Searches for New Physics in Colliders

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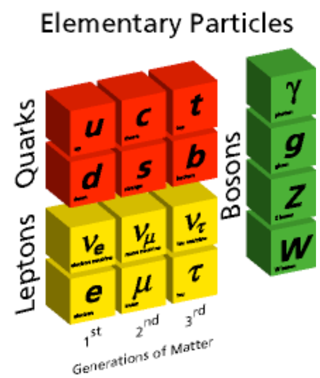
NEPPSR 2009

Outline

- Grandiose Beginning: Why do we search?
- Hadron Collider Experiments
    - What do you produce in pp or ppbar collisions?
    - How do we detect those things?
- A brief survey of New Phenomena Search Strategies and Results
    - Searches for SUSY
    - Model-independent (signature-based) Searches
    - Searches for the SM (what about the Higgs Boson?)

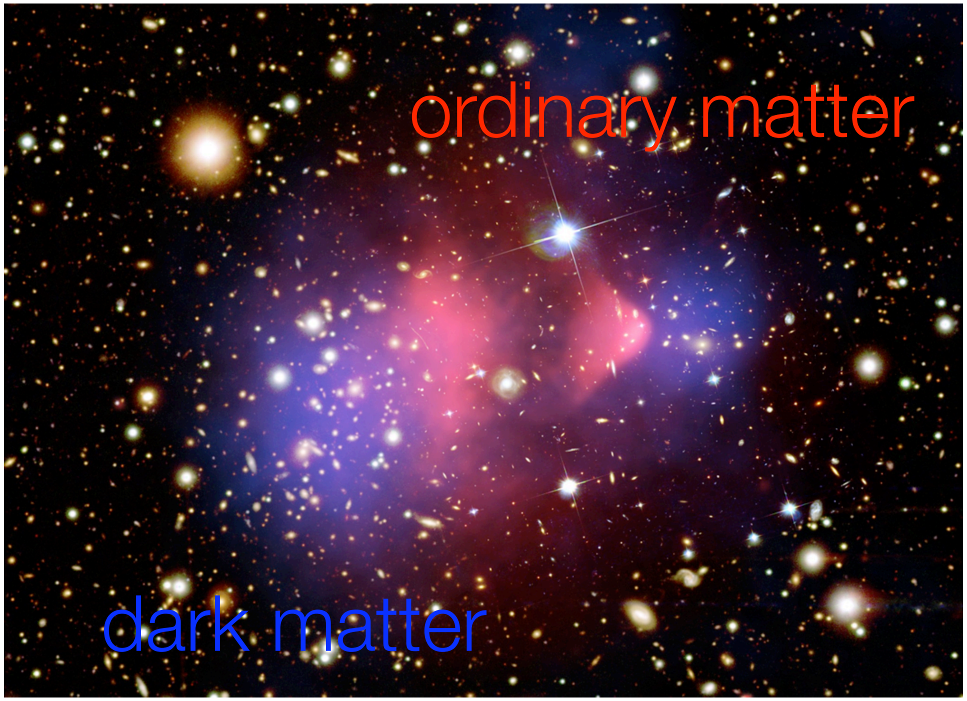


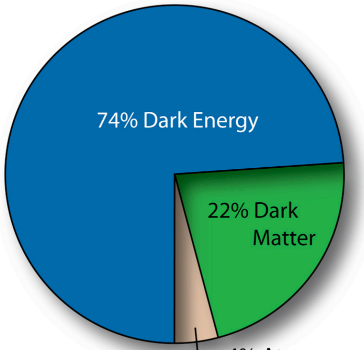
Q: Why are we searching for new particles?

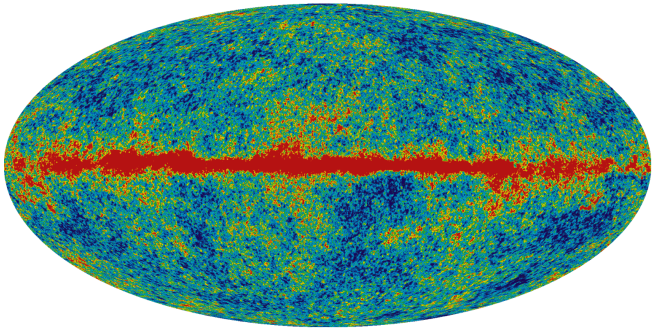
A: Answer fundamental questions about the universe

Dark Matter and Dark Energy

- What is dark matter and dark energy?
- Dark matter
  - 1933: Cluster rotation
  - 1975: Galaxy rotation
  - 2006: Galaxy cluster 1E 0657-56
    - Gravitational lensing
    - Chandra X-ray
- Dark energy
  - 1922: Einstein's Λ
  - 1998: Type 1A supernovae
  - 2003: WMAP

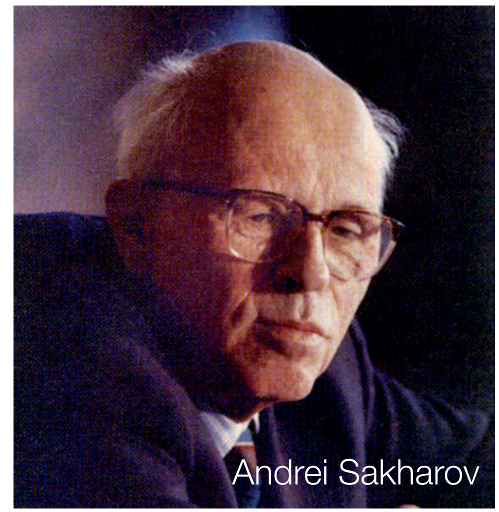


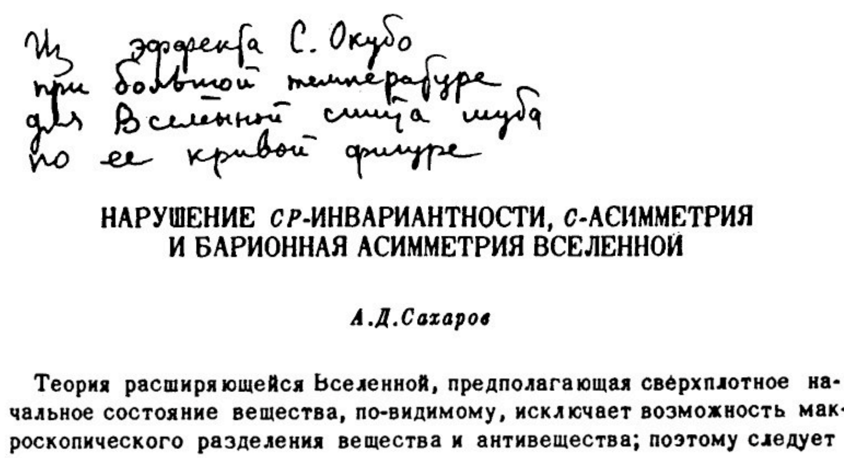




Matter-Dominated Universe

- Why do we live in a matter-dominated universe?
- 1966 - Sakharov's conditions:
  - Baryon number violation
  - CP violation
    - Not enough in quark sector
    - Neutrinos?
  - Thermal non-equilibrium





Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

Extra Dimensions

A Large Mass Hierarchy from a Small Extra Dimension

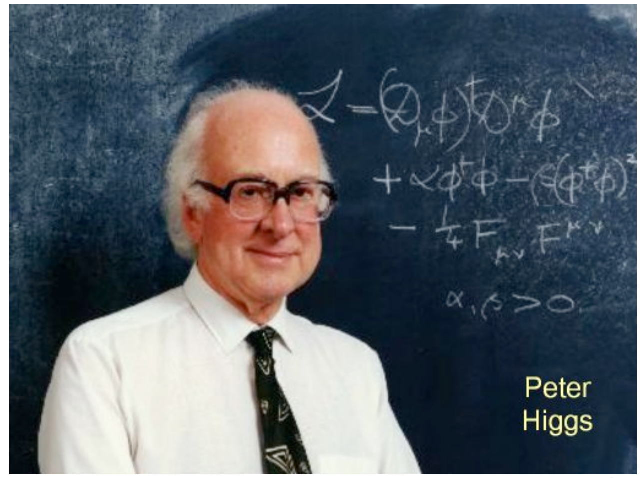
Lisa Randall
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08543, USA
and
Center for Theoretical Physics,
Massachusetts Institute of Technology, Cambridge, MA 02139, USA
Raman Sundrum
Department of Physics,
Boston University, Boston, MA 02215, USA

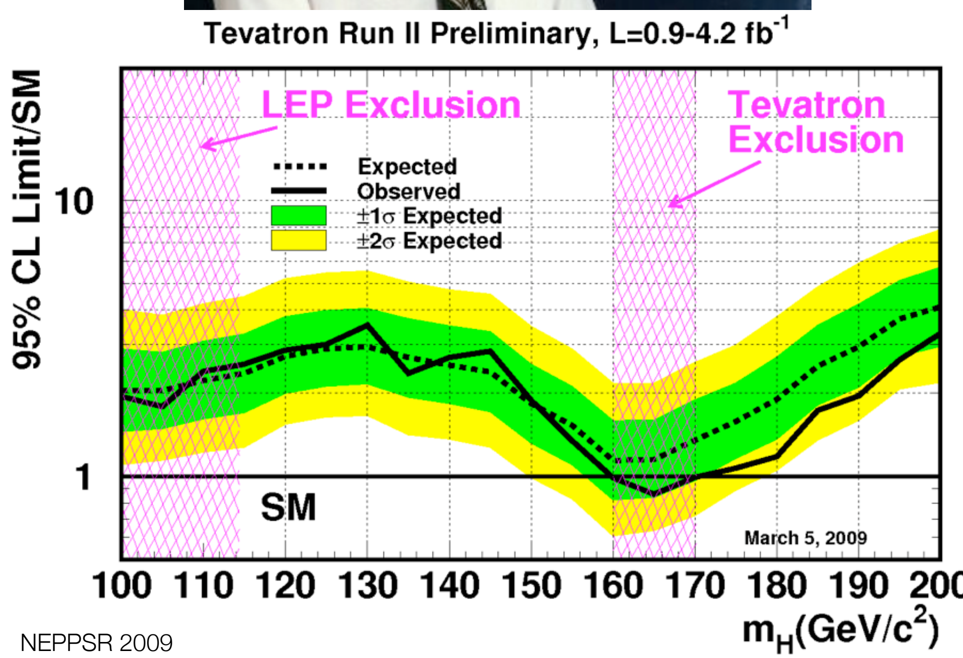
PRL **83**, 3370 (1999)

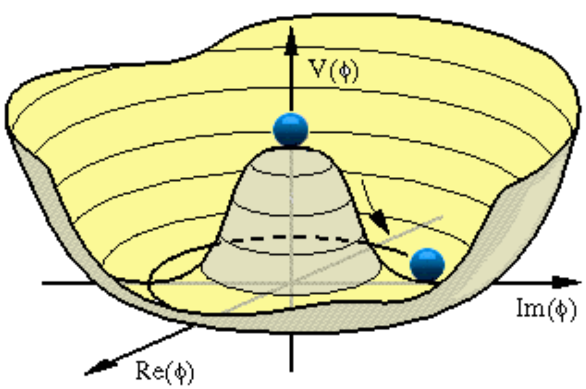
- Are there hidden dimensions of space?
- Many models in recent years
  - Can explain weakness of gravity
    "hierarchy problem"
  - Connection to dark matter?

Electroweak Symmetry Breaking

- What is the origin of electroweak symmetry breaking?
- Favored explanation: Higgs mechanism
  - Imparts mass to all particles in standard model
  - Higgs boson not yet observed
  - Other explanations possible





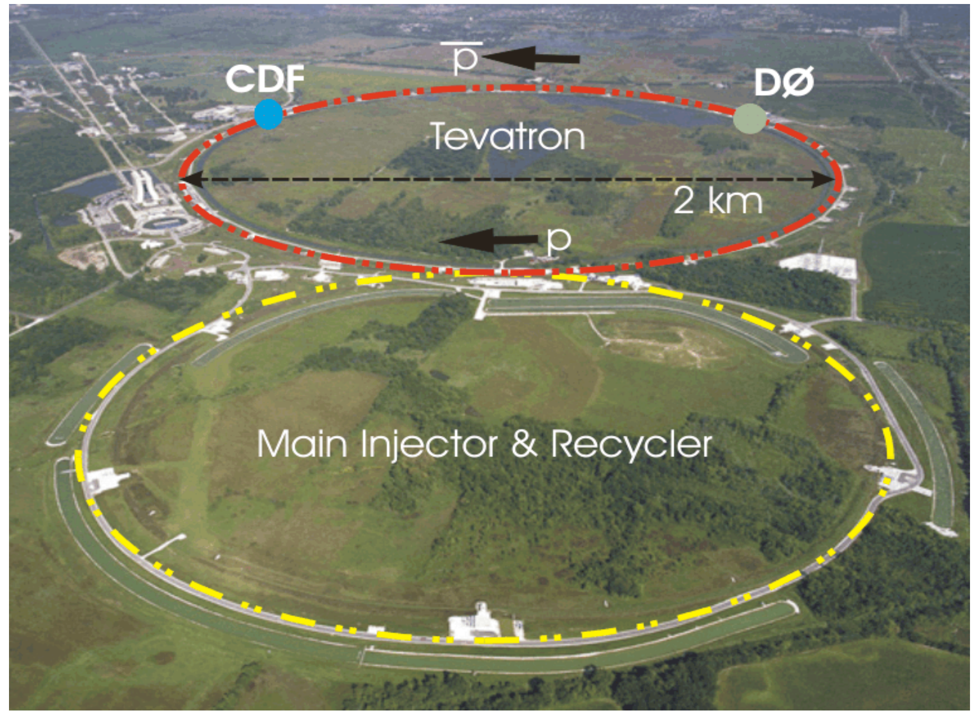


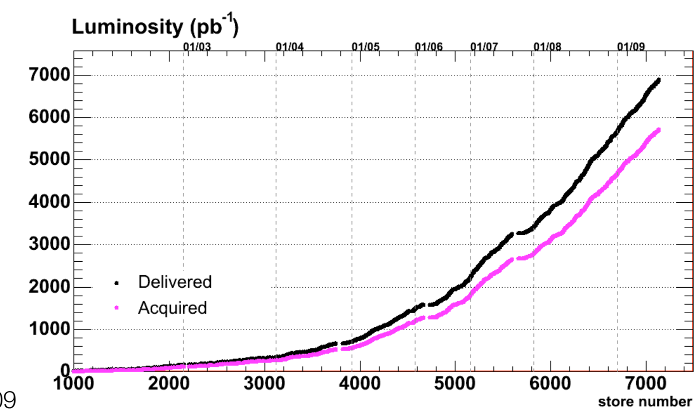
Why do we search for new particles?

- Answer fundamental questions about the universe:
  - What are dark matter and dark energy?
  - Why do we live in a matter-dominated universe?
  - Are there hidden dimensions?
  - What is the origin of electroweak symmetry breaking?
- How do we answer these questions?
  - Find the particles and interactions responsible
    - Particle colliders

The Tevatron Collider at Fermilab

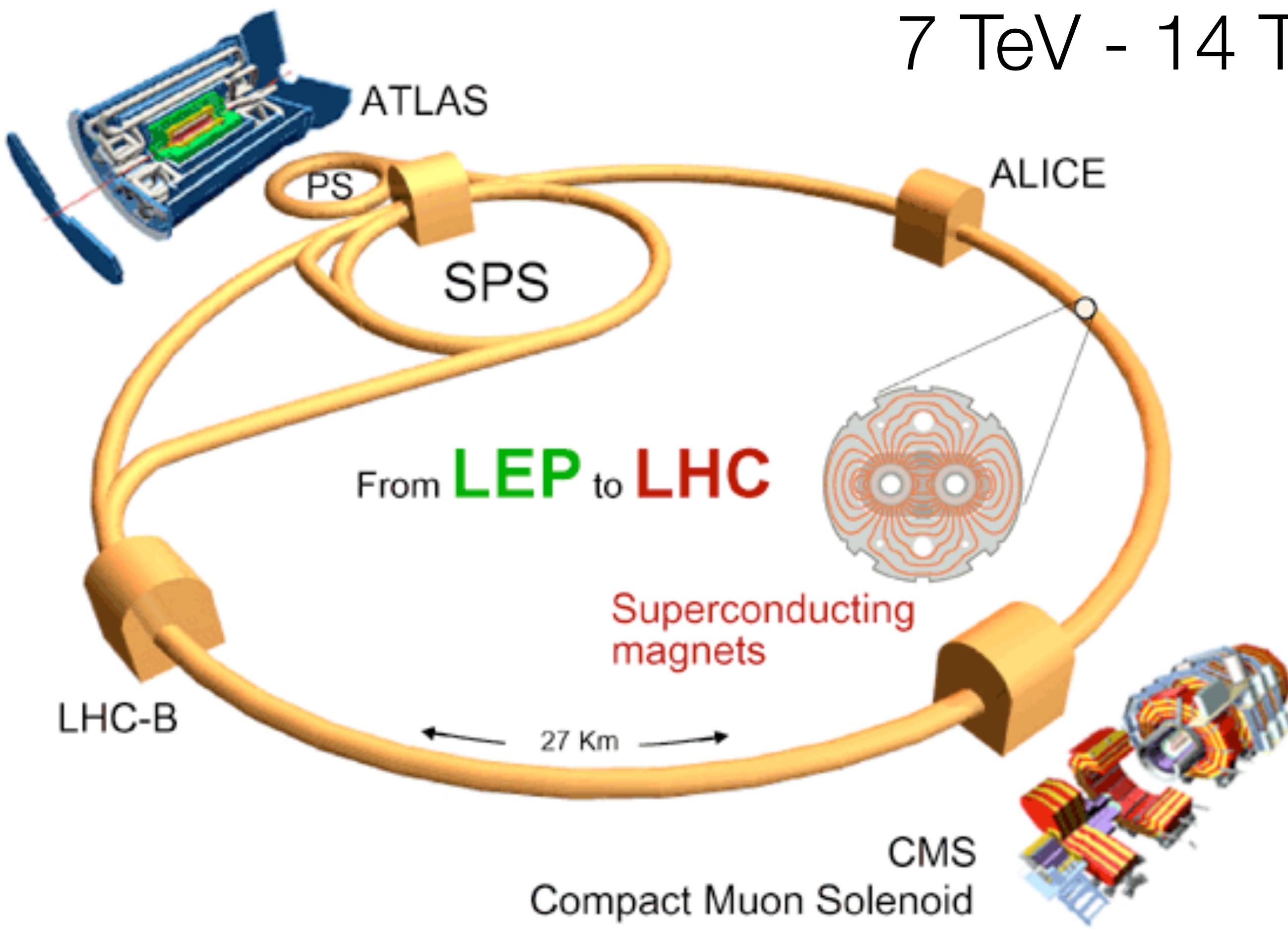
- Presently most energetic collider in the world
- Collides protons and antiprotons
- $E_{CM} = 1.96$ TeV
- Still in operation, still collecting data
  - ~7 fb^{-1} delivered, ~6 fb^{-1} acquired each by CDF and D0
- Many searches for New Phenomena (NP)
- Now excluding a range of SM Higgs masses

