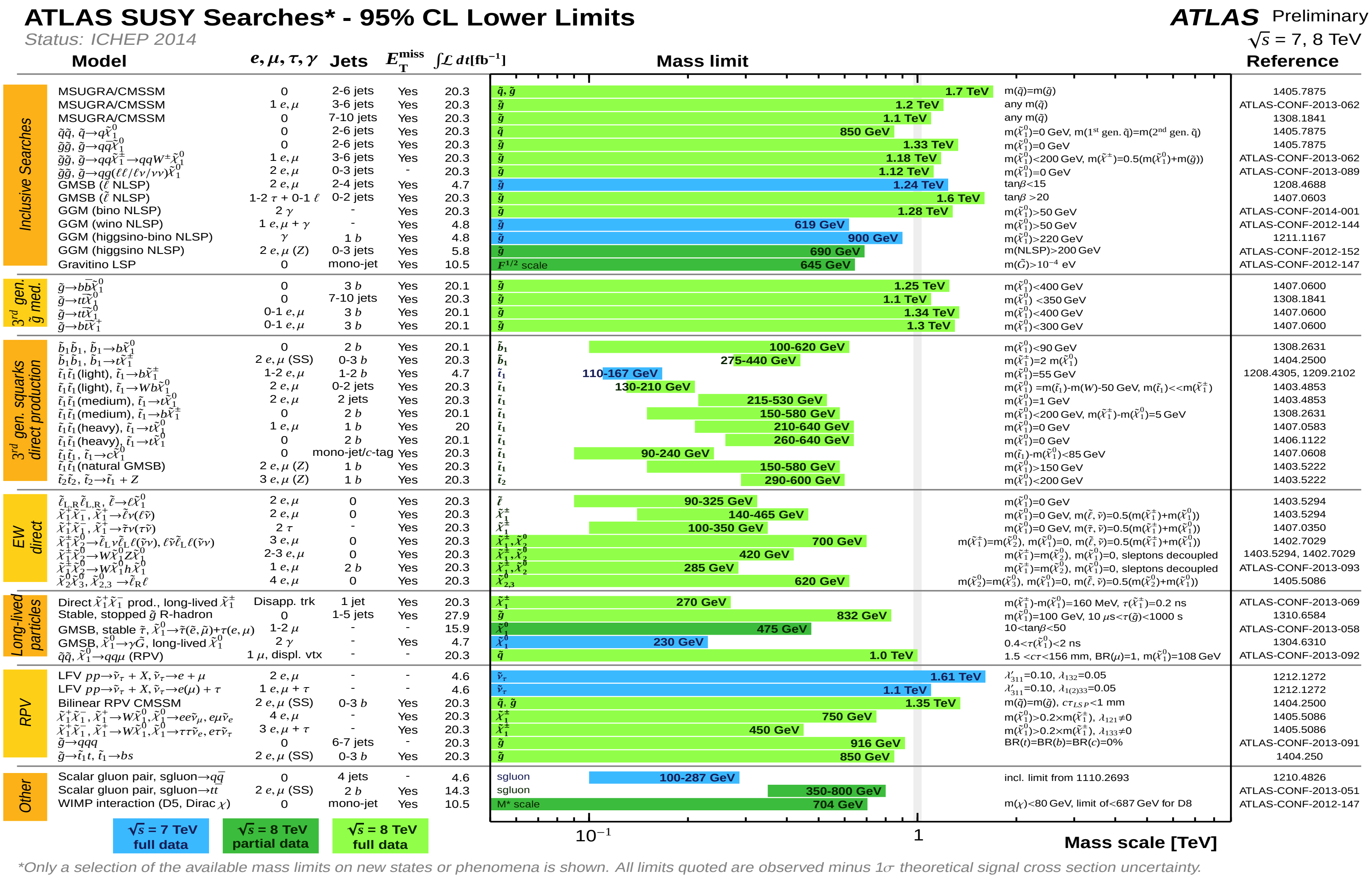
In particular no evidence **SO FAR** ($\sim 5fb^{-1}$ at 7 TeV & $\sim 21fb^{-1}$ at 8 TeV), for **ANY** supersymmetric particle!

References:

https://twiki.cern.ch/twikibin/view/CMSPublic/PhysicsResultsSUS

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


Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother + (1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