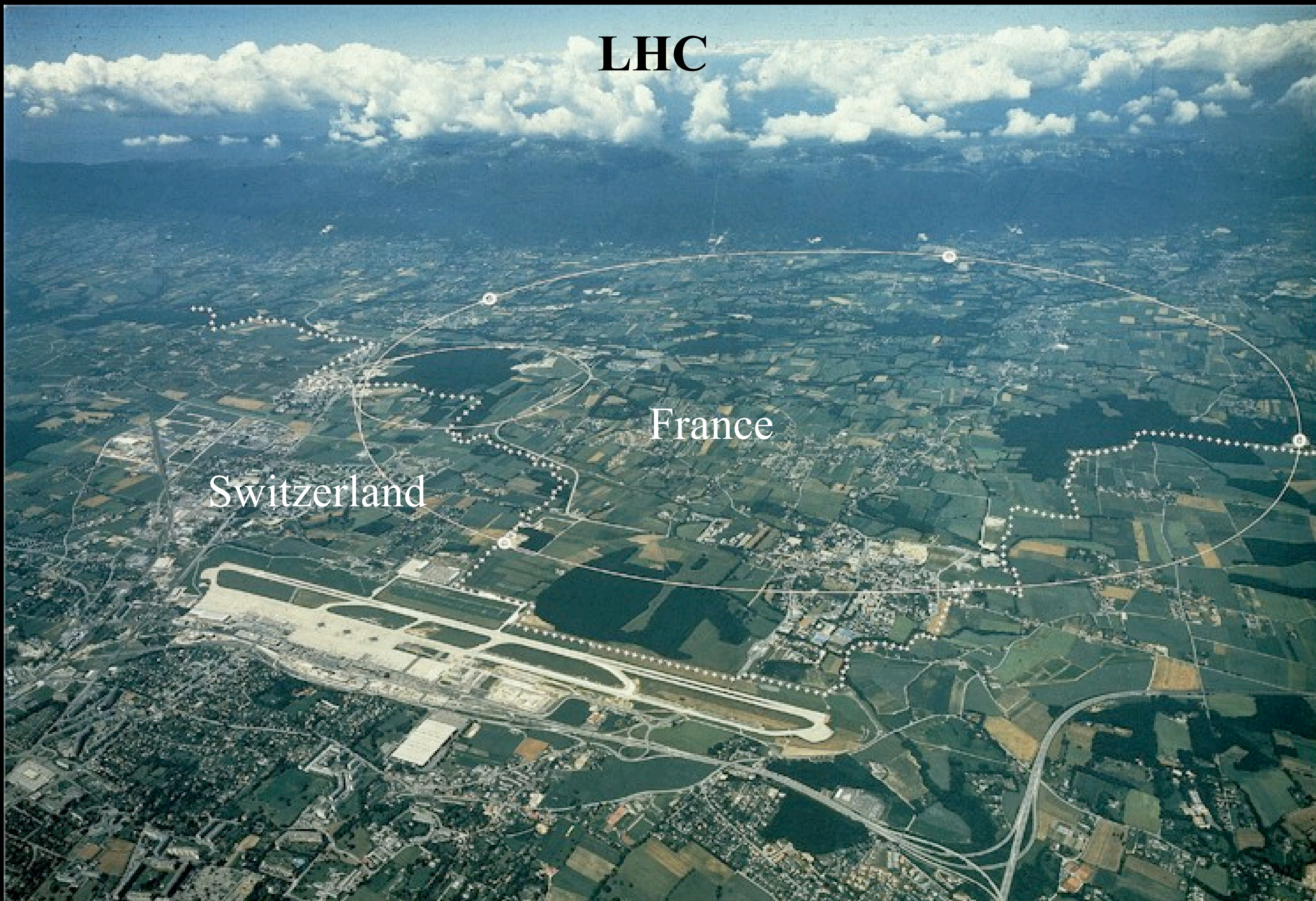




The CERN Large Hadron Collider

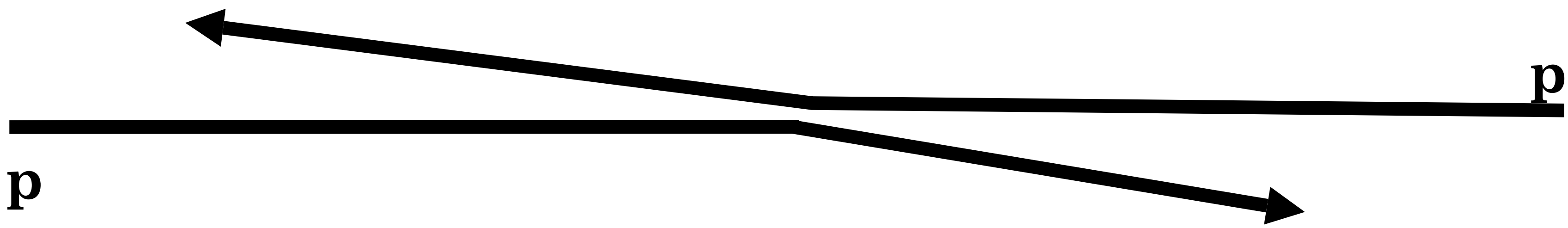
7 TeV - 14 TeV



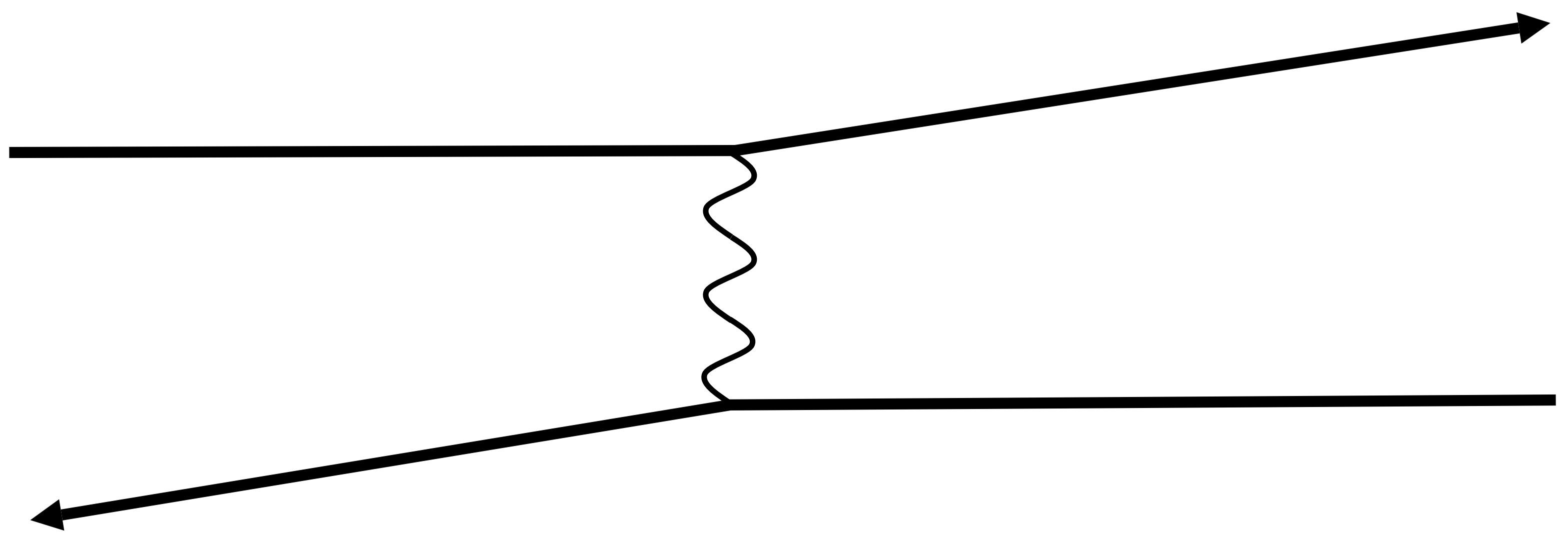

LHC
France
Switzerland

Proton Proton Collisions (or p anti-p)

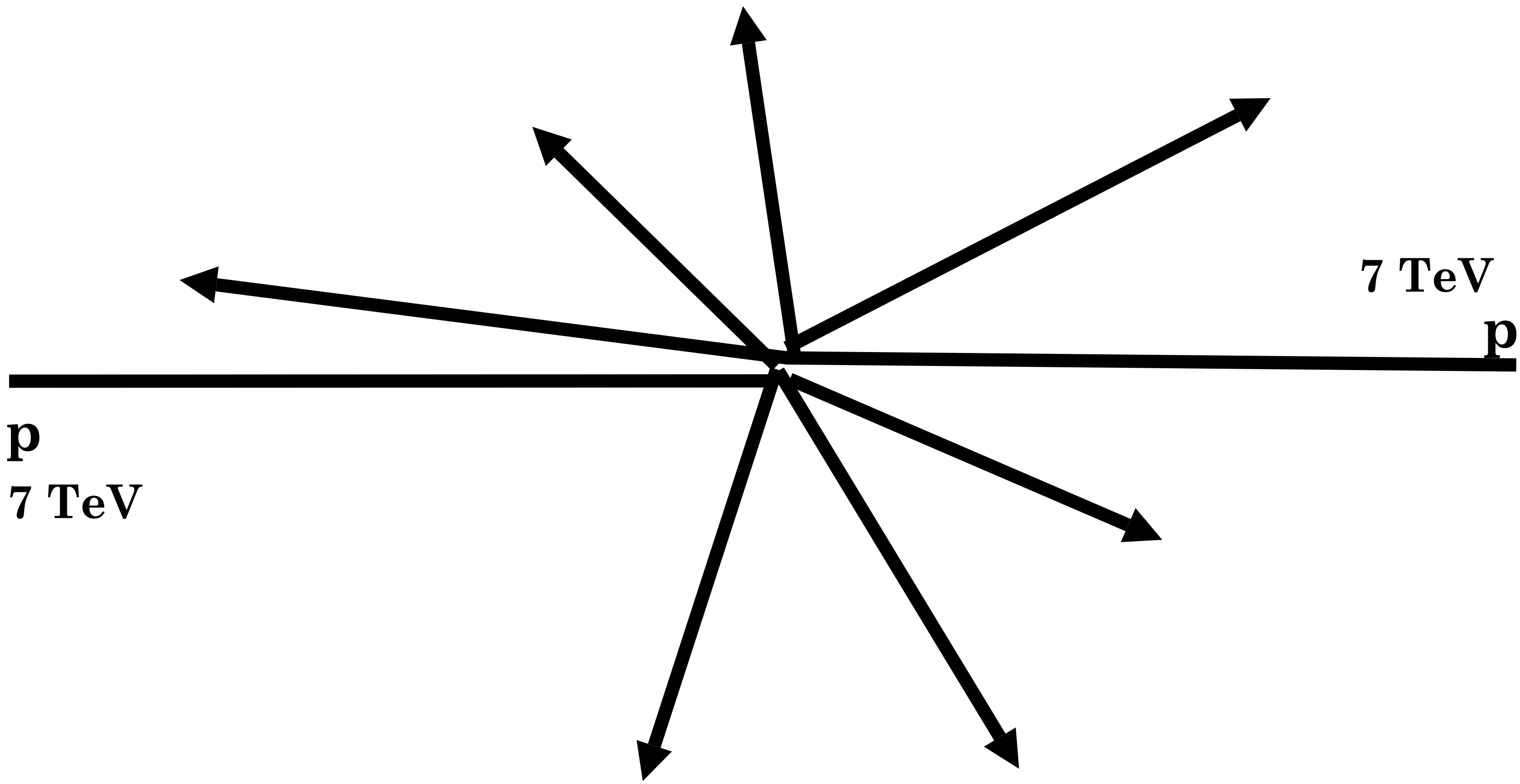
Proton Proton Collisions



Proton Proton Collisions

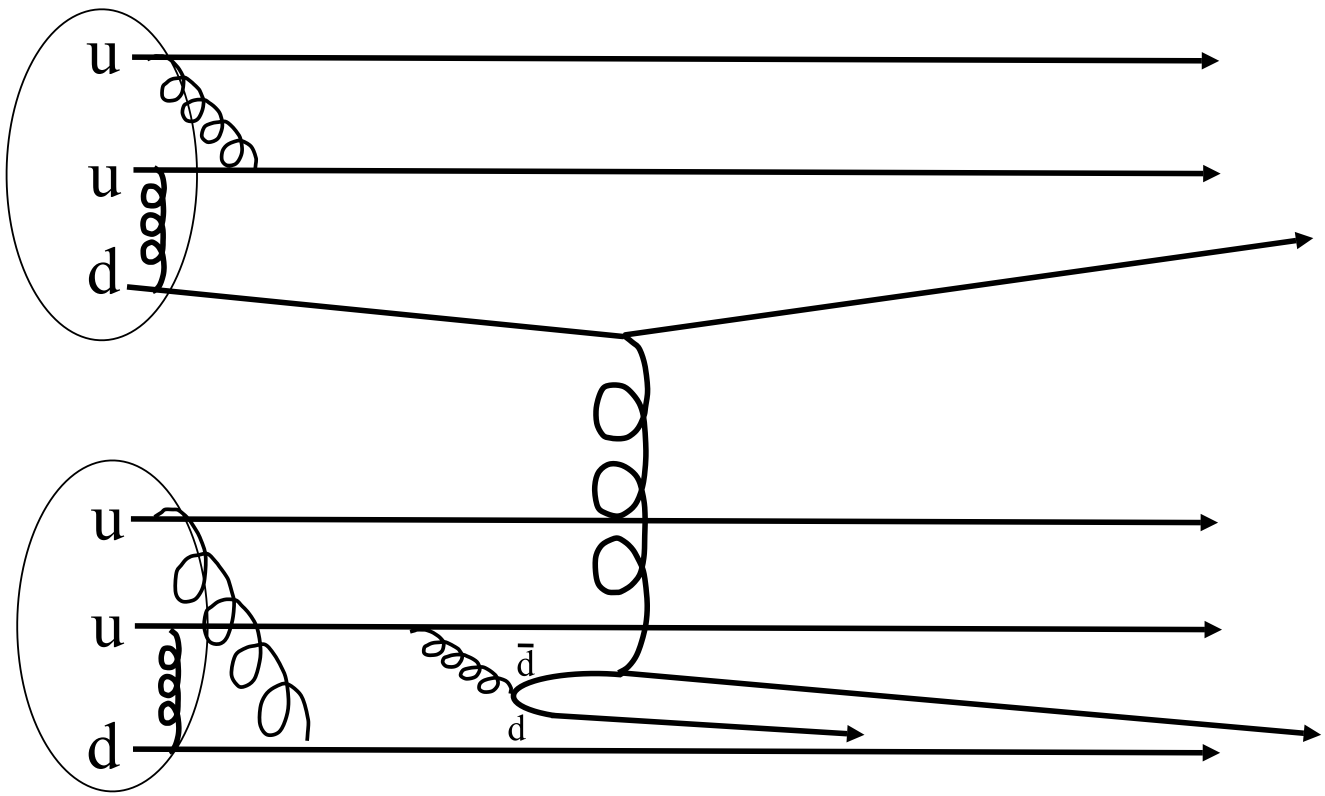


Proton Proton Collisions



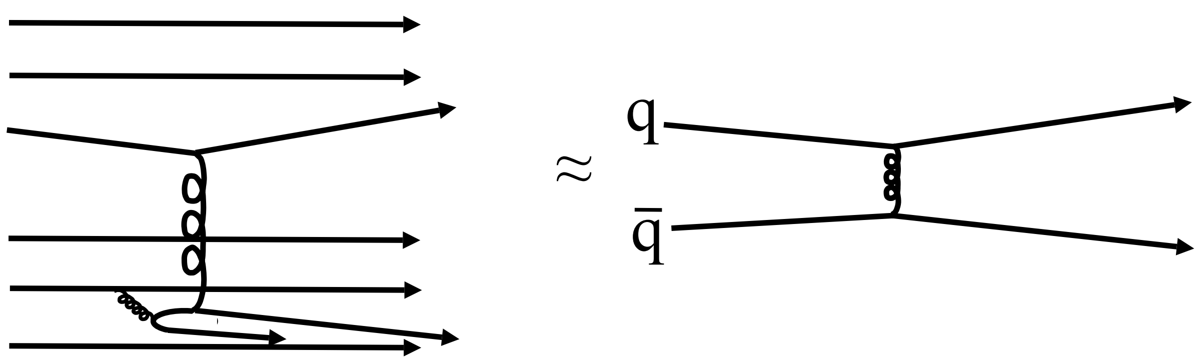
$E=mc^2$

A more realistic picture:



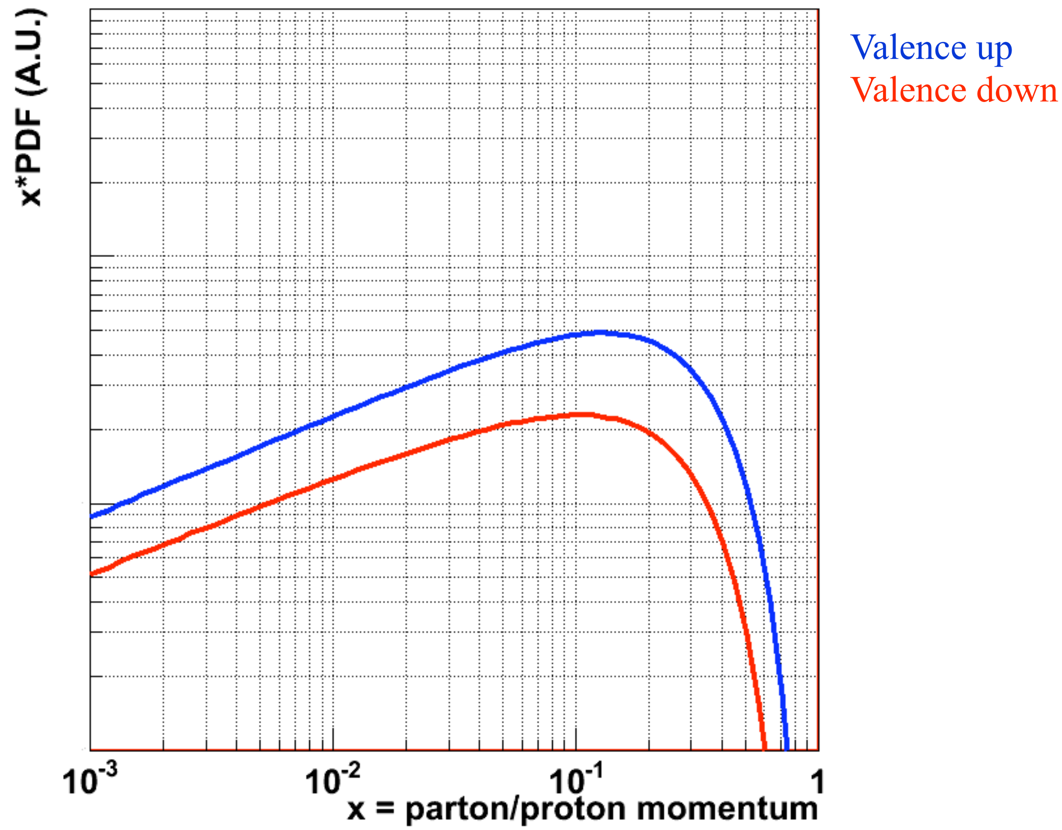
- Protons are really bound states of quarks and gluons. Each quark and gluon jiggles around within the quantum bound state.
  - Energy and Momenta of quarks and gluons is unknown.

How we really think about it:



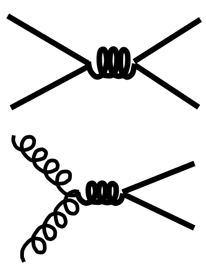
- As physicists, we like to approximate everything as spherical and flat and infinite (simple) so we can calculate something about it.
- This approximation is good enough, provided we include in our description an estimate of the distribution of the partons (quarks/gluons) within the proton.
  - “Parton Distribution Functions” (PDFs) can’t be calculated. Must be measured.