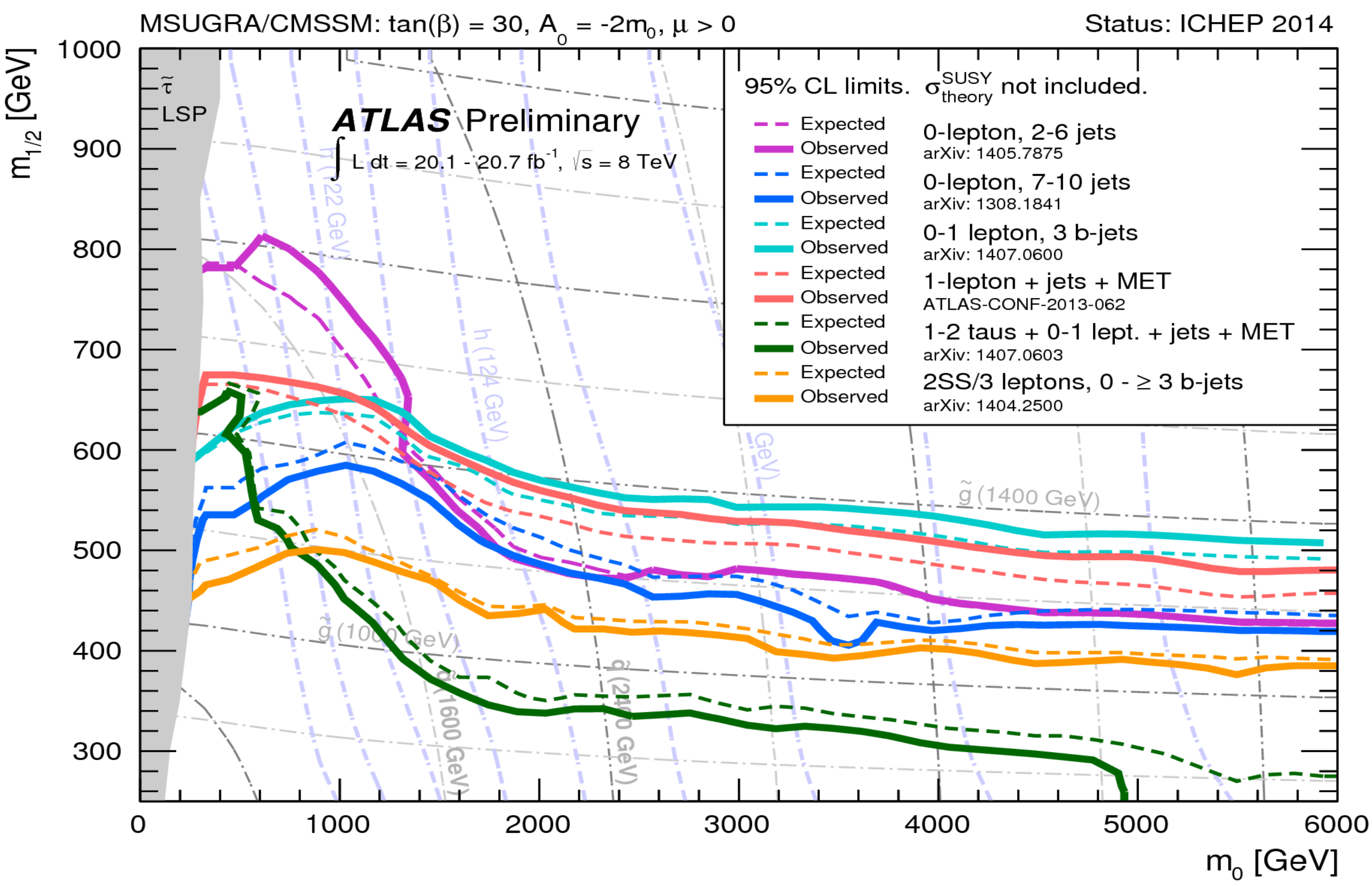
ATLAS Preliminary
$\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 e,μ + γ	-	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	m($\tilde{G}$)>10^{-4} eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1$ + Z	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_{\mathrm{L}}\nu\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 285 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_{\mathrm{R}}\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$	1 e,μ + τ	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

🟦 $\sqrt{s}$ = 7 TeV full data
🟩 $\sqrt{s}$ = 8 TeV partial data
🟩 $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

No *other* new physics!



The two results seem to be in some tension!

A **light** Higgs: for many a telltale indication of SUSY?

For many the raison de'être for Supersymmetry!

Recall the dark ages b4 the discovery of a SM-Higgs!

Let us recall reasons for the physics beyond the SM!

- Dark Matter makes up 26% of the Universe.!
- Direct evidence for the nonzero ν masses
- Quantitative explanation of the Baryon Asymmetry in the Universe!
- Cosmic Acceleration?

- **Instability of the EW scale under radiative corrections**
- Need to get a basic understanding of the flavour Issue
- Unification of couplings
- Inclusion of Gravity in the picture?
- Dark Energy!

SUSY addresses quite a few of them!

- **Dark Matter makes up** 26% **of the Universe.!** Y
- Direct evidence for the nonzero ν masses Y
- **Quantitative explanation of the Baryon Asymmetry in the Universe!** Y

- **Instability of the EW scale under radiative corrections. Higgs should be light!** Y
- Need to get a basic understanding of the flavour Issue
- **Unification of couplings** Y
- Inclusion of Gravity in the picture? Y

Now that the Higgs has been found in fact the 'theoretical' reason in some sense moves up to 'observational' reason above the red line!

We know the Higgs is light!

TeV scale SUSY keeps the Higgs 'naturally' light!

In fact upper bound on the mass of the lightest higgs of ~ 130 GeV is one of the most stout 'prediction' of SUSY!

But no evidence for 'SUSY' yet!

So that is the tension!

How to judge what is the degree of this tension?

1. We need to understand what do those limits mean? What goes in setting those limits?

2. How to interpret and/or understand the plots presented by our friends?

3. What do those results mean for SUSY?

    - Is it dead? What it means SUSY not relevant as an idea useful to solve the theoretical issues we mentioned!

    - Is it ill and in hospital? *The run of LHC at 13 TeV very crucial*!

    - Is it **hiding** in plain sight?

Which investigations at the future colliders can tell us which one of the above three is true!

I do not expect the lectures to provide a clear cut answer to these questions. In fact no 'completely objective' answer exists.

But I would like to at least introduce the framework which can be used to begin to answer these questions!

Plan of lectures:

1. Generalities of Collider physics: kinematics, essentials of theoretical inputs required in collider phenomenology.
2. How kinematics helps to separate wheat from chaff? .
3. How to use 1 and 2 to probe new physics : in this case SUSY.
4. **What do we do for SUSY searches in the next run and next colliders**: where and how do we go on?

The slides in the end will have detailed references for the entire lectures.

For collider physics part:

1)Barger and Phillips: Collider Physics

2)Rev. of Mod. Physics: Eichten, Hinchliffe, Lane, Quigg

---

3)Lectures given at Tasi: Maxim Perelstein 1002.0274v2

4) ” : Tao Han, 0508097

5)Lectures given at SERC schools in THEP, (in India): D. Choudhury & Pratushruti Saha

---

6) Lectures given by Stefano Frixione and Fabio Maltoni on Monte Carlo for BSM.

Since we are looking at the results which have come from the large hadron collider (LHC) first step is then to understand how do we in general probe physics at the colliders!

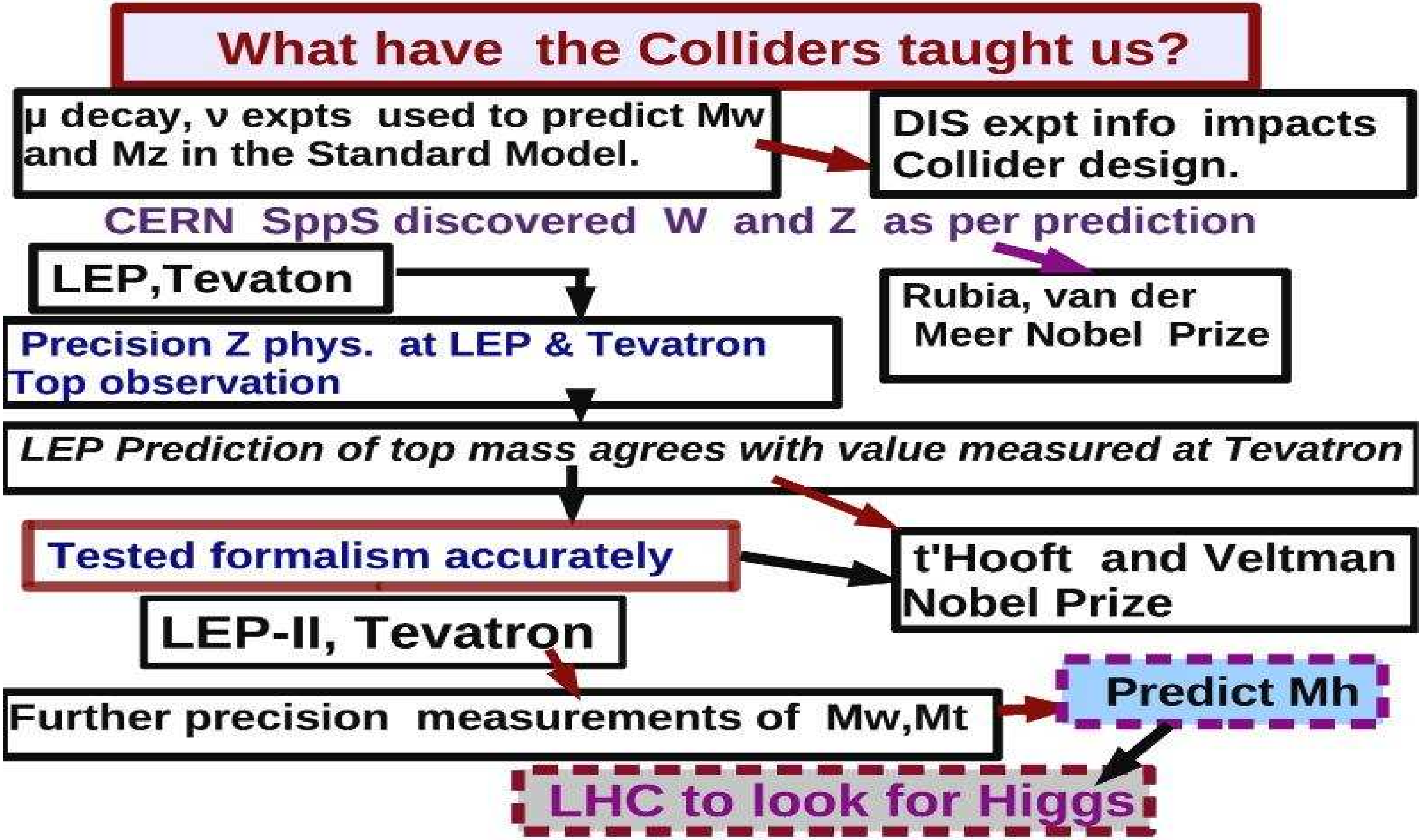
Colliders have driven the progress of particle physics since the beginning of particle physics!

Period	Type	Energy GeV	Perimeter
1971-1976	pp (ISR) Circular,CERN	32×32	$\sim 7km$
1983-1985	$p\bar{p}$ $Sp\bar{p}S$, Circular,CERN	270×270	”
1987–	$p\bar{p}$, Circular, Tevatron, USA	980×980	$\sim 6km$
2009	LHC, pp,Circular	1180×1180	$\sim 27km$
2010–2013	CERN	3500×3500	
2015–		6500×6500	
???	Future Circular Colliders	50000×50000	

List of hadronic colliders of interest, only one in action.

Period	Type	Energy GeV	Perimeter (Circular Length (Linear)
1973-1983	e^+e^-, Circular SPEAR, USA	1.5×1.5 3.5×3.5	$\sim 0.6 km$
1978-1986	e^+e^-, Circular PETRA, Germany	6.0×6.0 23.4×23.4	$\sim 2.3 km$
1990-2007	$e^\pm p$, Circular HERA, Germany	26.5×800	$\sim 6.3 km$
1989-2000	e^+e^-, Circular,CERN LEP-I, LEP-II	$\sim 45 \times \sim 45$ 104.5×104.5	$\sim 27 km$
1989-1999	e^+e^-, Linear SLC, USA	50×50	$\sim 3.2 km$
??? ??? ???	e^+e^-,ILC,Linear e^+e^-, CLIC,Linear e^+e^-,TLEP, circular	500×500 1500×1500 175×175	30 km $\sim$ 20-40 km ???