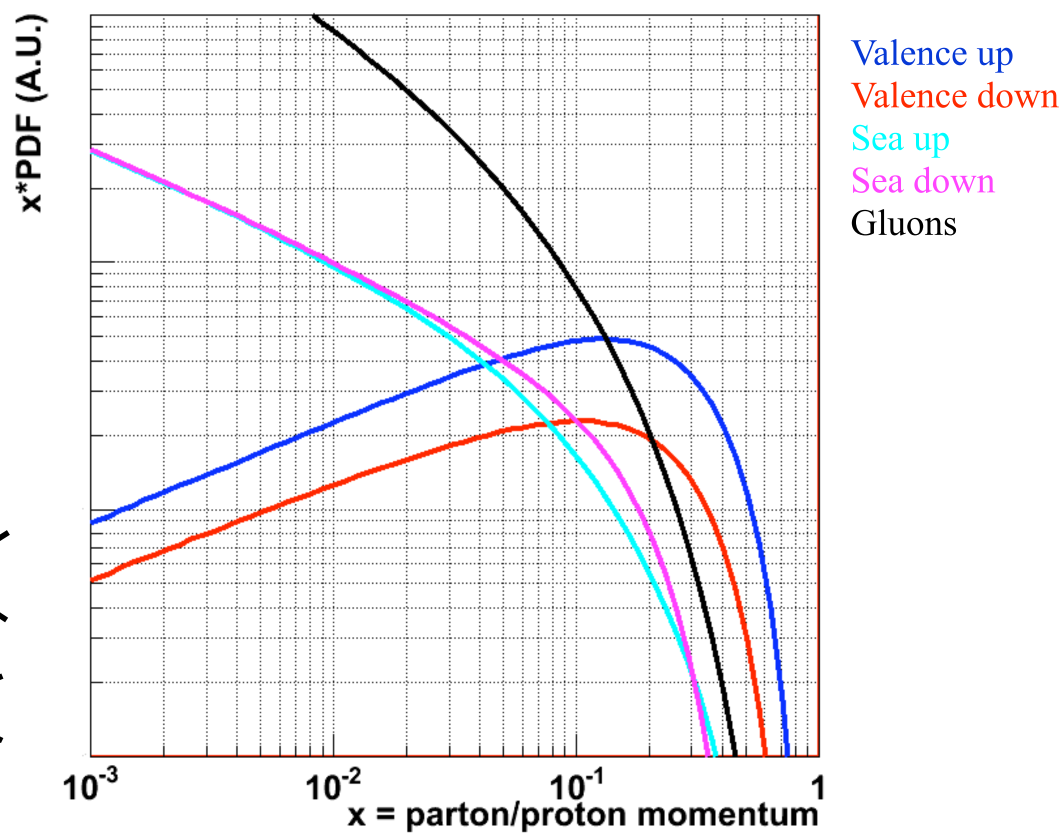
Parton Distribution Functions



Derived from CTEQ6L global fits, with simplistic sea/valence subtraction. $Q^2 = (100\ \text{GeV})^2$

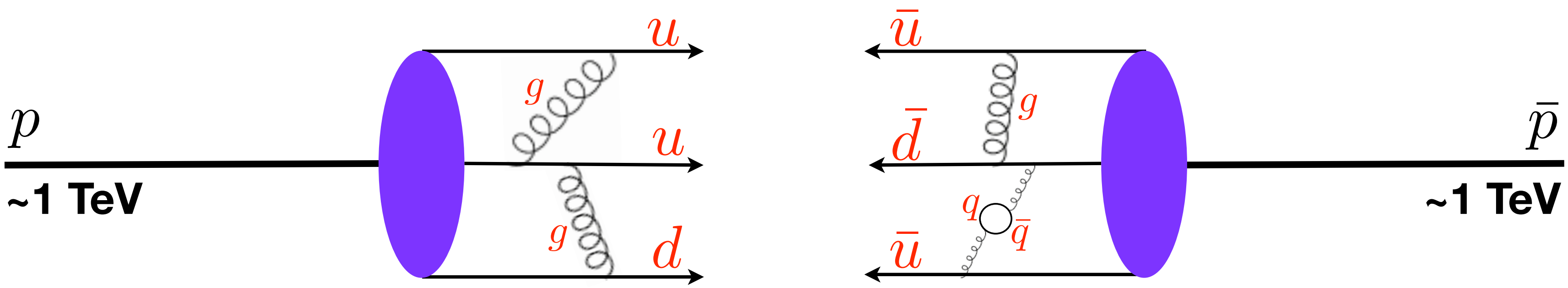
Parton Distribution Functions



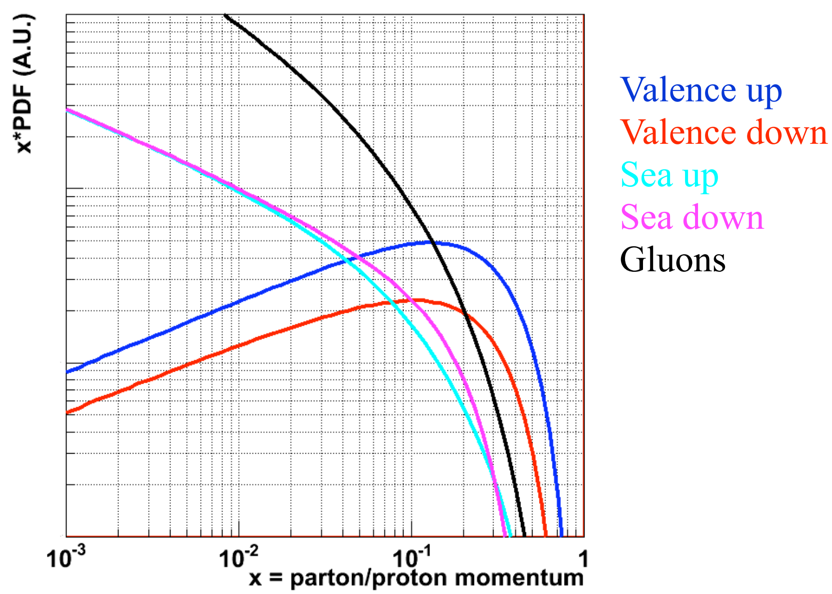


Derived from CTEQ6L global fits, with simplistic sea/valence subtraction. $Q^2 = (100\ \mathrm{GeV})^2$

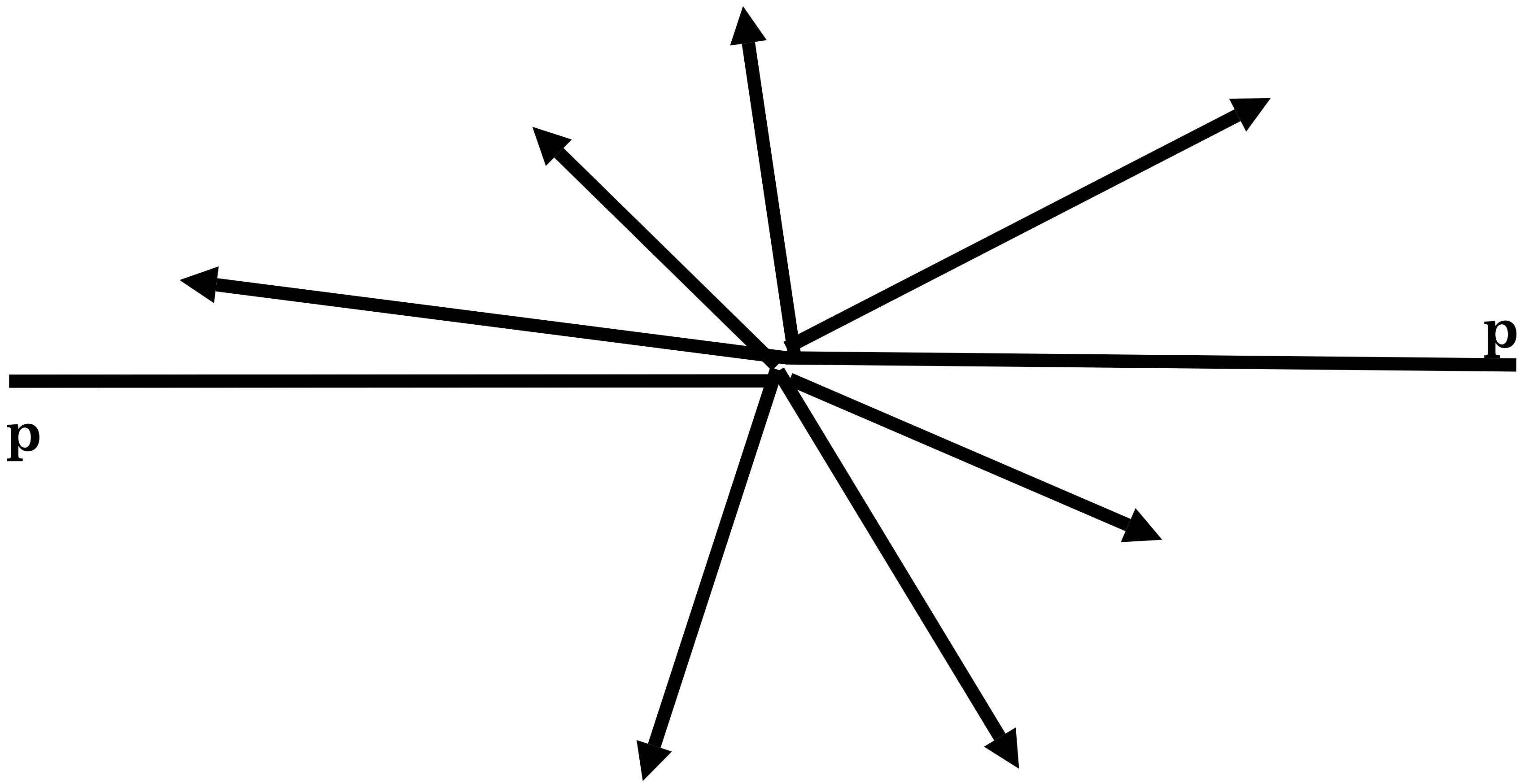
$p\bar{p}$ (or pp) Collisions Summary:



- Only a fraction of proton's energy is involved
- pp collisions are really parton collisions
    - CM is not known
        - Fraction of proton's momentum determined by PDF
    - Simultaneous probe of many energies
- Contribution from gluon interactions can be significant



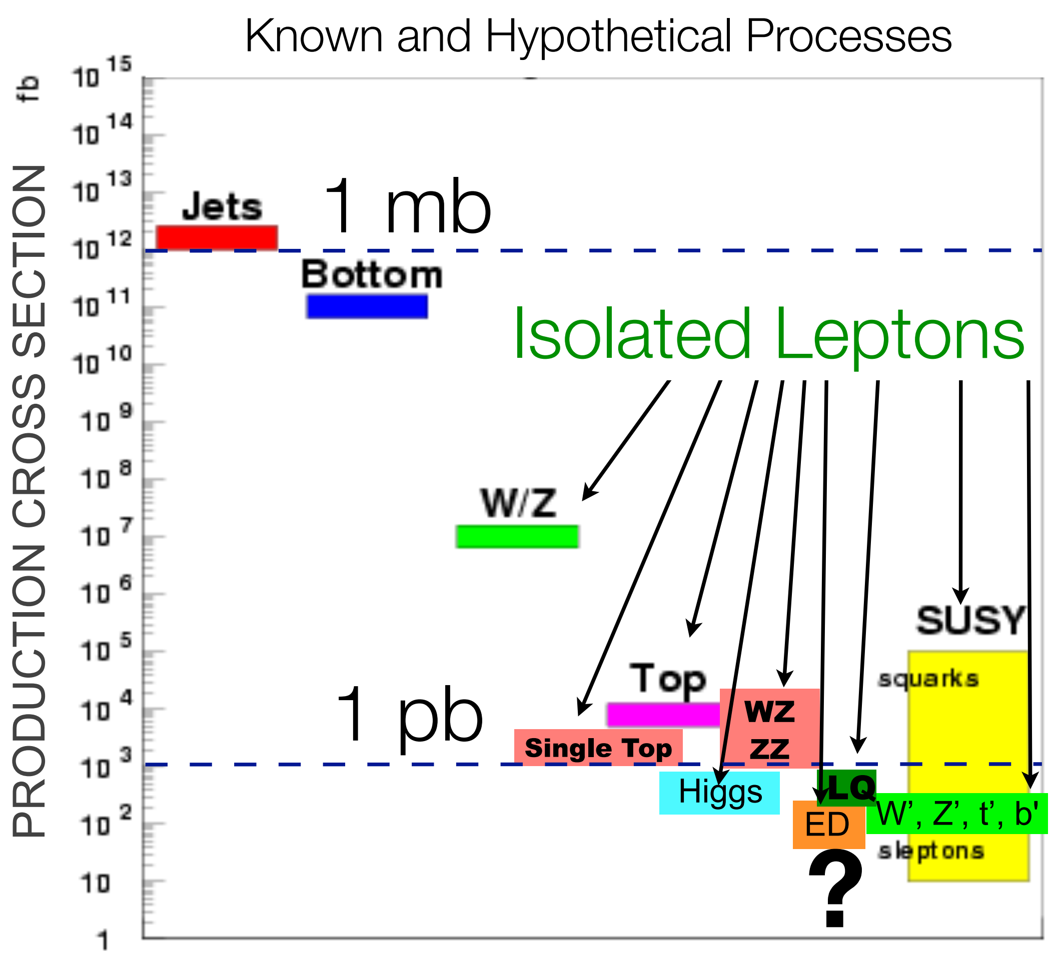
Proton Proton Collisions



$E=mc^2$

What is produced in a $p\bar{p}$ collision at 2 TeV?

- Light quark jets (hadrons)
- b-quark jets (hadrons)
- Gauge bosons $W^{\pm}$,Z^0
- Top quark pairs
- Single top quark
- Di-boson
  $W^{\pm}W^{\mp}$, $W^{\pm}Z^0$, Z^0Z^0
- Higgs
- Higgs + boson: ZH,WH
- SUSY, Technicolor, Leptoquarks, Z',W', excited quarks,
  excited leptons...



What is produced in a pp collision at 14 TeV?

Process	Comments	Reference	Order in pert. theory	σ (nb)
Total inelastic pp		PYTHIA [2]		$79 \cdot 10^6$
Non Single Diffractive		PYTHIA [2]		$65 \cdot 10^6$
Dijet	$p_T^{jet} > 25$ GeV	PYTHIA [2]	LO	$367 \cdot 10^3$
		NLOJET++ [3,4]	NLO	$477 \cdot 10^3$
γ-jet	$p_T^{\gamma} > 25$ GeV	PYTHIA [2]	LO	180
$b\bar{b} \to \mu + X$	$p_T^{\mu} > 6$ GeV	PYTHIA [2]	LO	$6.1 \cdot 10^3$
$b\bar{b} \to \mu\mu + X$	$p_T^{\mu_1/\mu_2} > 6 / 4$ GeV	PYTHIA [2]	LO	110
$t\bar{t}$			NLO	0.794
		Ref. [5]	NLO+NLL	0.833
Single top production	t-channel	AcerMC [6]	LO	0.251
		Ref. [7–9]	NLO	0.246
	s-channel	AcerMC [6]	LO	0.007
		Ref. [7]	NLO	0.011
	Wt	AcerMC [6]	LO	0.058
		Ref. [10–12]	NLO	0.066
$W \to \ell\nu$		FEWZ [13]	LO	16.8
		FEWZ [13]	NLO	20.7
		FEWZ [13]	NNLO	20.5
$Z \to \ell\ell$	$m_{\ell\ell} > 60$ GeV	FEWZ [13]	LO	1.66
		FEWZ [13]	NLO	2.03
		FEWZ [13]	NNLO	2.02
WW	$m_{W^{(*)}} > 20$ GeV, $p_T^W > 10$ GeV	MCFM [14]	LO	0.072
		MCFM [14]	NLO	0.112
WZ	$m_{W^{(*)}/Z^{(*)}} > 20$ GeV, $p_T^{W/Z} > 10$ GeV	MCFM [14]	LO	0.032
		MCFM [14]	NLO	0.056
ZZ	$m_{Z^{(*)}} > 12$ GeV	MCFM [14]	LO	0.0165
		MCFM [14]	NLO	0.0221
$\gamma\gamma$ $(qq, qg \to \gamma\gamma)$	$80 < m_{\gamma\gamma} < 150$ GeV	RESBOS [15]	NLO	0.0209
$(gg \to \gamma\gamma)$	$80 < m_{\gamma\gamma} < 150$ GeV	RESBOS [15]	NLO	0.0080

From "The Expected Performance of the ATLAS Experient", CERN-OPEN-2008-020

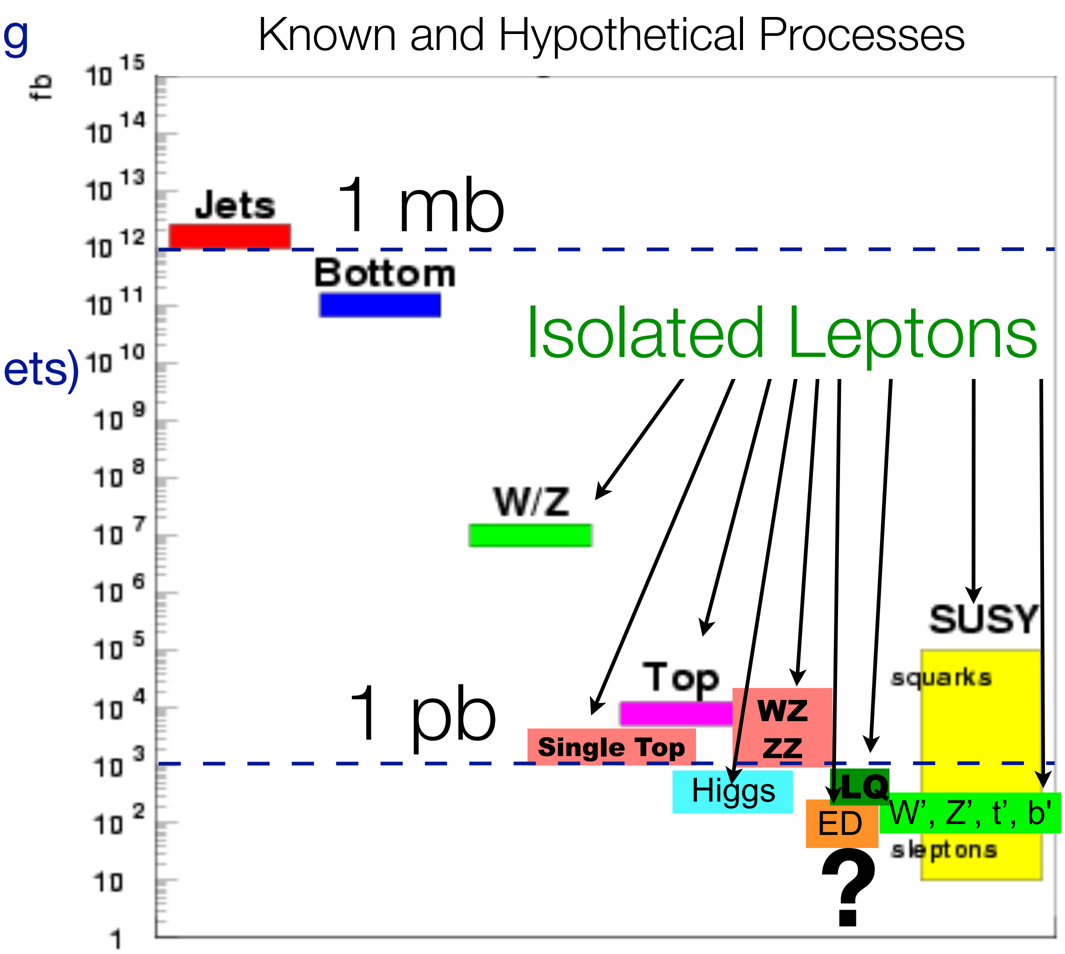
Example Rate Calculation:

- LHC Design $L=10^{34}/cm^2s$
- pp inelastic: $\sigma = 79 \times 10^6$ nb
- 1 barn = 10^{-24} cm^2
- pp inelastic: $\sigma = 79 \times 10^6 \times 10^{-9} \times 10^{-24}$ cm^2
- pp inelastic: $\sigma = 79 \times 10^{-27}$ cm^2

- Rate = $L\sigma = 10^{34}/cm^2s \times 79 \times 10^{-27}\ cm^2 = 7.9 \times 10^8/s \sim 10^9/s$
- O(20) interactions per bunch crossing
- Still, simply cannot record every event.

Solution: Trigger

- Only save events with interesting objects
  - Leptons (e, mu, tau)
  - High-energy jets
  - Displaced vertices (b-quark jets)
  - Missing energy
- Risk: throwing away the new physics signal!
  - Solution: have to think of everything you want to save ahead of time.



RunSummary for run 271746
<271745 | 271747>

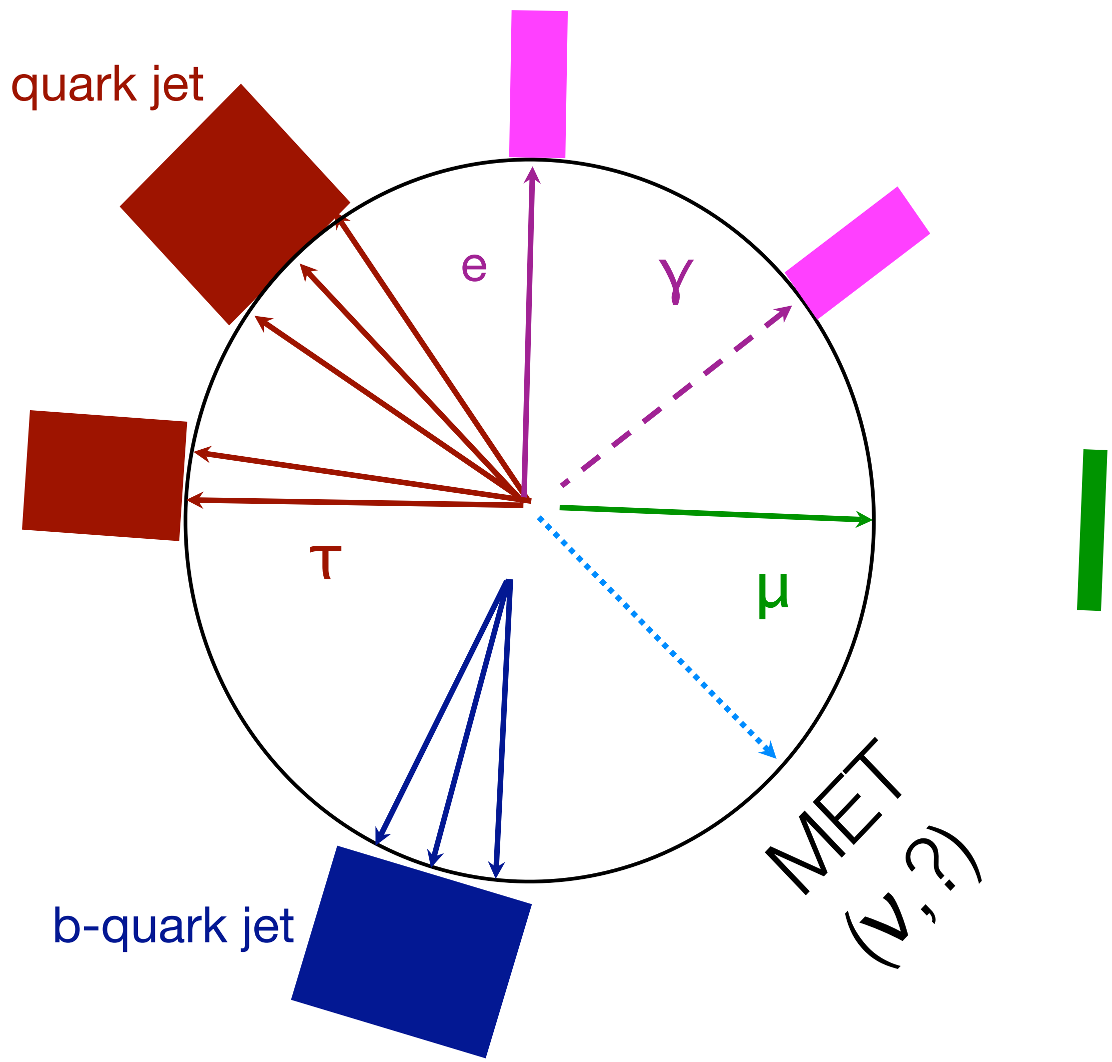
L1 | L2 | L2Latency | L3 | ShiftLog | ErrorLog | Reformatter | L3Filter | SessionLog | RunControl | RunSet | SEvb | HEvb-L3-I/O | TS-TM-I/O | CSL | AcNet | Consumers | ConsumerRootFileBrowser | DownTime | Store | SlowControl | PhysMon | DfcLumi | OfflineStatus

Trigger Paths (L3) for run 271746

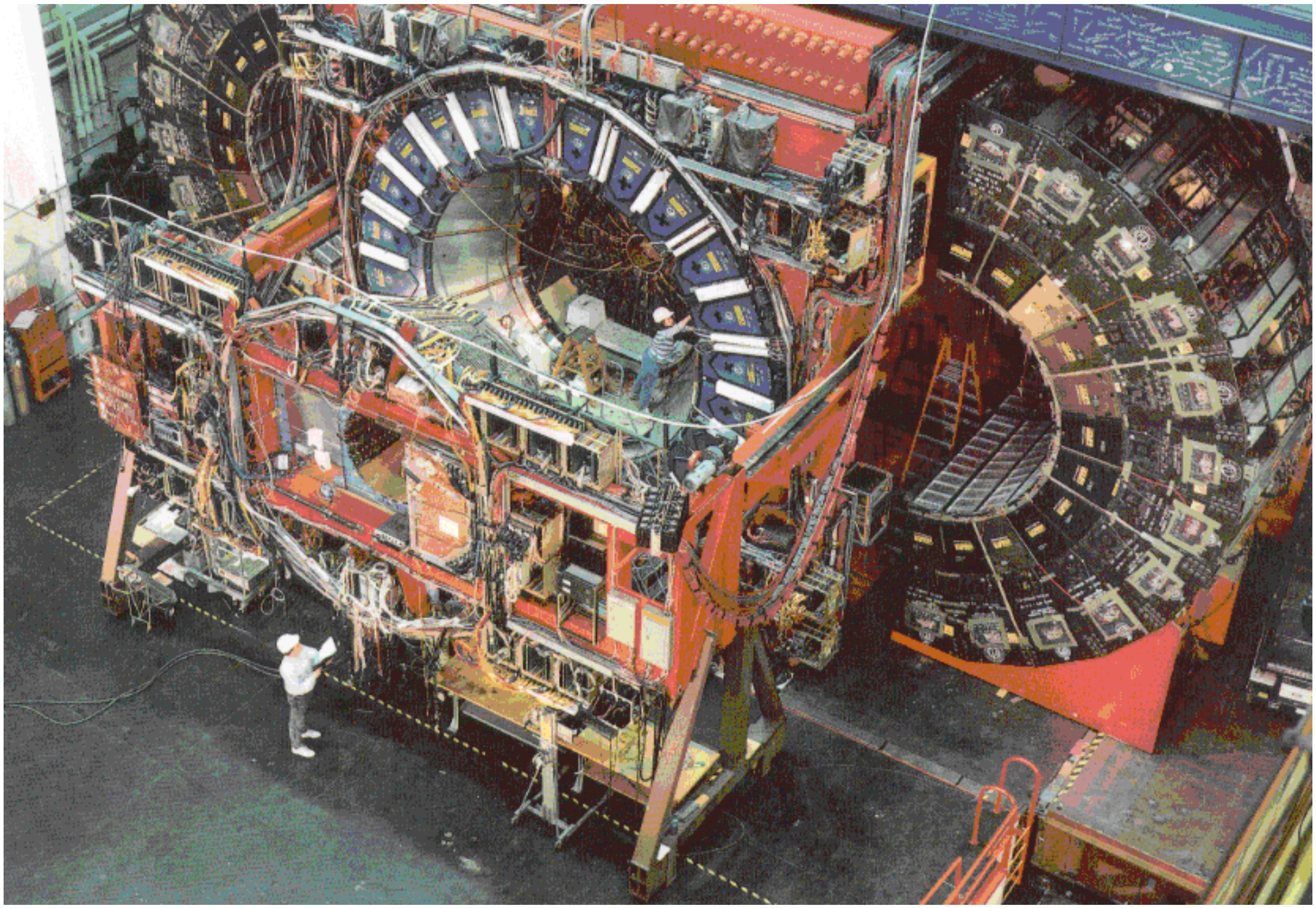
CSBIT	PATH_NAME_FROM	DATASET	PRESCALED	RATE_HZ	NB	STREAM	S
0	AAAAA_ALL_RECO_5.1_NOCOMP:1	null	21	0.00	0.00	none	
1	BBBAR_CMUP3_CMU1.5_DPS:6	B_DIMUON	130708	3.22	22.30	StreamJ	
2	BBBAR_CMUP3_CMX2_DPS:6	B_DIMUON	29854	0.73	5.09	StreamJ	
3	BBBAR_TWO_CMUP3_DPS:6	B_DIMUON	8446	0.21	1.44	StreamJ	
4	B_CHARM_HIGHPT_L1_CLCM_DPS:8	B_HADRONIC	248758	6.12	42.45	StreamH	
5	B_CHARM_HIGHPT_PS12500:3	B_HADRONIC	75	0.00	0.01	StreamH	
6	B_CHARM_L1_LUMI_80:5	B_HADRONIC	0	0.00	0.00	StreamH	
7	B_CHARM_L1_UPS:6	B_HADRONIC	256193	6.30	43.72	StreamH	
8	B_CHARM_LOWPT_CMU_L1_DPS:7	B_HADRONIC	47158	1.16	8.05	StreamH	
9	B_CHARM_LOWPT_CMX_L1_DPS:7	B_HADRONIC	15284	0.38	2.61	StreamH	
10	B_CHARM_LOWPT_L1_LUMI_35:4	B_HADRONIC	0	0.00	0.00	StreamH	
11	B_CHARM_LOWPT_L1_PS2_LUMI_50:5	B_HADRONIC	0	0.00	0.00	StreamH	
12	B_CHARM_NO_OPPQ_L1_LUMI_65:2	B_HADRONIC	0	0.00	0.00	StreamH	
13	B_CHARM_PHI_L1_UPS:7	B_HADRONIC	56805	1.40	9.69	StreamH	
14	B_CHARM_PHI_LOWPT_L1_PS2_LUMI_50:3	B_HADRONIC	0	0.00	0.00	StreamH	
15	B_CHARM_PHI_LOWPT_LUMI_35:2	B_HADRONIC	0	0.00	0.00	StreamH	
16	B_D0_PS10_L1_CLCM_DPS:4	EXPRESS	3671	0.09	0.63	StreamA	

CSBIT	PATH_NAME_FROM	DATASET	PRESCALED	RATE_HZ	NB	STREAM	S
49	ELECTRON_CENTRAL_18:13	HIGH_PT_ELECTRON	135843	3.34	23.18	StreamB	1,273,704
49	ELECTRON_CENTRAL_18:13	SUSY_DILEPTON	135843	3.34	23.18	StreamE	1,531,258
50	ELECTRON_CENTRAL_18_LOOSE_L3PS50:5	HIGH_PT_ELECTRON	6566	0.16	1.12	StreamB	1,273,704
51	ELECTRON_CENTRAL_18_NO_L2:9	HIGH_PT_ELECTRON	1625	0.04	0.28	StreamB	1,273,704
52	ELECTRON_CENTRAL_4:16	B_ELECTRON	4176	0.10	0.71	StreamJ	919,698
53	ELECTRON_CENTRAL_4_NOL2:8	B_ELECTRON	9404	0.23	1.60	StreamJ	919,698
54	ELECTRON_CENTRAL_8_&_TRACK8_DPS:5	SUSY_DILEPTON	171356	4.22	29.24	StreamE	1,531,258
55	ELECTRON_CENTRAL_8_L2_DPS:8	LEPTON_CALIB	74961	1.84	12.79	StreamB	1,273,704
56	ELECTRON_CENTRAL_8_NO_L2:9	LEPTON_CALIB	4953	0.12	0.85	StreamB	1,273,704
57	ELECTRON_CENTRAL_PS2K_L1_CEM8_PT8:2	LEPTON_CALIB	4239	0.10	0.72	StreamB	1,273,704
58	ELECTRON_CENTRAL_PS50_L1_CEM4_PT4:2	B_ELECTRON	11525	0.28	1.97	StreamJ	919,698
59	EXPRESS_MET_PEM:13	PLUG_ELECTRON	15631	0.38	2.67	StreamB	1,273,704
60	EXPRESS_MUON_CMUP22:4	EXPRESS	13058	0.32	2.23	StreamA	184,053
60	EXPRESS_MUON_CMUP22:4	HIGH_PT_MUON	13058	0.32	2.23	StreamB	1,273,704
61	EXPRESS_MUON_CMX22:3	EXPRESS	11788	0.29	2.01	StreamA	184,053
61	EXPRESS_MUON_CMX22:3	HIGH_PT_MUON	11788	0.29	2.01	StreamB	1,273,704
62	EXPRESS_W:9	HIGH_PT_ELECTRON	17717	0.44	3.02	StreamB	1,273,704
62	EXPRESS_W:9	EXPRESS	17717	0.44	3.02	StreamA	184,053
63	EXPRESS_W_NOTRACK:14	HIGH_PT_ELECTRON	4660	0.11	0.80	StreamB	1,273,704
63	EXPRESS_W_NOTRACK:14	EXPRESS	4660	0.11	0.80	StreamA	184,053
64	EXPRESS_Z:10	HIGH_PT_ELECTRON	7964	0.20	1.36	StreamB	1,273,704

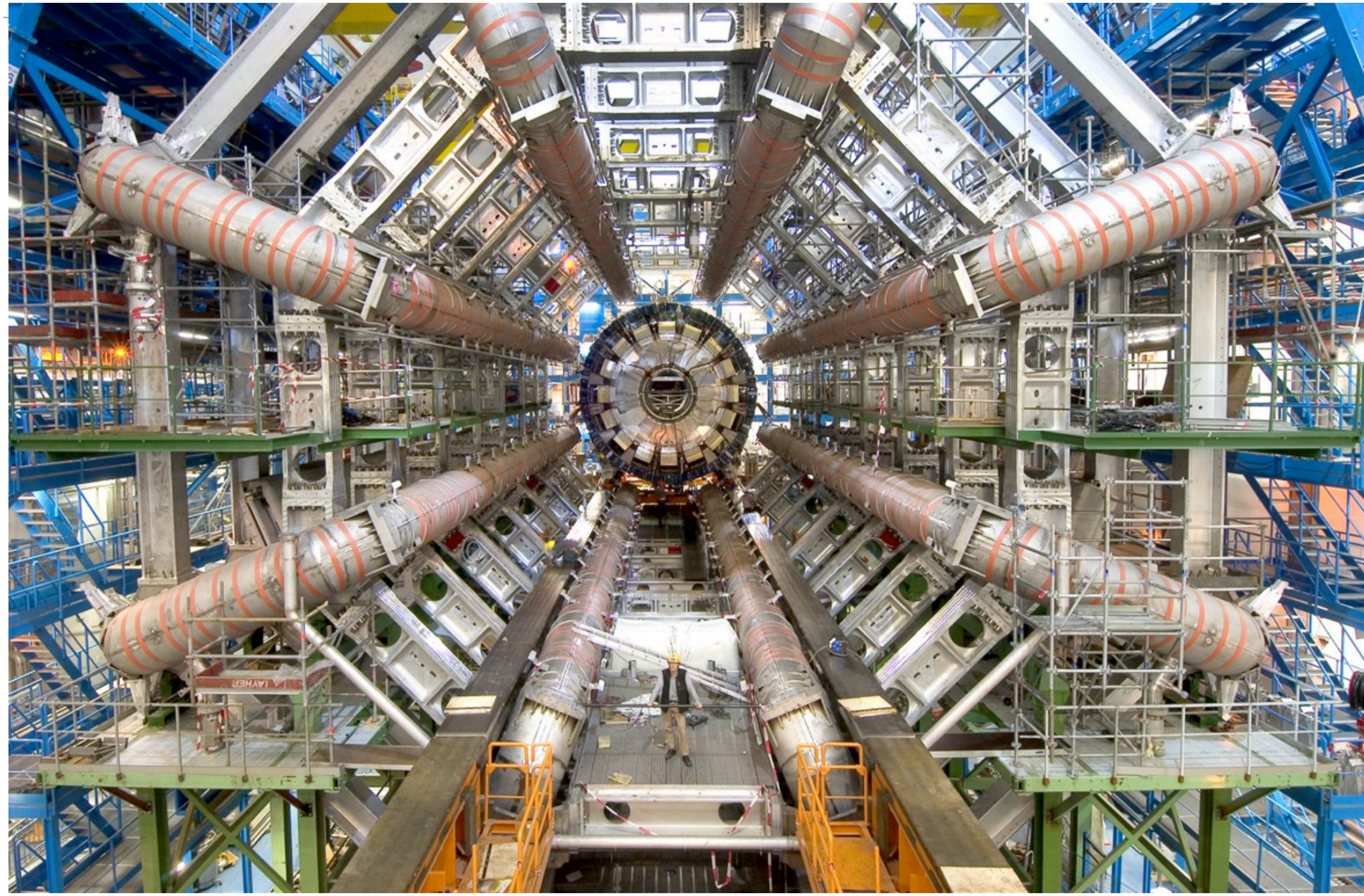
Particles as seen by Collider Detectors: Idealized (end view)



Detectors: CDF



Detectors: ATLAS (well some of it)



Modern Collider Experiment Detectors

Ideally:

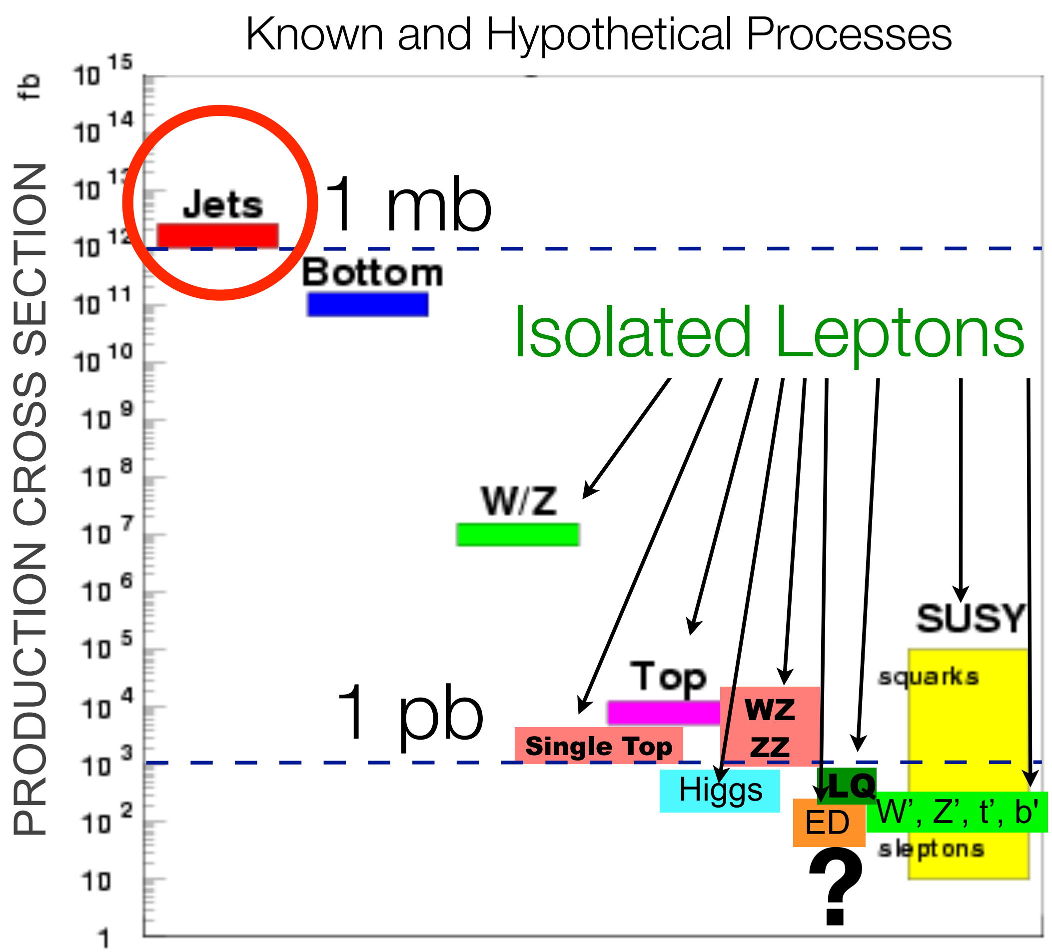
- Can identify and precisely measure jets (energy, trajectory), and their origin, and even whether they originate from a high energy quark or gluon.
- Can measure all energy in an event (and the missing momentum).
- Can detect and reconstruct energy, trajectories of e,μ with no background.
- A τ is just the third kind of charged lepton, right? We can measure leptons.
- Can identify and precisely measure b-quark jets.