CLEO, BELLE, BABAR... not included!



What have the Colliders taught us?

μ decay, ν expts used to predict Mw and Mz in the Standard Model.

DIS expt info impacts Collider design.

CERN SppS discovered W and Z as per prediction

LEP,Tevaton

Rubia, van der Meer Nobel Prize

Precision Z phys. at LEP & Tevatron
Top observation

LEP Prediction of top mass agrees with value measured at Tevatron

Tested formalism accurately

t'Hooft and Veltman Nobel Prize

LEP-II, Tevatron

Further precision measurements of Mw,Mt

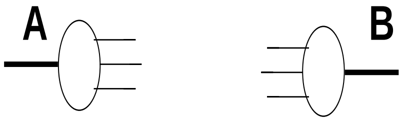
Predict Mh

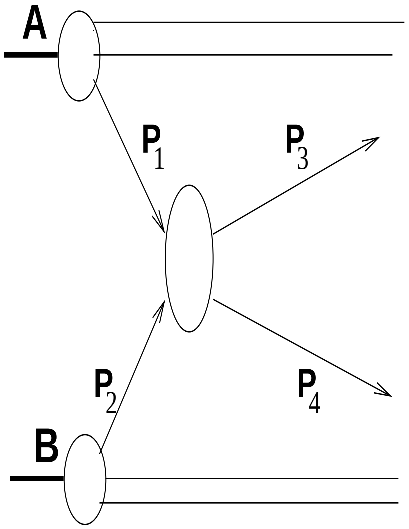
LHC to look for Higgs

Accelerator physicists build them!

Experimentalists build the detectors and study results of colliding particles together.

At a hadronic collider what happens is





$$\mathbf{A} + \mathbf{B} \longrightarrow \mathbf{jet} + \mathbf{jet} + \mathbf{X}$$

e^+e^- simpler. Colliding particles are fundamental particles. Call them A, B.

$P_A = (E, 0, 0, E), P_B = (E, 0, 0, -E)$

For example $e^+e^- \to \mu^+\mu^-$

Number of events of a particular type per unit time

$R = \mathcal{L}\sigma$ with $\mathcal{L} = \frac{N_A N_B f}{A}$

where N are the numbers of particles in each beam, cross-sectional area $\mathcal{A}$ and f collision frequency.

$10^{33} cm^{-2} s^{-1} = 1 nb^{-1} s^{-1} \simeq 10 fb^{-1}$ /year. (Assuming the machine to run 1/3 year $\sim 10^7$ s)

So when experimentalists quote 'integrated luminosity' they are simply quoting this number integrated over the time the collisions took place.

Hence expected number of events of a particular type are given by calculating σ

OR

experimentalists extract the cross-section for a particular process from measured number of events using $\mathcal{L}$.

What is folded in the measurement is also a factor of efficiency. For example the detector may have a limited coverage. So one needs to know that usually while interpreting the results.

Where do the theorists come in picture?

a)Making predictions for σ in the framework of a given theory!

b)For past many decades the 'baseline' has been the SM!

c)Suggesting measurements which would be crucial to testing aspects of new theoretical models being suggested

AND

d)how to pick up signal from background!

Being a collider physicist is both very easy and very complex!

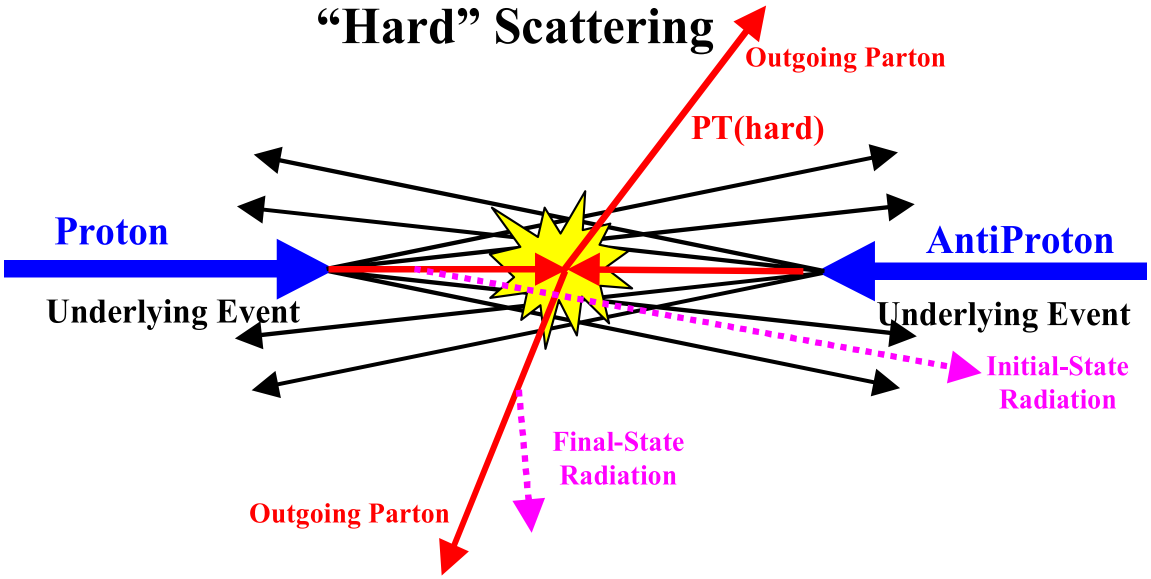
In fact for hadronic colliders situation is different from the simple e^+e^- case.

The accelerator people can give only the energy E, N_A, N_B for the $p, \bar{p}$ beams.

What is actually happening is a collision between quarks and gluons.