Realistically:

- "Jet" is another word for the spray of mostly hadronic particles that originates from quarks and gluons
  "A jet is a jet is a jet"
  "A jet isn't a jet isn't a jet!"
- "Underlying event", pileup, detector noise, mis-measurements all affect MET resolution.
- Electrons radiate and loose energy, photons convert to e^+e^-, pions decay to muons.
- Reconstructing τ leptons is very hard: they look more like jets than leptons
- Displaced vertices from b-quarks are hard to find and can be faked by light quark jets

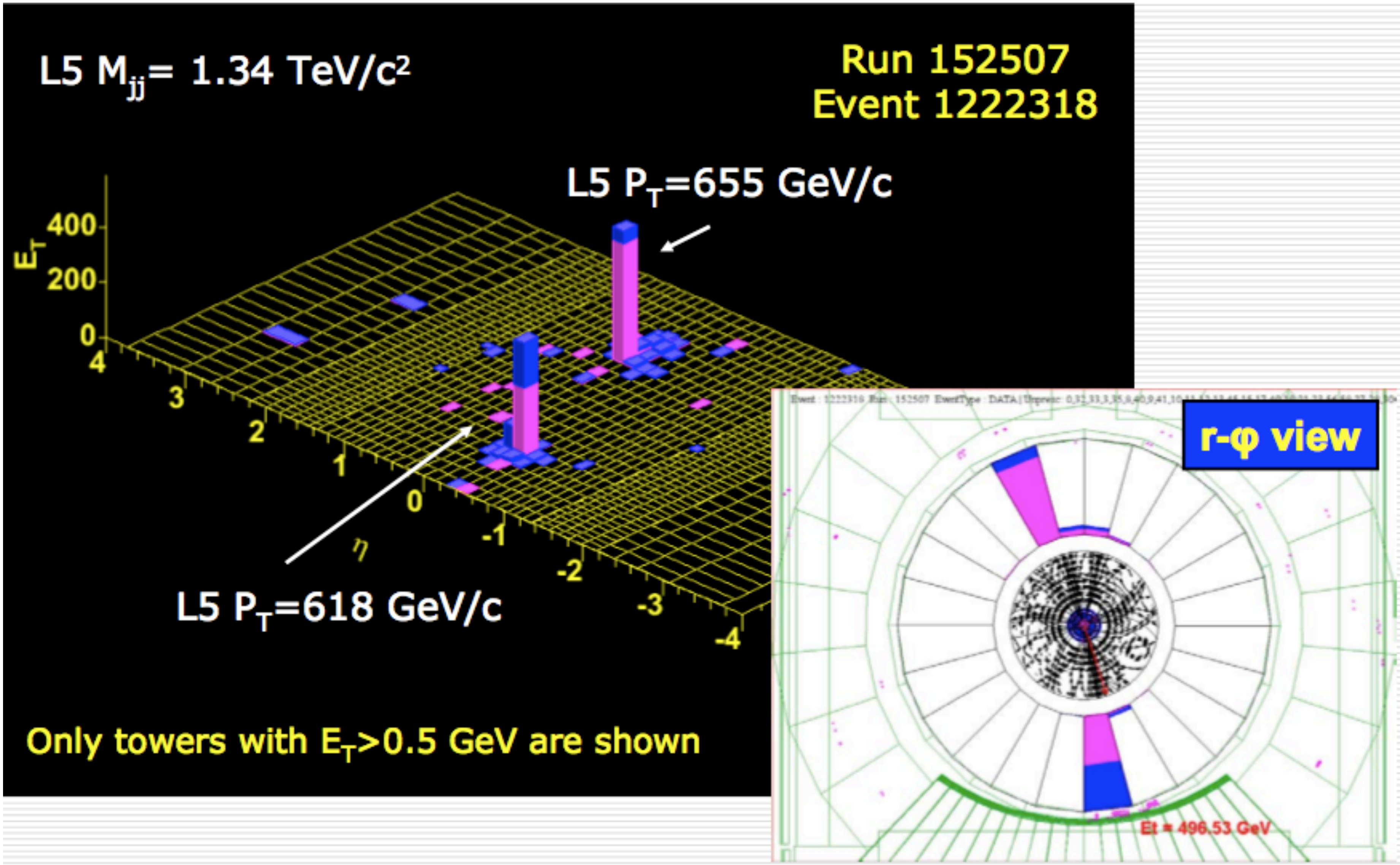
Event Displays

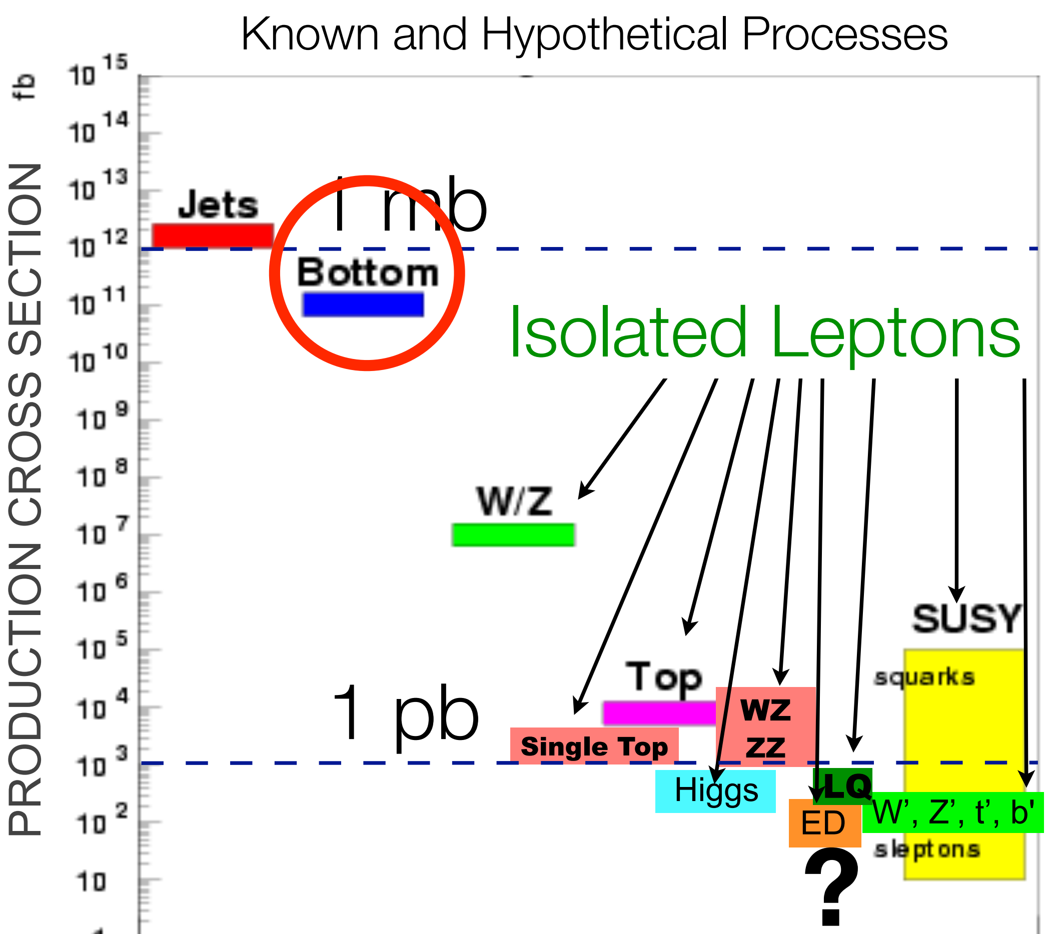
(CDF)



Known and Hypothetical Processes
PRODUCTION CROSS SECTION fb
10 15
10 14
10 13
10 12
10 11
10 10
10 9
10 8
10 7
10 6
10 5
10 4
10 3
10 2
10
1
Jets
1 mb
Bottom
Isolated Leptons
W/Z
SUSY
squarks
Top
1 pb
WZ
ZZ
Single Top
Higgs
LQ
ED
W', Z', t', b'
sleptons
?

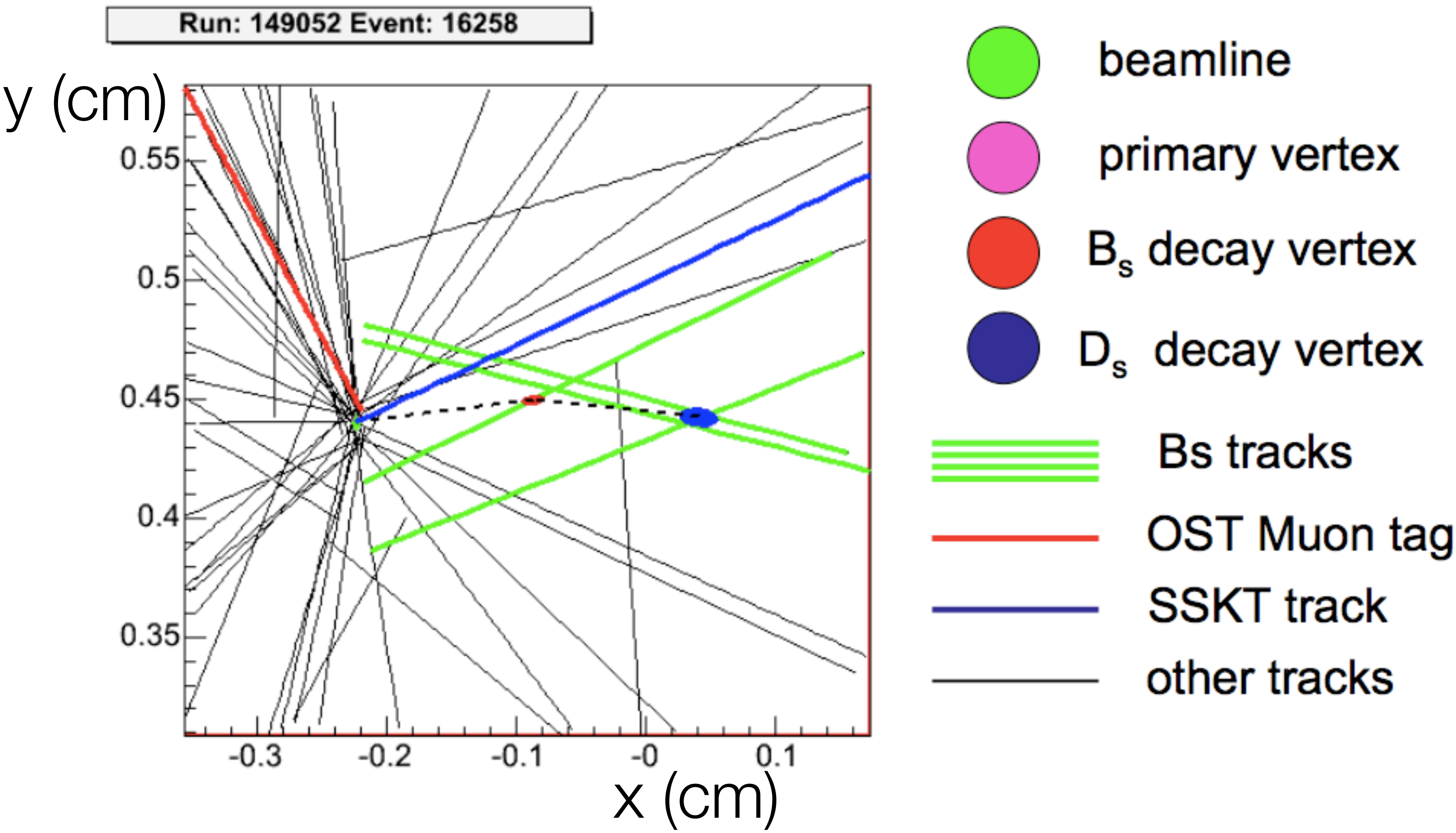
High-Mass Di-Jet Event

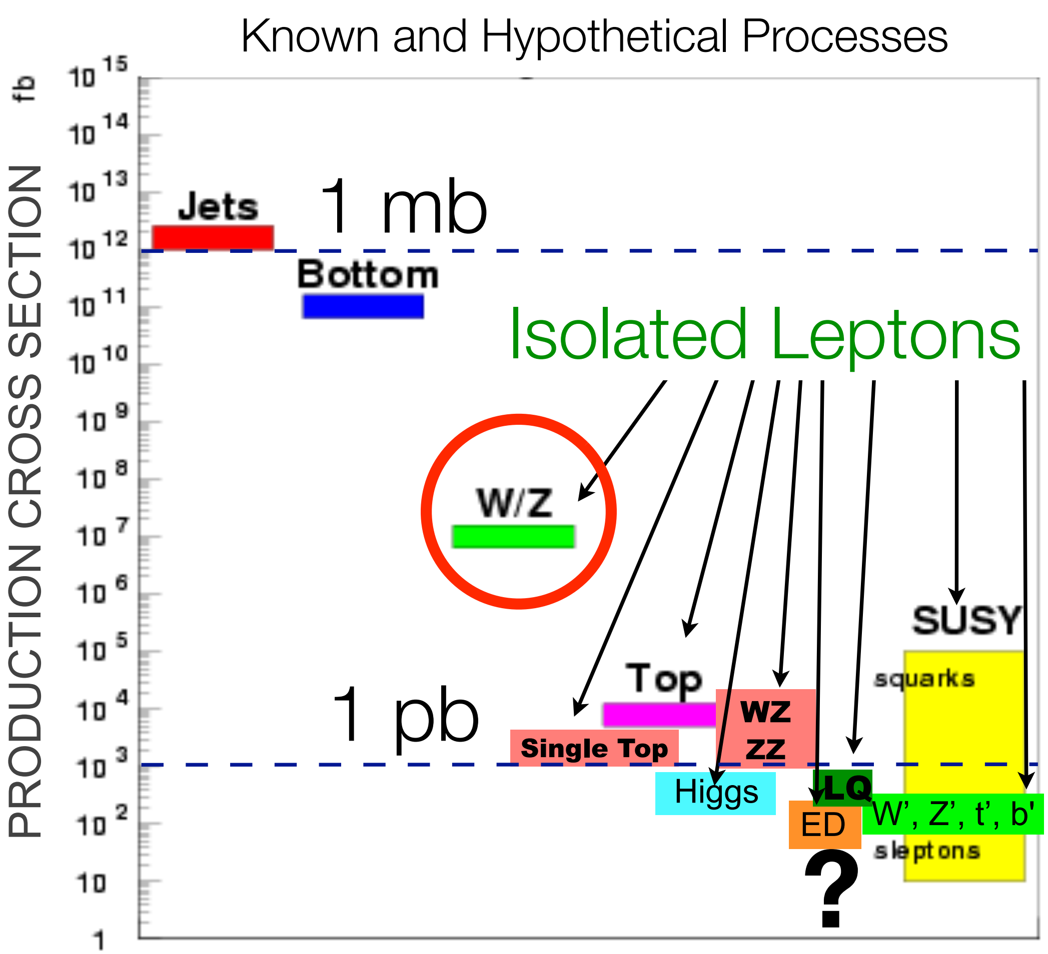




Known and Hypothetical Processes
PRODUCTION CROSS SECTION fb
10^15
10^14
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
Jets
1 mb
Bottom
Isolated Leptons
W/Z
SUSY
squarks
Top
WZ
ZZ
1 pb
Single Top
Higgs
LQ
ED
W', Z', t', b'
sleptons
?

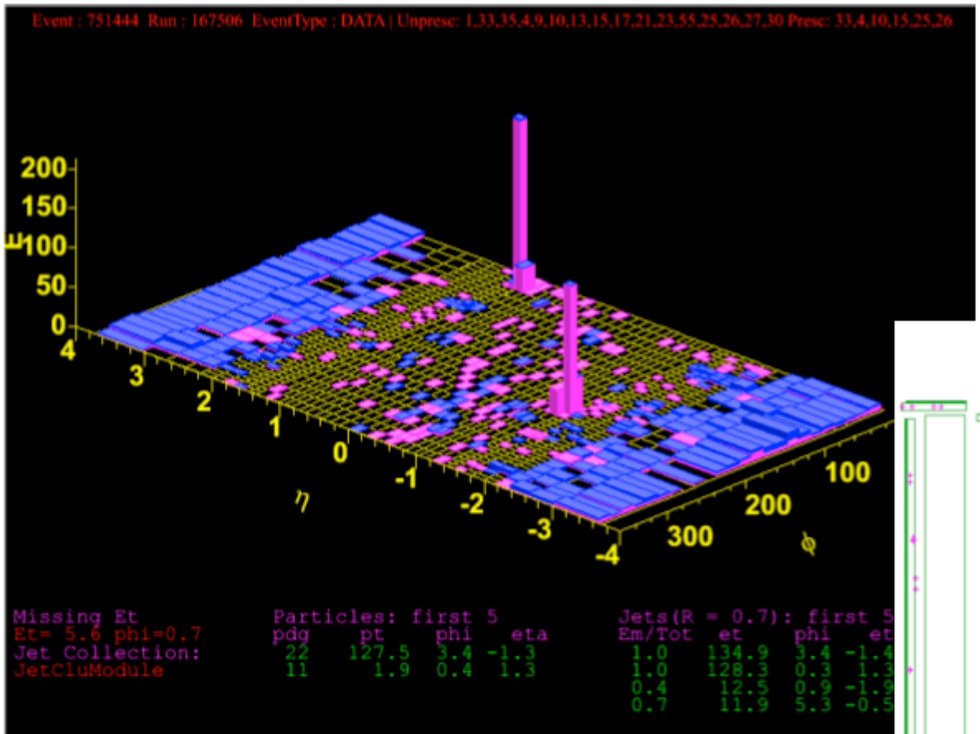
A B_s Event (Vertex)





Known and Hypothetical Processes
PRODUCTION CROSS SECTION fb
10 15
10 14
10 13
10 12
10 11
10 10
10 9
10 8
10 7
10 6
10 5
10 4
10 3
10 2
10
1
Jets
1 mb
Bottom
Isolated Leptons
W/Z
SUSY
squarks
Top
1 pb
WZ
ZZ
Single Top
Higgs
LQ
ED
W', Z', t', b'
sleptons
?

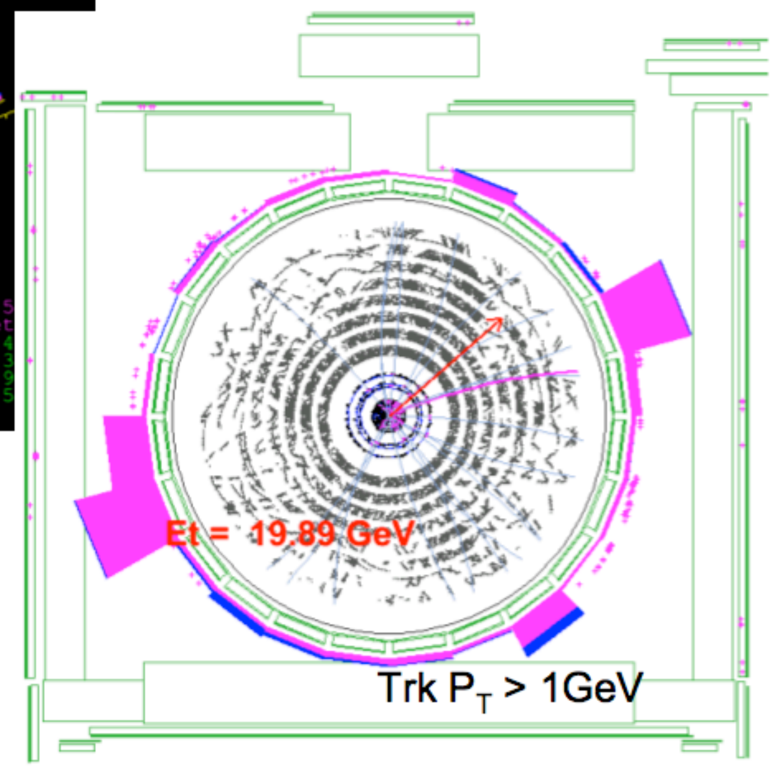
CDF Event Display: High Mass Electrons

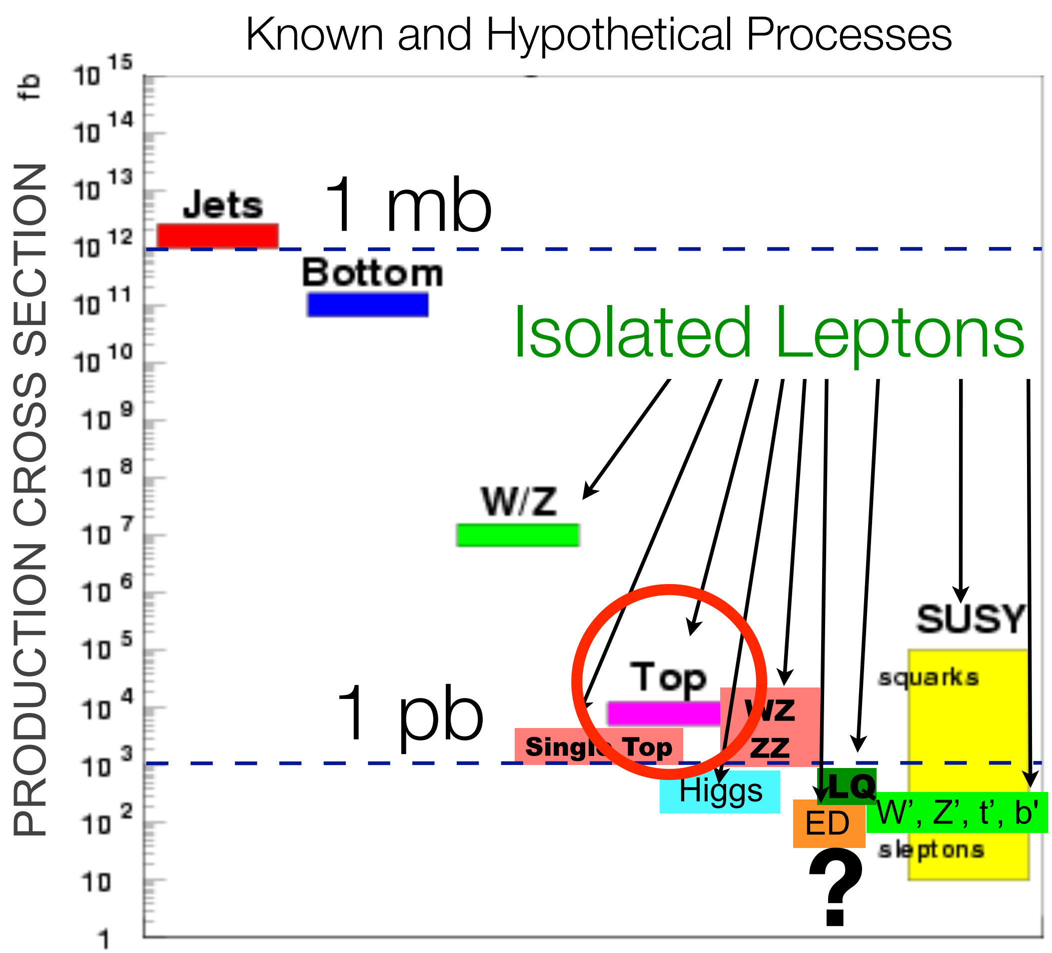


run: 167506, event: 751444

plug-plug

M_{ee} = 536 GeV/c^2





Known and Hypothetical Processes
PRODUCTION CROSS SECTION fb
10 15
10 14
10 13
10 12
10 11
10 10
10 9
10 8
10 7
10 6
10 5
10 4
10 3
10 2
10
1
Jets
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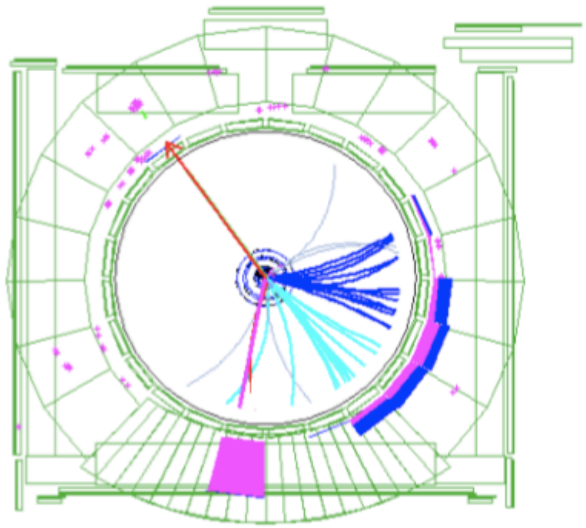
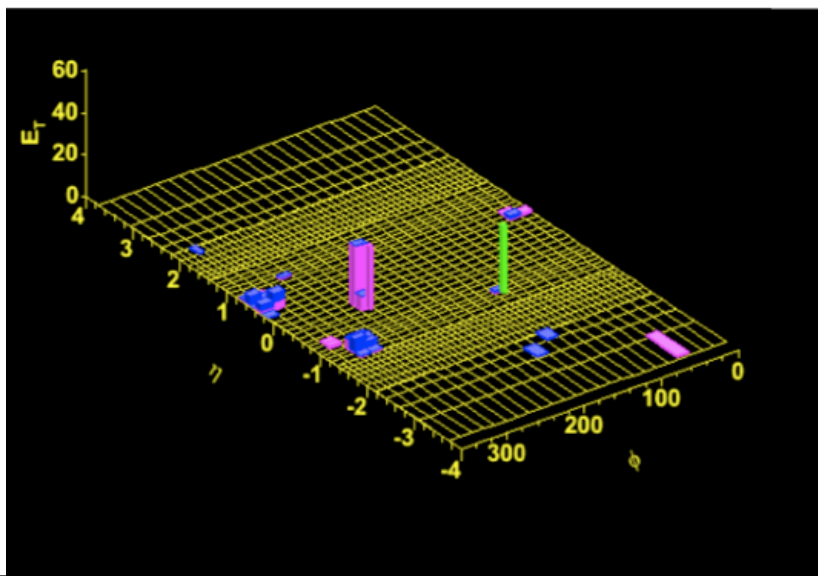
Bottom
Isolated Leptons
W/Z
SUSY
Top
squarks
1 pb
WZ
Single Top
ZZ
LQ
Higgs
ED
W', Z', t', b'
sleptons
?

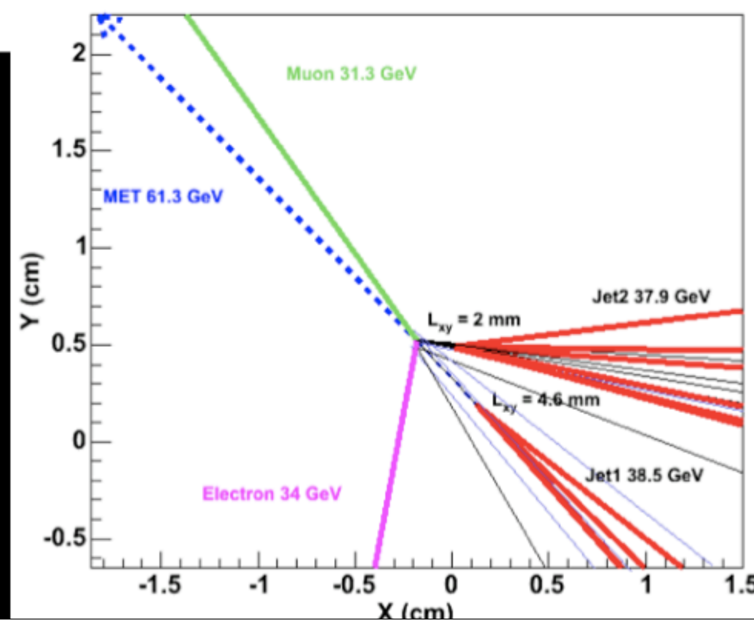
A tt̄ Dilepton Event

$$t\bar{t}, t \to W^+ b, \bar{t} \to W^- \bar{b}$$



Run number 167631
Event number 2058969
eμ event (CEM-CMX)





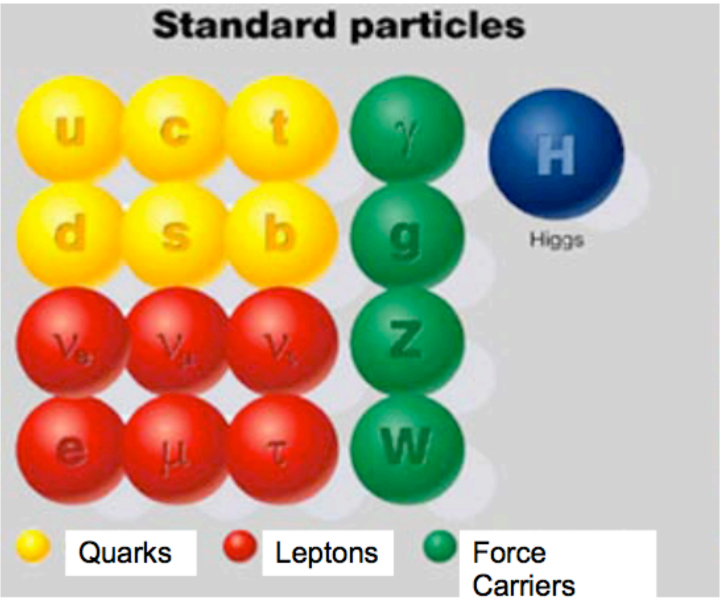
Search Strategies

- Model-Dependent: Pick a model. Study the phenomenology. Optimize search for a model
  - Supersymmetry
  - Leptoquarks
  - Technicolor
  - New Gauge Bosons
  - Extra Dimensions
  - ...

- Model-Independent
- Pick a signature
  - Optimize for detector acceptance and background rejection
- Quantify Backgrounds
- Look for excess
- Do all signatures simultaneously?

Supersymmetry Phenomenology (for experimentalists)

- Proposes a new symmetry:
  - Fermions ↔ Bosons



- Every fermion has a boson superpartner and vice-versa
- New (conserved) quantum number called R-Parity:

$$R_p = (-1)^{B+L+2s}$$

electron ↔ selectron

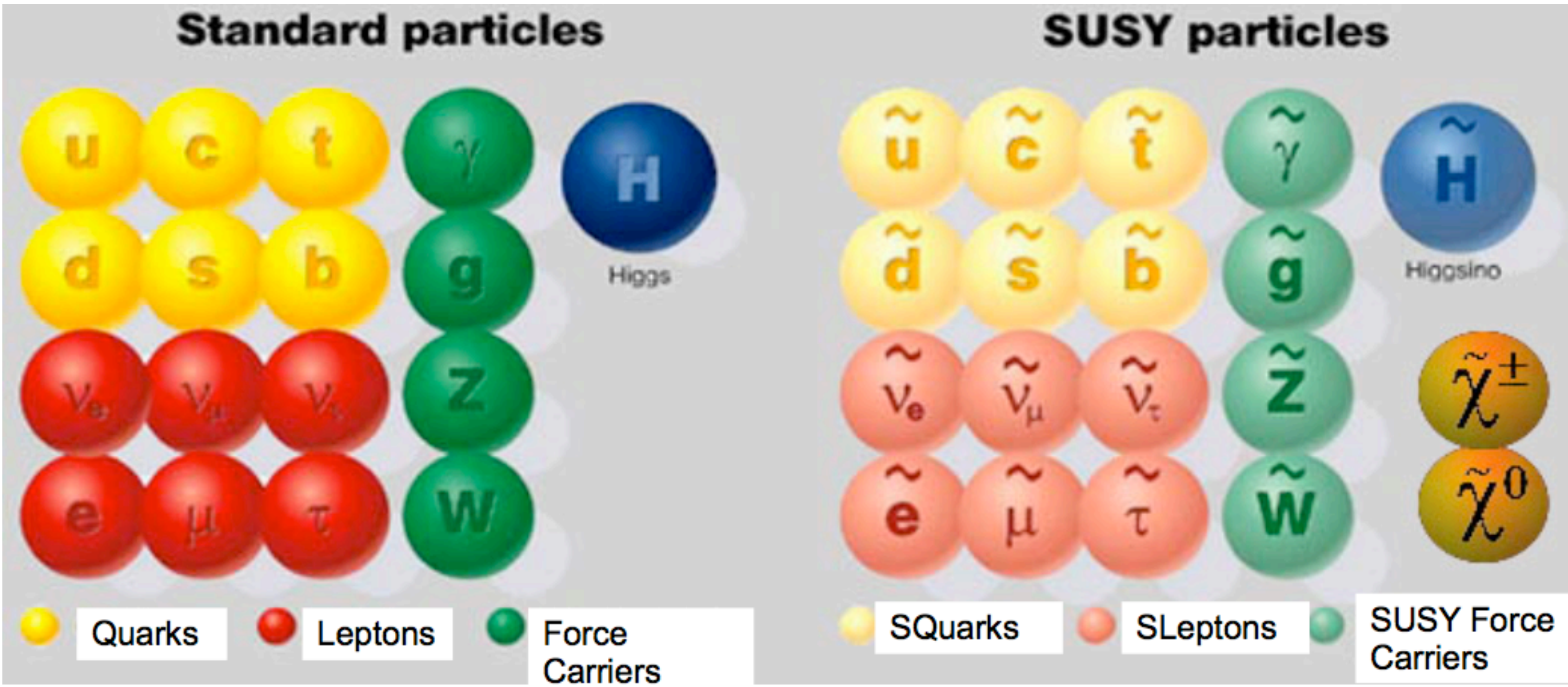
$R_p = 1$ $R_p = -1$

photon ↔ photino

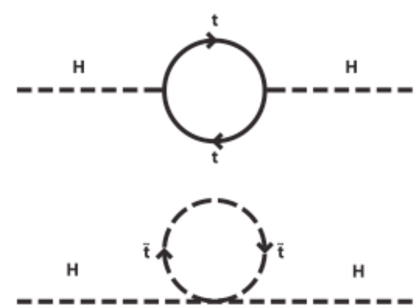
$R_p = 1$ $R_p = -1$

- Consequences if R-Parity is conserved:
  - Supersymmetric particles are *pair-produced* in colliders.
  - The Lightest Supersymmetric Particle (LSP) is *stable*.
  - SUSY particles decay to SM particles and the LSP (which can result in missing energy).

The SUSY Zoo



- SUSY solves the heirarchy problem.
- Removes divergences to Higgs mass.
- Vanilla SUSY: >100 Parameters. Traded one problem for another.



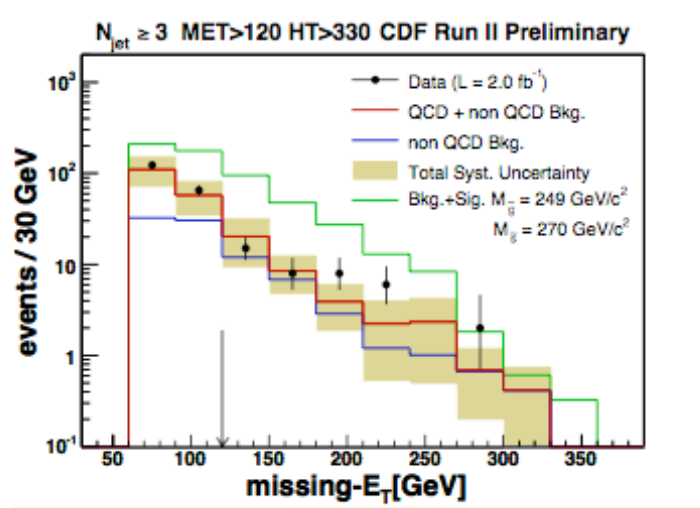
Minimal Supergravity (mSUGRA)

- SUSY is a broken symmetry: spin 3/2 gravitino breaks Supersymmetry.
- Reduces the number of SUSY parameters from >100 to 5:
  - m_0: Scalar mass at the GUT scale.
  - $m_{1/2}$: Fermion mass at the GUT scale.
  - $\tan(\beta)$: Ratio of Higgs vacuum expectation values.
  - A_0: Trilinear scalar interaction at the GUT scale (Higgs - sfermionL - sfermionR).
  - $\text{sign}(\mu)$: Higgsino mass parameter (value is determined by EWSB).
- Specifying these 5 parameters determines SUSY spectrum.
  - Enables meaningful comparisons between experiments.