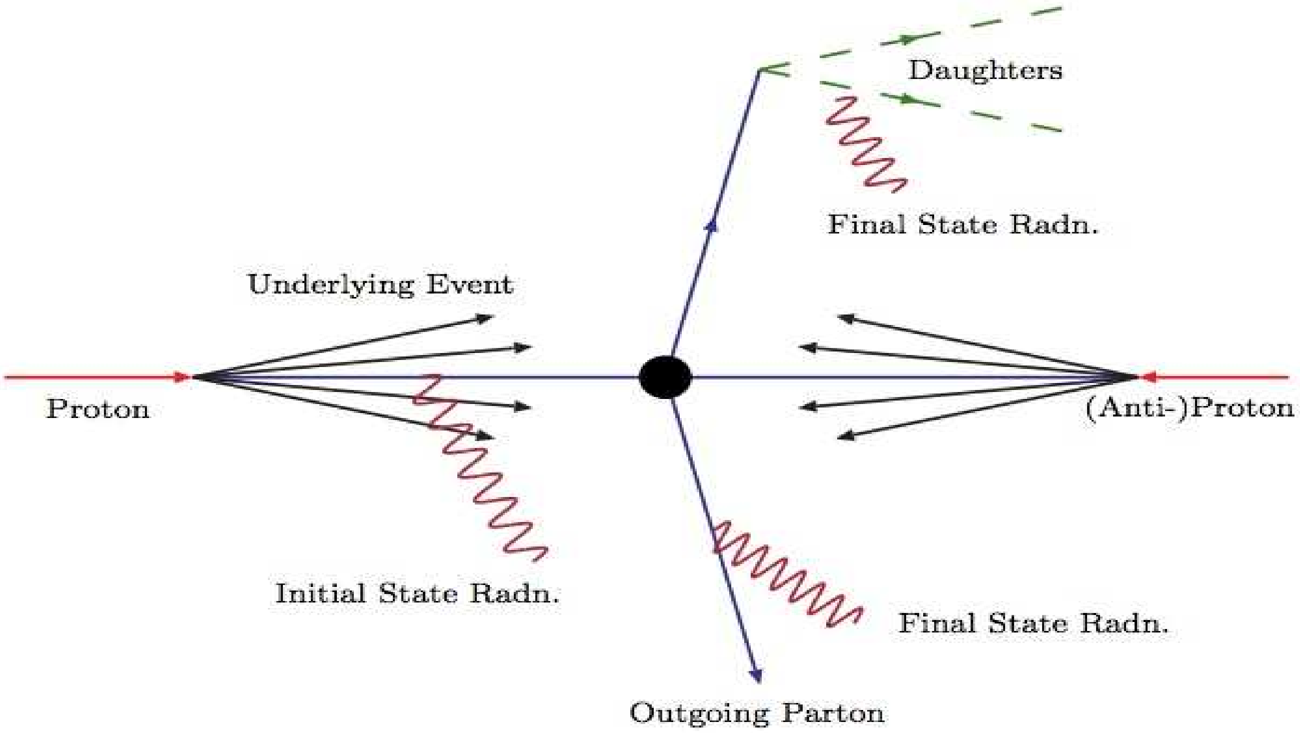
So one needs theory to give the luminosity functions for individual quarks, gluons of a given energy!

Actually many more important differences between e^+e^- and hadronic colliders. We may come back to it in the end!



Final state patrons: at large p_T : large transverse momentum w.r.t. the beam direction!

What happens in a pp machine!



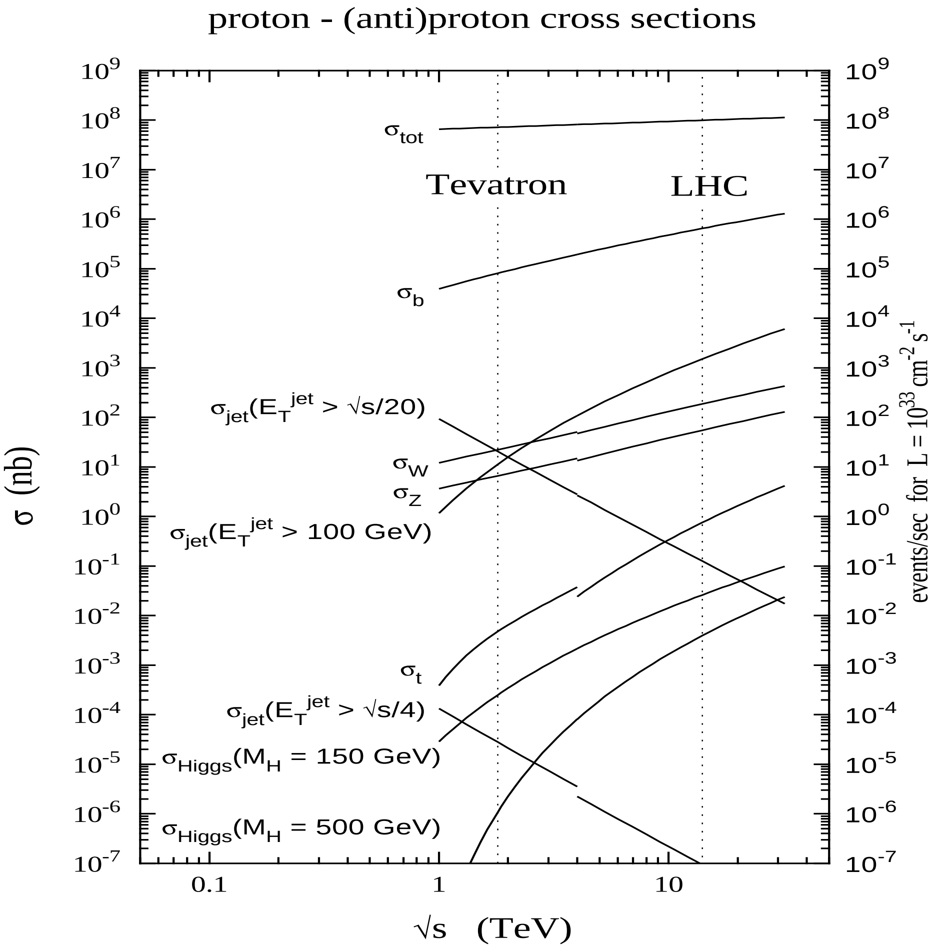
Initial State	subprocess	final state
parton density distributions PDF	$\sigma(a + b \to X)$	Fragmentation Functions.