Searches for Squarks/Gluinos at CDF

$$p\bar{p} \longrightarrow \tilde{q}\tilde{q}X \longrightarrow q\tilde{\chi}^0 q\tilde{\chi}^0 X$$
$$p\bar{p} \longrightarrow \tilde{g}\tilde{q}X \longrightarrow q\bar{q}\tilde{\chi}^0 q\tilde{\chi}^0 X$$
$$p\bar{p} \longrightarrow \tilde{g}\tilde{g}X \longrightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0 X$$

- Strongly Produced
- Decay to jets and MET
- Neutralino is LSP
- Searches
  - Look for 2, 3, or 4 jets and MET
  - Are optimized in several different regions of mSUGRA parameter space to maximize sensitivity
  - Require lots of MET, large total jet energy
- Background: Mainly QCD (jets)

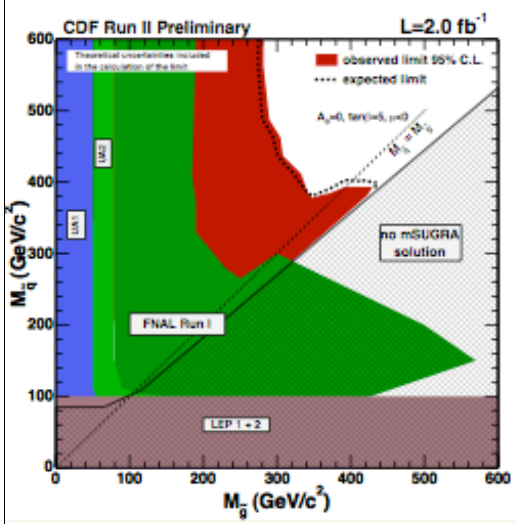


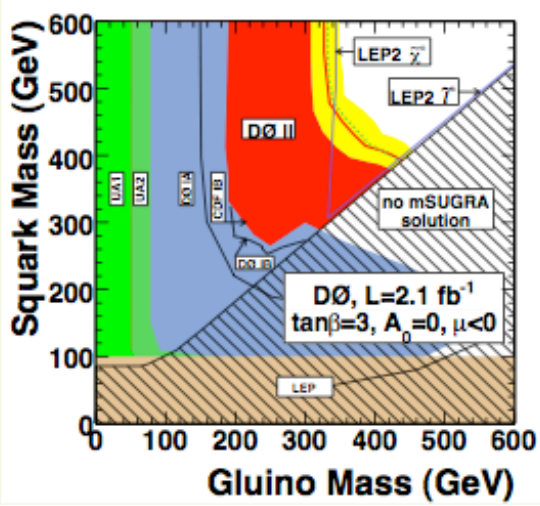
Searches for Squarks/Gluinos at CDF

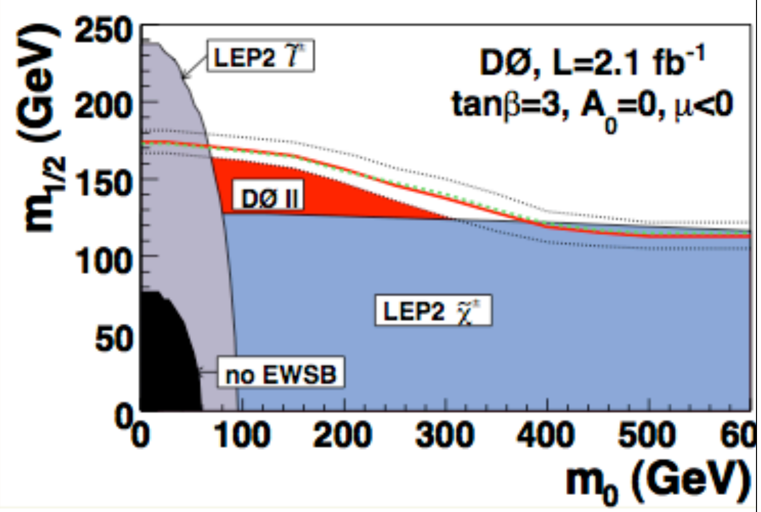
- Final results:

	CDF (2 fb^{-1})		DØ (2.1 fb^{-1})	
Analyses	**Expected**	**Observed**	**Expected**	**Observed**
2-jets	16 ± 5	18	$11 \pm 1^{+3}_{-2}$	11
3-jets	37 ± 12	38	$11 \pm 1^{+3}_{-2}$	9
4-jets	48 ± 17	45	$18 \pm 1^{+6}_{-3}$	20

- Limits are set
  - Squark/Gluino plane for a choice of tan(β)= 3, A_0=0, μ<0

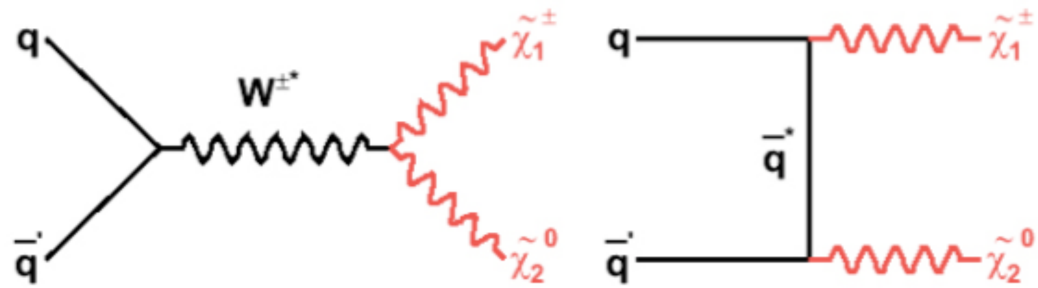




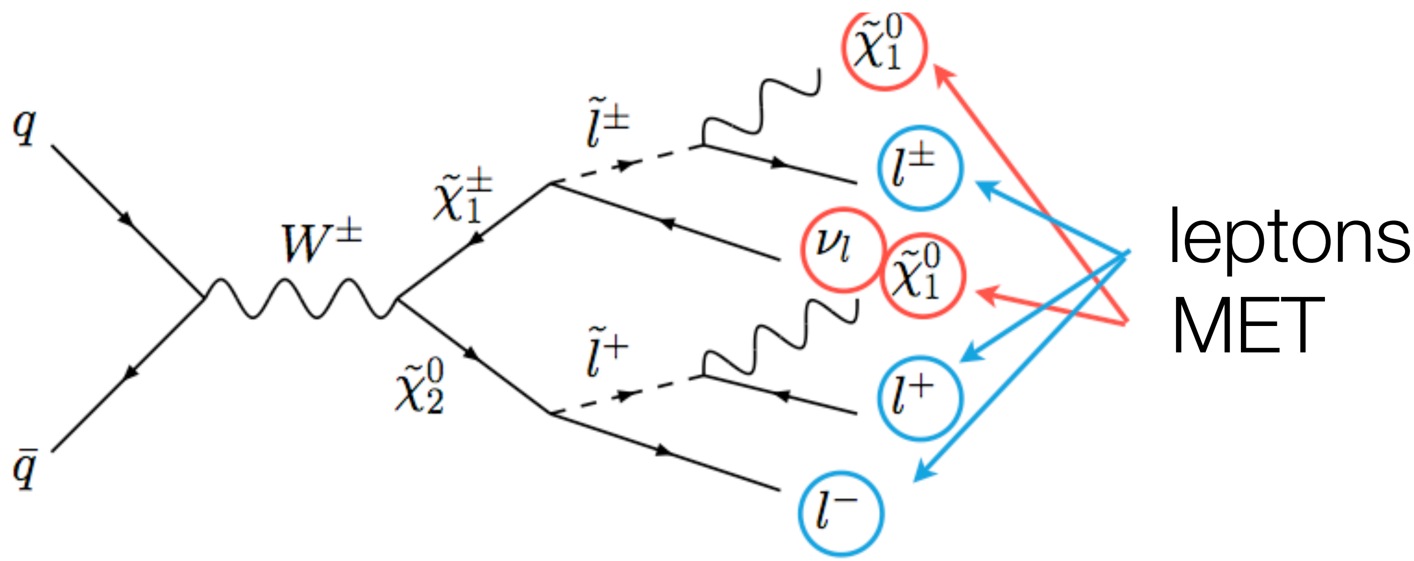


Search for Charginos/Neutralinos at CDF

- "Golden" mode for SUSY discovery at Tevatron
- Production:

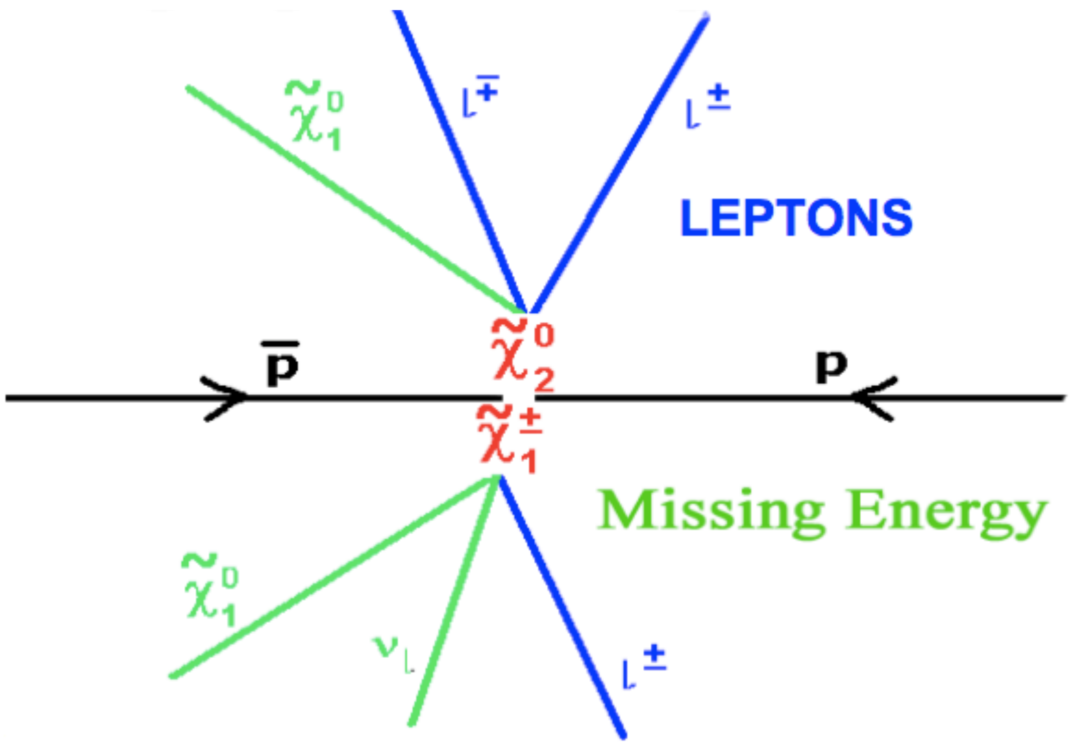


- Decay:



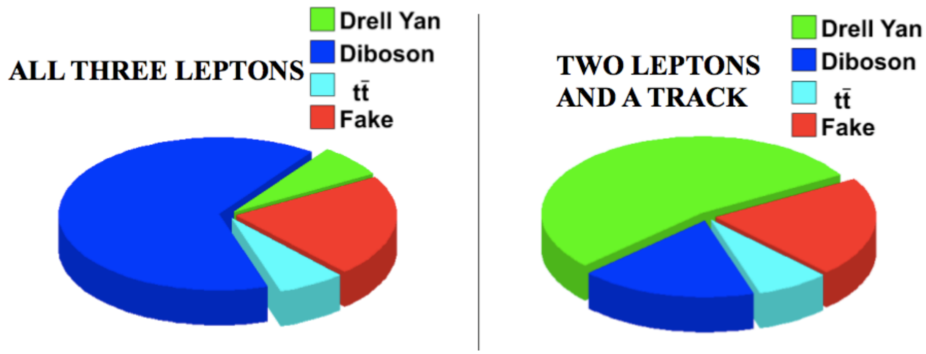
Search for Charginos/Neutralinos at CDF

- Decay via virtual W, Z, or sleptons.
- Observe 3 leptons, MET from decay of Chargino ($\chi^{\pm}{}_1$) and next-to-lightest Neutralino($\chi^0{}_2$)

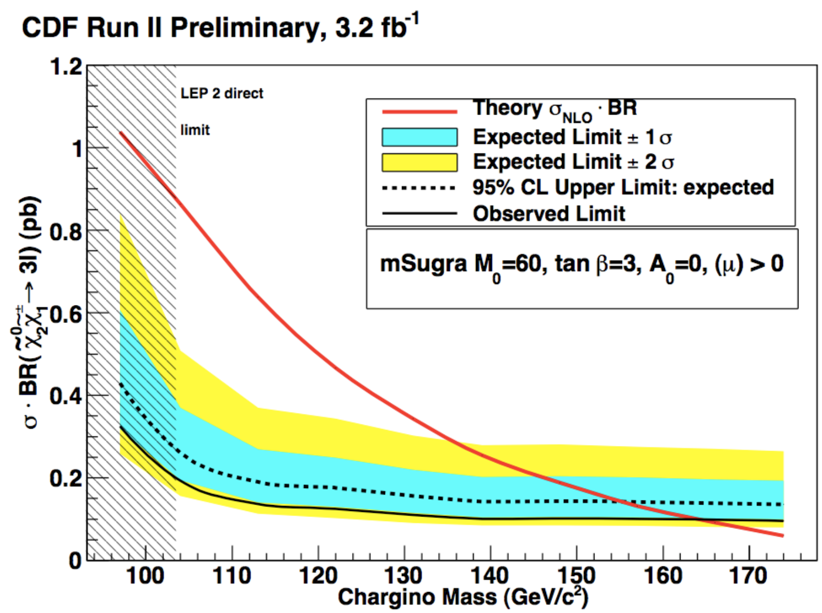


Search for Charginos/Neutralinos at CDF

Process	σ(bkg)/σ(sig)	What it has	What it needs
WZ		3 leptons + MET	-
ZZ	~ 1	≥ 3 leptons	MET
WW		2 leptons + MET	one lepton
Top-pair	~ 10	3 leptons + MET	-
DY	~ 1000	2 leptons	one lepton + MET
Zγ→llγ	~ 30	≥ 3 leptons	MET
W	~ 5000	1 lepton + MET	two leptons



CDF ($3.2\ fb^{-1}$)	Expected	Observed
3-leptons	1.5 ± 0.2	1
3-leptons+track	9.4 ± 1.4	6



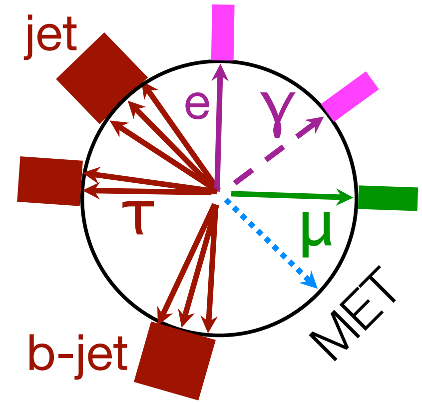
Other Tevatron Searches

- Too many to go into details (or even list them all!) Partial list of searches:
  - Scalar Top
  - Scalar Bottom
  - Leptoquarks
  - Large Extra Dimensions
  - High-Mass resonances
  - New or Excited Fermions
  - Technicolor
  - Anomalous production of exotic signatures (e.g. MET + γ + b-jet)
- The SM Higgs is only one particle we're looking for.

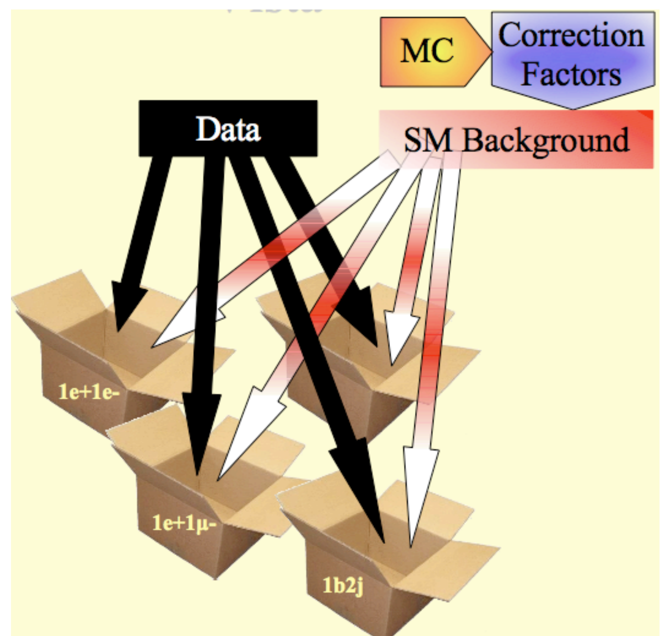
Model-Independent Global Searches

- Idea: Can't we try to model all the data all at once?
- Very ambitious. CDF and D0 have done this.

“Model Independent Algorithmic”



- Classify events by their object content (final state)
- Simulate standard model with Monte Carlo
- Global fit to extract correction factors (luminosity, k-factors, mis-id rates, trigger efficiencies, jet energy scale)
- Look for anomalies in distributions (bulk)
- Look for excesses in high sum E_T distributions
  - Assumes NP will be at high sum E_T and appear as an excess
- Order final states by how discrepant they are
  - Flag interesting states for further study
- Iterative procedure to identify and account for detector effects
- Sensitivity to new physics depends on details of final state
- Provides a safety net to avoid missing the obvious
- CDF has a 2 fb^{-1} result, D0 has a 1 fb^{-1} result.