1)How do I calculate signal and background cross-sections accurately

2)How does one try to increase signal to background ratio?

One important adage: Today's signal is tomorrow's background!

Now we are lucky! Automated calculational tools exist!



Many of us think that it just means hitting a button and running madgraph 5, calchep..These are just calculated using rules of field theory! But much more than that!

Loops and legs: large number of particles in the final state or loops in the subprocess!

What do these really do and involve? What affects the uncertainty in these calculations? Can we predict differential distributions accurately?

Important to understand this.

QCD factorisation theorem for short distance, inlcusive processes:

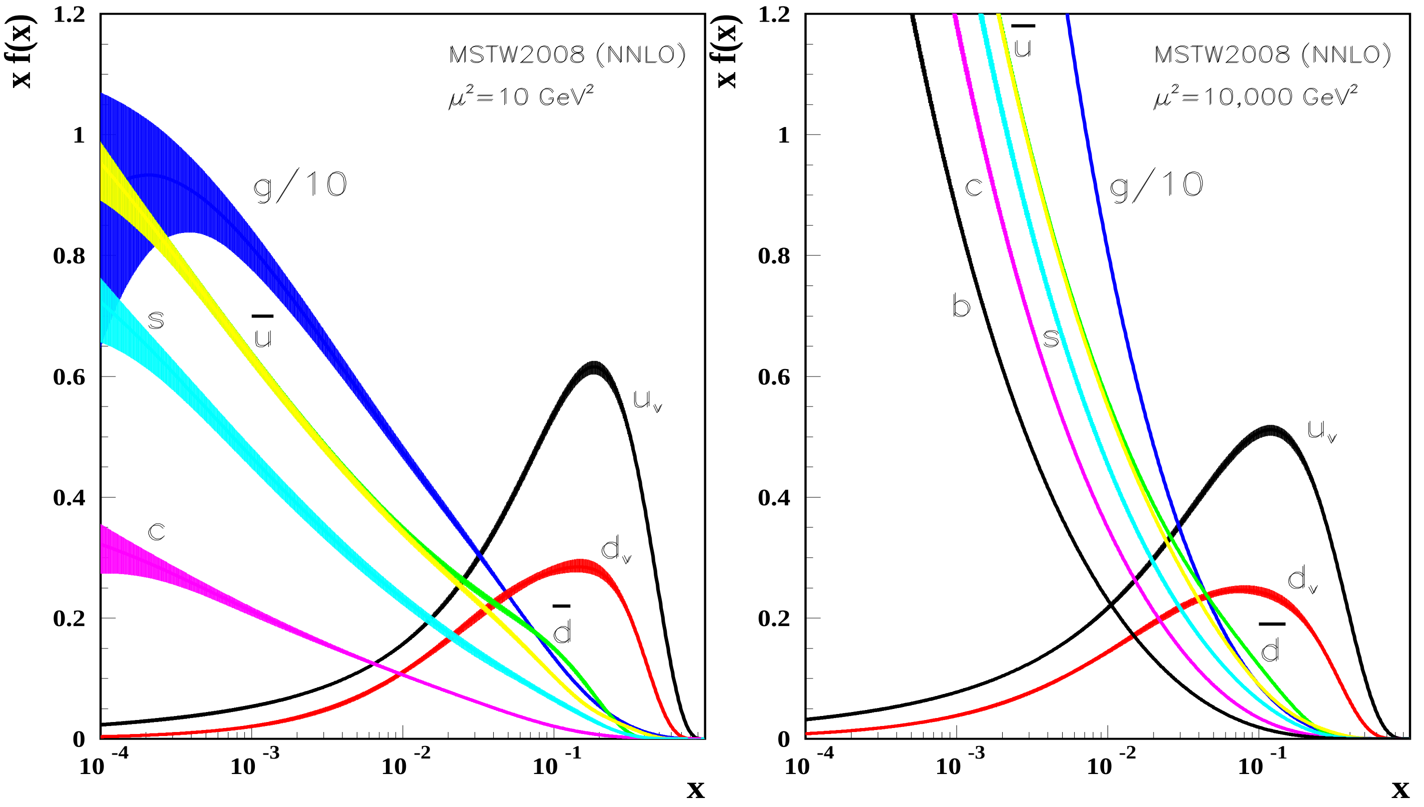
$$
\begin{aligned}
d\sigma(pp \to X + ..) &= \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \\
&\times d\hat{\sigma}(a + b \to X) \left(x_1, x_2, \mu_R^2, \alpha_s(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right)
\end{aligned}
$$

$f_a(x_1, \mu_F^2)$ etc. are the probability of finding parton a with momentum fraction x_1 of the proton etc.

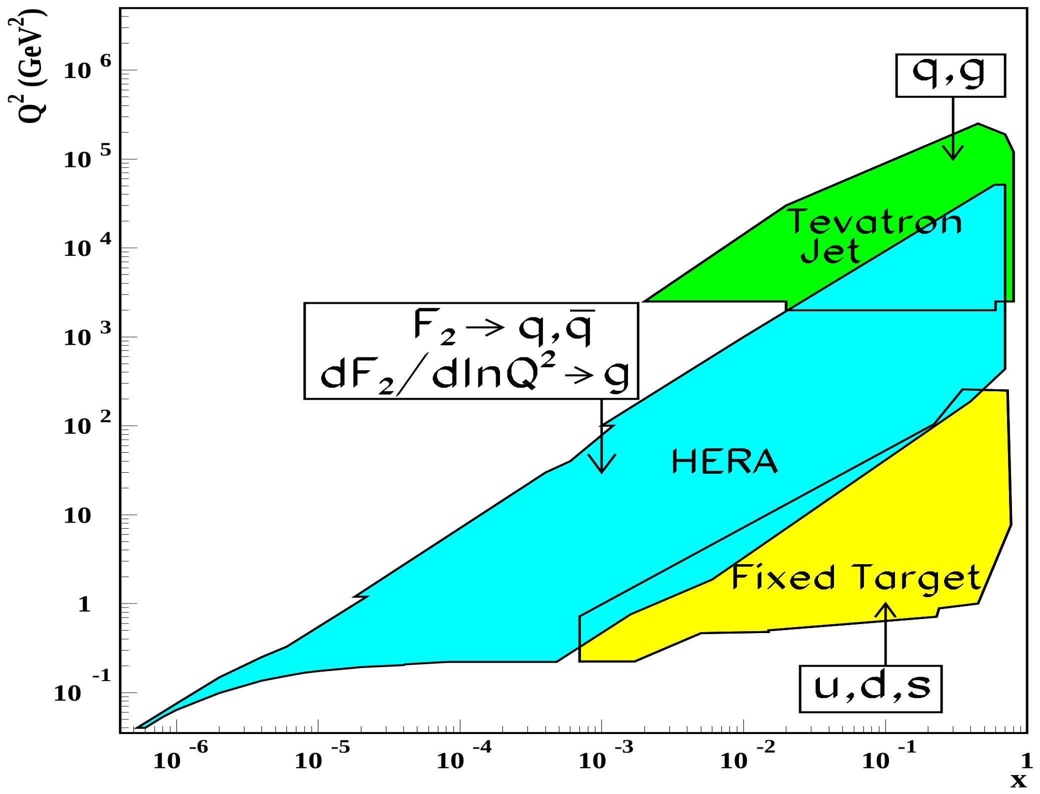
Factorisation between the soft, nonperturbative physics and hard,perturbative physics.

μ_F is the factorization scale and μ_R is the renormalisation scale. Completely nontrivial theory input!

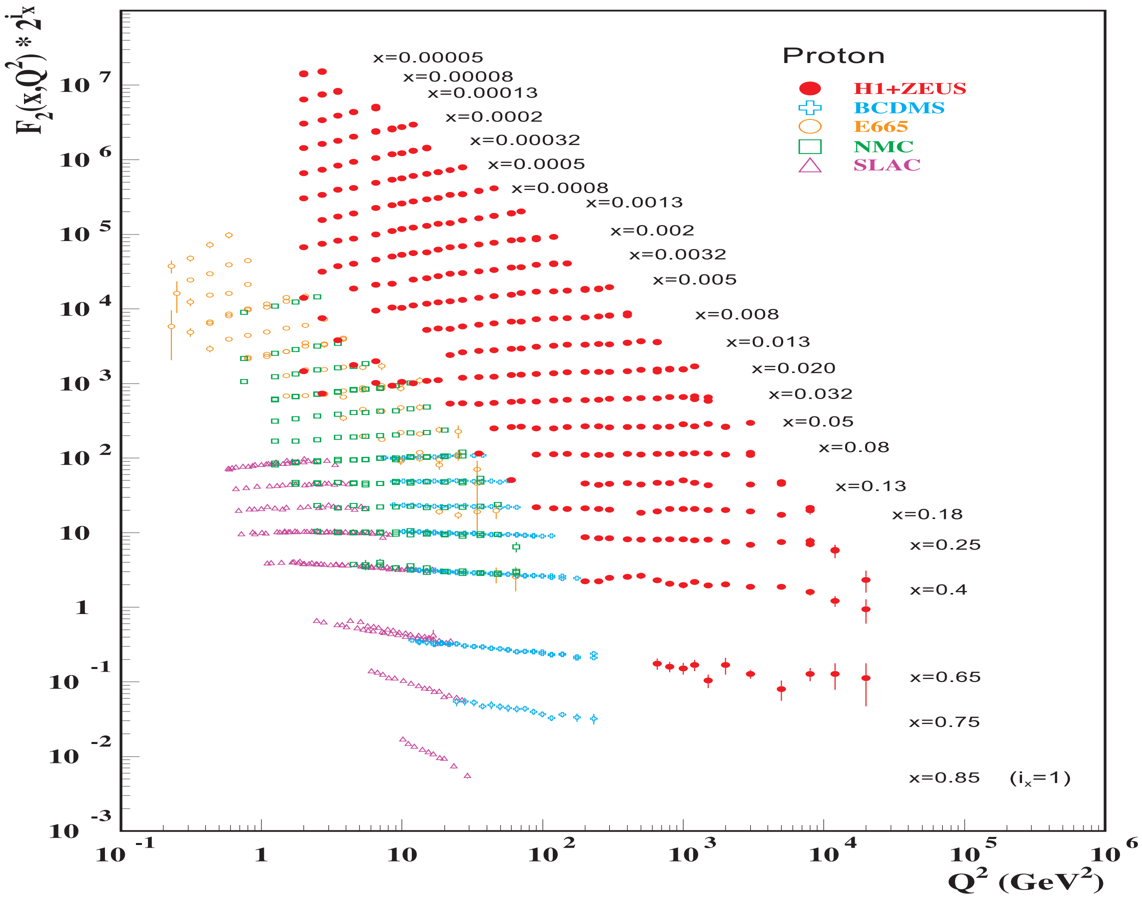
Dependency on scale of f_a, f_b: perturbative, but the boundary value at a given scale non perturbative. Obtained by fits to the data!



Parton densities $f_a(x)$ at low Q^2 and the evolved ones.



Some regions where need the information for LHC are not covered currently. LHC itself will provide the information!



$F_2(x,Q^2) * 2^{i_x}$
Proton
● H1+ZEUS
✚ BCDMS
○ E665
□ NMC
△ SLAC
x=0.00005
x=0.00008
x=0.00013
x=0.0002
x=0.00032
x=0.0005
x=0.0008
x=0.0013
x=0.002
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.020
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
x=0.75
x=0.85 (i_x=1)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
Q^2 (GeV^2)

These are basically the inputs to the calculations which are performed loosely speaking in 'QCD improved parton model.

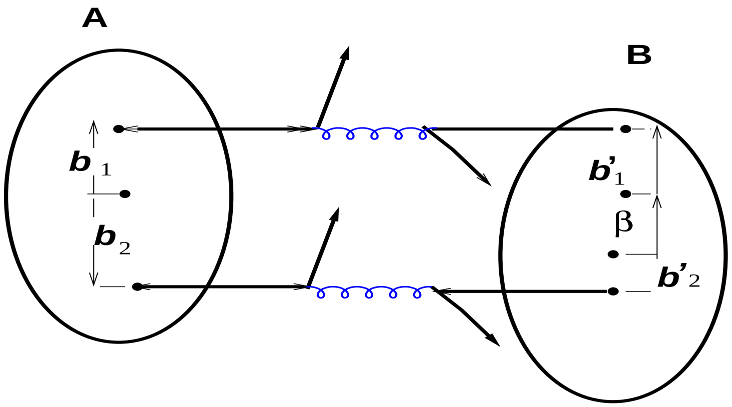
Lot of subtle issues in this. Will touch on some of them!

Before that some kinematics.

Basic assumption underlying the parton model:

High energies only the longitudinal dynamics is important. The transverse momentum of the patrons is negligible $\sim few \times 100$ MeV, w.r.t. the longitudinal momentum.

At still higher energies even multiple pairs of patrons will participate in 'hard' scattering! Multi Parton Scattering!



Transverse Overlap of the hadrons

At high energies:

In the Laboratory frame E energy of proton

$$P_{p_1} = x_1(E, 0, 0, E), P_{p_2} = x_2(E, 0, 0, -E)$$

(neglecting mass of the (anti)proton!)

So patrons have much less energy than the protons. In the parton parton c.o.m.

$$\hat{s} = 4E^2_{c.o.m.} = S * x_1 x_2 = 4E^2 x_1 x_2 = \tau S$$

So these are the analogs of E used for e^+e^- case and the $f_a(x_1, \mu_F^2)$ etc. give the parton luminosities.

The two initial state partons have a relative motion in the laboratory frame

The frame where they are at rest relative to each other is the parton-parton c.o.m frame: *parton frame*.

Because the transverse dynamics of initial partons is neglected, the lab frame and parton frame are related by a boost along the collision axis:

$$\beta_{cm} = \frac{x_1 - x_2}{x_1 + x_2}$$

Then in the laboratory frame, the total four momentum of the parton system:

$$P_{cm} = P_{p_1} + P_{p_2} = E\left[(x_1 + x_2), 0, 0, (x_1 - x_2)\right]$$

$$y_{cm} = \frac{}{2} \ln \frac{(E_{cm}+P_{z,cm})}{(E_{cm}-P_{z,cm})} = \frac{1}{2} \ln \frac{1+\beta_{cm}}{1-\beta cm} = \frac{1}{2} \ln \frac{x_1}{x_2}$$

The initial state kinematics controlled by two quantities:

x_1, x_2

OR $\hat{s}, \beta_{cm}$

OR τ, y_{cm}.

So in hadronic case the initial collision energy and boost is not known!

Net predictions are averages over these.

The $d\sigma$ calculated integrating over Lorentz Invariant phase space

$$\frac{d^3\vec{p}}{E} = dp_x dp_y \frac{dp_z}{E} = p_T dp_T d\cos\phi \frac{dp_z}{E}$$

ϕ is just the azimuthal angle and $p_T = \sqrt{p_x^2 + p_y^2} = p\sin\theta$.

This volume element is invariant under a boost along z axis.

Rapidity $y = \frac{1}{2}\ln\frac{(E+p_z)}{(E-p_z)}$

Under longitudinal boosts the rapidity changes only by a constant.

$d\sigma$ can be calculated either in the *parton frame* or *laboratory frame*.

Neglecting mass of the particle $y = -\ln \tan \theta/2 = \eta$

η : pseudo-rapidity

Large rapidities: close to the z-direction, small rapidities: transverse directions.

$\eta = 0 \Longleftrightarrow$ particle comes in the transverse direction!

If we consider

$P_1 + P_2 \to P_3 + P_4$

in the laboratory frame variables, one can show that in terms of M^2 the invariant mass of the P_3, P_4 system (same as $\hat{s}$), P_T of the measured patrons in the laboratory, and the rapidity of the two jets, one can actually construct x_1, x_2

Consider for example a Z (or for that matter any particle coupling to $P_1 P_2$) which decays to two leptons.

Measuring the invariant mass of the two leptons $M^2_{l^+l^-} = (P_{l^+} + P_{l^-})^2$, P_T and y of one of the leptons, is enough to construct the entire kinematics x_1, x_2 and the angle of scattering.