Model-Independend Algorithmic: Standard Model MC Cocktail

Dataset	Process	Weights *	Number =	Total weight
pyth_jj_000	Pythia jj 0<pT<10	1000	2	2055.45
pyth_pj_008	Pythia gamma j 8<pT<12	350	3	1038.11
pyth_jj_010	Pythia jj 10<pT<18	95	144	13744.8
mrenna_e-ve-	MadEvent W(->ev)	15	424	6294.31
mrenna_e+ve	MadEvent W(->ev)	15	404	5984.59
mrenna_mu-vm-	MadEvent W(->muv)	13	301	3967.26
mrenna_mu+vm	MadEvent W(->muv)	13	293	3852.91
pyth_jj_090	Pythia jj 90<pT<120	12	1791	21573.4
pyth_jj_018	Pythia jj 18<pT<40	11	22381	255804
pyth_pj_012	Pythia gamma j 12<pT<22	9.9	2243	22195.4
mad_e+ve	MadEvent W(->ev)	6.6	34	225.49
mad_veve-j	MadEvent Z(->vv) j	6.3	5	31.3
mrenna_mu+mu-	MadEvent Z(->mumu)	6.2	601	3704.11
mad_mu+vm	MadEvent W(->muv)	5.9	21	123.2
mad_vtvt-j	MadEvent Z(->vv) j	5.7	5	28.58
mad_e-ve-	MadEvent W(->ev)	5.7	47	268.52
mrenna_e+e-	MadEvent Z(->ee)	5.4	4884	26259.6
mad_mu-vm-	MadEvent W(->muv)	5.3	20	105.76
pyth_jj_120	Pythia jj 120<pT<150	5	2782	13967.2
cosmic_j_lo	Cosmic (jet20)	4.7	92	428.91
pyth_bj_010	Pythia bj 10<pT<18	3.3	137	458.81
pyth_jj_060	Pythia jj 60<pT<90	3.1	25066	76827.8
mrenna_mu+vmj	MadEvent W(->muv) j	2.4	8262	19519.6
mrenna_mu-vm-j	MadEvent W(->muv) j	2.4	8246	19468.7
mrenna_mu+mu-j	MadEvent Z(->mumu) j	2.3	5053	11585
cosmic_ph	Cosmic (photon_25_iso)	2.2	1136	2501.8
pyth_jj_040	Pythia jj 40<pT<60	2	112425	227788
pyth_jj_200	Pythia jj 200<pT<300	1.7	72266	119638
sewkad	Pythia W(->ev)	1.5	304263	458816
mrenna_e+vej	MadEvent W(->ev) j	1.5	25313	37338.1
mrenna_e-ve-j	MadEvent W(->ev) j	1.5	25298	37297.8
pyth_pj_022	Pythia gamma j 22<pT<45	1.4	28761	39696.7
pyth_jj_150	Pythia jj 150<pT<200	1.2	63063	78705.9
pyth_pj_080	Pythia gamma j 80<pT	0.93	15891	14749.8
mad_e+e-jj	MadEvent Z(->ee) jj	0.92	505	464.88
pyth_pj_045	Pythia gamma j 45<pT<80	0.76	69834	53036.9
mrenna_e+vejj	MadEvent W(->ev) jj	0.74	17218	12819.9
mrenna_e-ve-jj	MadEvent W(->ev) jj	0.74	17221	12816.9
pyth_bj_018	Pythia bj 18<pT<40	0.67	14722	9932.61
mrenna_mu+vmjj	MadEvent W(->muv) jj	0.64	10151	6481.97
mrenna_mu-vm-jj	MadEvent W(->muv) jj	0.64	10162	6487.74
mad_vtvt-j_f	MadEvent Z(->vv) j	0.62	10	6.22
pyth_bj_060	Pythia bj 60<pT<90	0.58	8089	4658.75
mad_e-ve-jj	MadEvent W(->ev) jj	0.56	278	154.63
mrenna_e+e-j	MadEvent Z(->ee) j	0.55	34874	19320.7
mad_e-ve-j	MadEvent W(->ev) j	0.54	305	164.93
mad_e+e-	MadEvent Z(->ee)	0.5	1076	534.77
mad_mu-vm-j	MadEvent W(->muv) j	0.49	198	97.19
mad_mu-vm-jj	MadEvent W(->muv) jj	0.49	236	115.06
mad_veve-j_f	MadEvent Z(->vv) j	0.45	11	4.93
mrenna_e+e-jj	MadEvent Z(->ee) jj	0.44	11265	5006.31
pyth_bj_090	Pythia bj 90<pT<120	0.43	2219	964.7
mad_mu+mu-	MadEvent Z(->mumu)	0.43	616	266.71
mad_vtvt-a_f	MadEvent Z(->vv) gamma	0.43	39	16.66
mad_veve-a_f	MadEvent Z(->vv) gamma	0.41	38	15.69
tewk1e	Pythia Z(->ee)	0.41	151898	62592.4
cosmic_j_hi	Cosmic (jet100)	0.4	10416	4195.08
mrenna_mu+mu-jj	MadEvent Z(->mumu) jj	0.39	6047	2357.39
pyth_bj_120	Pythia bj 120<pT<150	0.34	2751	940.23
mad_aaj	MadEvent gamma gamma j	0.32	593	190.3
wewk9t	Pythia W(->tau v)	0.31	76188	23358.7
wewk7m	Pythia W(->mu v)	0.27	329003	89354
wexo0m	Pythia W(->mu v)	0.24	360137	88144.3
mad_e+vej	MadEvent W(->ev) j	0.23	755	175.32
mad_mu+vmj	MadEvent W(->muv) j	0.2	549	108.77
pyth_bj_040	Pythia bj 40<pT<60	0.19	53968	10099.4
mad_e+e-j	MadEvent Z(->ee) j	0.18	751	138.04
hewk09	MadEvent W(->ev) gamma	0.16	16596	2737.64
mad_e+vejj	MadEvent W(->ev) jj	0.16	956	155.72
mad_mu+mu-j	MadEvent Z(->mumu) j	0.16	516	81.29
mad_mu+mu-jj	MadEvent Z(->mumu) jj	0.16	1758	276.94
mad_mu+vmjj	MadEvent W(->muv) jj	0.15	753	111.7
pyth_bj_150	Pythia bj 150<pT<200	0.15	29350	4352
mad_vtvt-a	MadEvent Z(->vv) gamma	0.15	122	17.94
mad_veve-a	MadEvent Z(->vv) gamma	0.15	123	17.96
hewk0a	MadEvent W(->muv) gamma	0.14	10254	1460.67
we0s8m	Pythia W(->mu v)	0.14	712708	97780.9
mrenna_e+vejjj	MadEvent W(->ev) jjj	0.13	15317	1937.54
mrenna_e-ve-jjj	MadEvent W(->ev) jjj	0.13	15365	1943.02
pyth_pp	Pythia gamma gamma	0.13	35980	4545.46
mad_e+e-b-b	MadEvent Z(->ee) bb	0.12	970	113.96
mrenna_mu-vm-jjj	MadEvent W(->muv) jjj	0.11	8462	965.16
mrenna_mu+vmjjj	MadEvent W(->muv) jjj	0.11	8455	963.69
mad_aajj	MadEvent gamma gamma jj	0.11	8032	875.83
mad_mu+mu-b-b	MadEvent Z(->mumu) bb	0.1	495	49.45
wenubb0p	Alpgen W(->ev) bb	0.096	5240	503.62
ztopcz	Pythia ZZ	0.091	577	52.72
mad_aaa_f	MadEvent gamma gamma gamma	0.09	51	4.6
pyth_jj_300	Pythia jj 300<pT<400	0.077	92271	7129.41
mad_aaa	MadEvent gamma gamma gamma	0.075	43	3.23
tewk1m	Pythia Z(->mu mu)	0.075	654354	49056.2
wmnubb0p	Alpgen W(->mu v) bb	0.075	3289	246.14
pyth_bj_200	Pythia bj 200<pT<300	0.075	99577	7428.85
hewk03	MadEvent Z(->ee) gamma	0.074	40797	3006.46
zewk9t	Pythia Z(->tau tau)	0.073	15963	1173.26
overlay	Overlaid events	0.073	5050	366.9
wenubb1p	Alpgen W(->ev) bb j	0.072	3370	244.18
wmnubb1p	Alpgen W(->mu v) bb j	0.072	1649	118.25
hewk04	MadEvent Z(->mumu) gamma	0.071	802	57.07
pyth_jj_400	Pythia jj 400<pT	0.069	6240	427.7
mrenna_mu+mu-jjj	MadEvent Z(->mumu) jjj	0.066	10159	669.53
wenubb2p	Alpgen W(->ev) bb jj	0.064	1014	64.82
wmnubb2p	Alpgen W(->mu v) bb jj	0.064	505	32.09
mrenna_e+e-jjj	MadEvent Z(->ee) jjj	0.063	22291	1405.92
wewk6d	Pythia WZ	0.055	2016	110.92
mrenna_e+vejjjj	MadEvent W(->ev) jjjj	0.053	7006	370.64
mrenna_e-ve-jjjj	MadEvent W(->ev) jjjj	0.053	6998	369.98
mrenna_mu-vm-jjjj	MadEvent W(->muv) jjjj	0.051	3646	185.71
mrenna_mu+vmjjjj	MadEvent W(->muv) jjjj	0.051	3609	183.68
ttop0z	Herwig ttbar	0.05	17452	878.99
sewkcd	Pythia WW	0.049	2204	108.67
Total:				2.13365e+06

Model-Independent Algorithmic: Correction Factors

CDF Run II Preliminary (2.0 fb^{-1})

Code	Category	Explanation	Value	Error	Error(%)
0001	luminosity	CDF integrated luminosity	1990	50	2.6
0002	k-factor	cosmic_ph	0.83	0.05	6.0
0003	k-factor	cosmic_j	0.192	0.006	3.1
0004	k-factor	$1\gamma 1j$ photon+jet(s)	0.92	0.04	4.4
0005	k-factor	$1\gamma 2j$	1.26	0.05	4.0
0006	k-factor	$1\gamma 3j$	1.61	0.08	5.0
0007	k-factor	$1\gamma 4j+$	1.94	0.16	8.3
0008	k-factor	$2\gamma 0j$ diphoton(+jets)	1.6	0.08	5.0
0009	k-factor	$2\gamma 1j$	2.99	0.17	5.7
0010	k-factor	$2\gamma 2j+$	1.2	0.09	7.5
0011	k-factor	W0j W (+jets)	1.38	0.03	2.2
0012	k-factor	W1j	1.33	0.03	2.3
0013	k-factor	W2j	1.99	0.05	2.5
0014	k-factor	W3j+	2.11	0.09	4.3
0015	k-factor	Z0j Z (+jets)	1.39	0.028	2.0
0016	k-factor	Z1j	1.23	0.04	3.2
0017	k-factor	Z2j+	1.02	0.04	3.9
0018	k-factor	2j $\hat{p}_T < 150$ dijet	1.003	0.027	2.7
0019	k-factor	2j $150 < \hat{p}_T$	1.34	0.03	2.2
0020	k-factor	3j $\hat{p}_T < 150$ multijet	0.941	0.025	2.7
0021	k-factor	3j $150 < \hat{p}_T$	1.48	0.04	2.7
0022	k-factor	4j $\hat{p}_T < 150$	1.06	0.03	2.8
0023	k-factor	4j $150 < \hat{p}_T$	1.93	0.06	3.1
0024	k-factor	5j low	1.33	0.05	3.8
0025	k-factor	1b2j $150 < \hat{p}_T$	2.22	0.11	5.0
0026	k-factor	1b3j $150 < \hat{p}_T$	2.98	0.15	5.0
0027	misId	$p(e \to e)$ central	0.978	0.006	0.6
0028	misId	$p(e \to e)$ plug	0.966	0.007	0.7
0029	misId	$p(\mu \to \mu)$ CMUP+CMX	0.888	0.007	0.8
0030	misId	$p(\gamma \to \gamma)$ central	0.949	0.018	1.9
0031	misId	$p(\gamma \to \gamma)$ plug	0.859	0.016	1.9
0032	misId	$p(b \to b)$ central	0.978	0.021	2.1
0033	misId	$p(\gamma \to e)$ plug	0.06	0.003	5.0
0034	misId	$p(q \to e)$ central	7.09×10^{-5}	1.9×10^{-6}	2.7
0035	misId	$p(q \to e)$ plug	0.000766	1.2×10^{-5}	1.6
0036	misId	$p(q \to \mu)$	1.14×10^{-5}	6×10^{-7}	5.2
0037	misId	$p(b \to \mu)$	3.3×10^{-5}	1.1×10^{-5}	33.0
0038	misId	$p(j \to b)$ $25 < p_T$	0.0183	0.0002	1.1
0039	misId	$p(q \to \tau)$	0.0052	0.0001	1.9
0040	misId	$p(q \to \gamma)$ central	0.000266	1.4×10^{-5}	5.3
0041	misId	$p(q \to \gamma)$ plug	0.00048	6×10^{-5}	12.6
0042	trigger	$p(e \to trig)$ plug, $p_T > 25$	0.86	0.007	0.8
0043	trigger	$p(\mu \to trig)$ CMUP+CMX, $p_T > 25$	0.916	0.004	0.4

MC Mis-Id Study

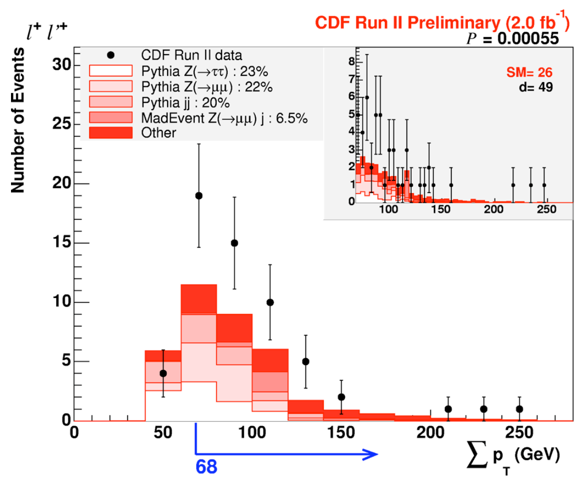
TABLE XXIII: Central single particle misidentification matrix. Using a single particle gun, 10^5 particles of each type shown at the left of the table are shot with $p_T = 25$ GeV into the central CDF detector, uniformly distributed in θ and in ϕ. The resulting reconstructed object types are shown at the top of the table, labeling the table columns. Thus the rightmost element of this matrix in the fourth row from the bottom shows $p(\tau^- \to j)$, the number of negatively charged tau leptons (out of 10^5) reconstructed as a jet.

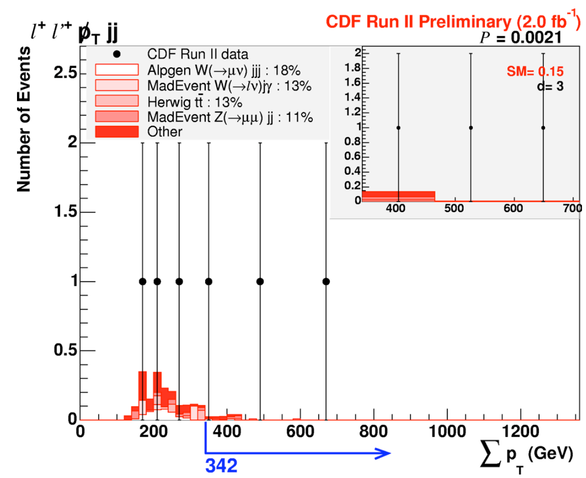
	e^+	e^-	μ^+	μ^-	τ^+	τ^-	γ	j	b
e^+	62228	33	0	0	182	0	2435	28140	0
e^-	24	62324	0	0	0	192	2455	28023	1
μ^+	0	0	50491	0	6	0	0	606	0
μ^-	0	1	0	50294	0	6	0	577	0
γ	1393	1327	0	0	1	1	67679	21468	0
π^0	1204	1228	0	0	5	8	58010	33370	0
π^+	266	0	115	0	41887	6	95	54189	37
π^-	1	361	0	88	13	41355	148	54692	44
K^+	156	1	273	0	42725	7	37	52317	24
K^-	1	248	0	165	28	41562	115	53917	22
B^+	100	0	77	1	100	10	40	66062	25861
B^-	2	85	3	68	11	99	45	66414	25621
B^0	88	27	87	17	77	32	21	65866	25046
$\bar{B}^0$	17	79	11	71	41	77	21	66034	25103
D^+	126	6	62	0	1485	67	207	79596	11620
D^-	4	134	3	74	64	1400	234	79977	11554
D^0	60	13	27	2	312	1053	248	88821	5487
$\bar{D}^0$	15	46	5	28	1027	253	237	89025	5480
K_L^0	1	4	0	0	71	60	202	96089	26
K_S^0	26	31	2	1	170	525	9715	76196	0
τ^+	1711	13	1449	0	4167	2	673	50866	607
τ^-	12	1716	0	1474	6	3940	621	51125	580
u	8	10	1	0	446	31	247	94074	26
d	3	4	0	0	64	308	191	94322	22
g	2	0	0	0	17	14	12	81865	99

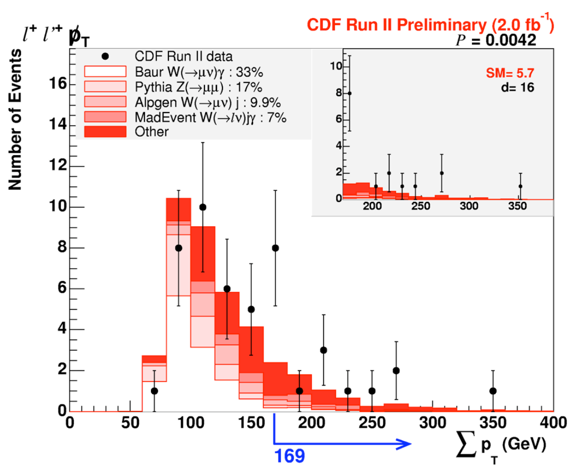
Model-Independent Algorithmic (Vista/Sleuth)

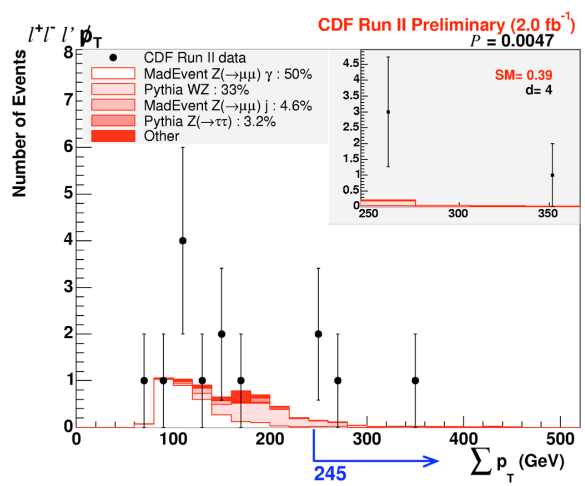
CDF Run II Preliminary (2.0 fb^{-1})

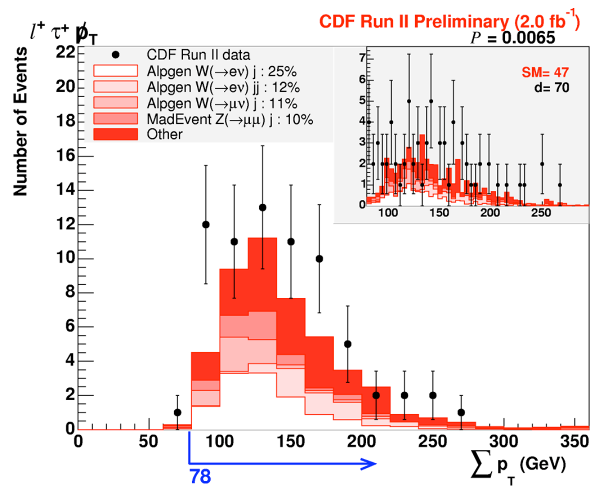
SLEUTH Final State	$\mathcal{P}$
$\ell^+\ell'^+$	0.00055
$\ell^+\ell'^+ \not{p}\, jj$	0.0021
$\ell^+\ell'^+ \not{p}$	0.0042
$\ell^+\ell^-\ell' \not{p}$	0.0047
$\ell^+\tau^+ \not{p}$	0.0065







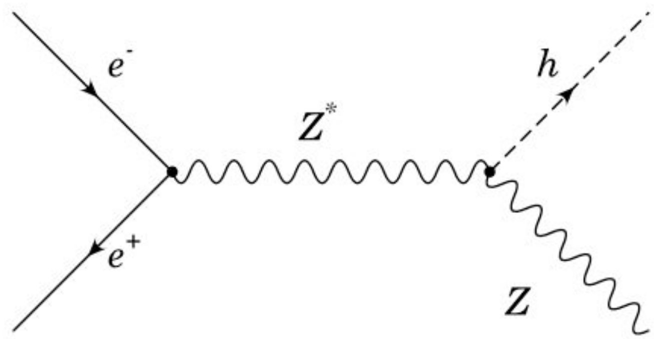




Higgs Boson Searches -- LEP

- Production: $e^+e^- \to Z^0 H$
- Look for “Higgsstrahlung”
- Mass reach limited by beam energies
- Sensitive to Higgs masses up to

$$\approx \sqrt{s} - m_{Z^0}$$

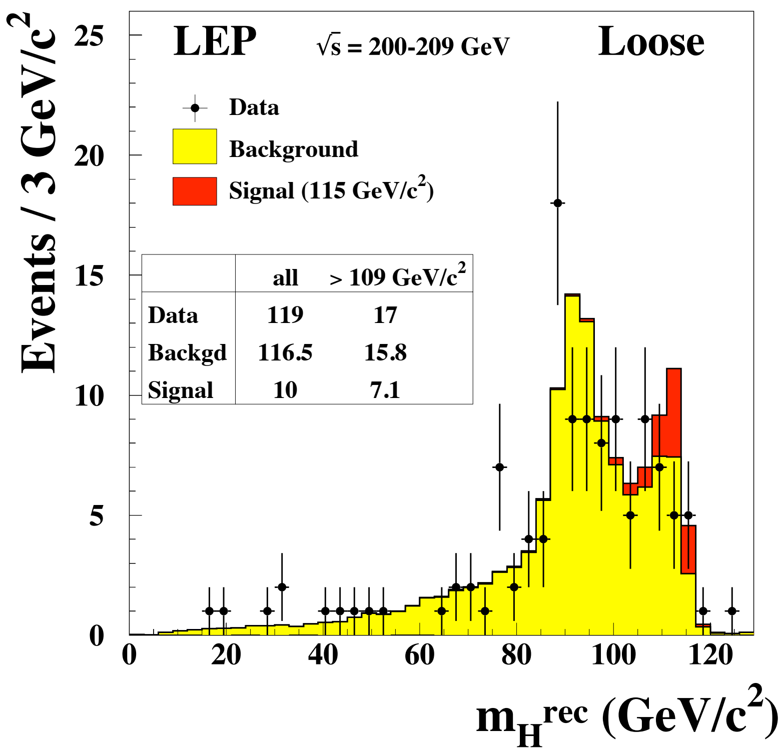


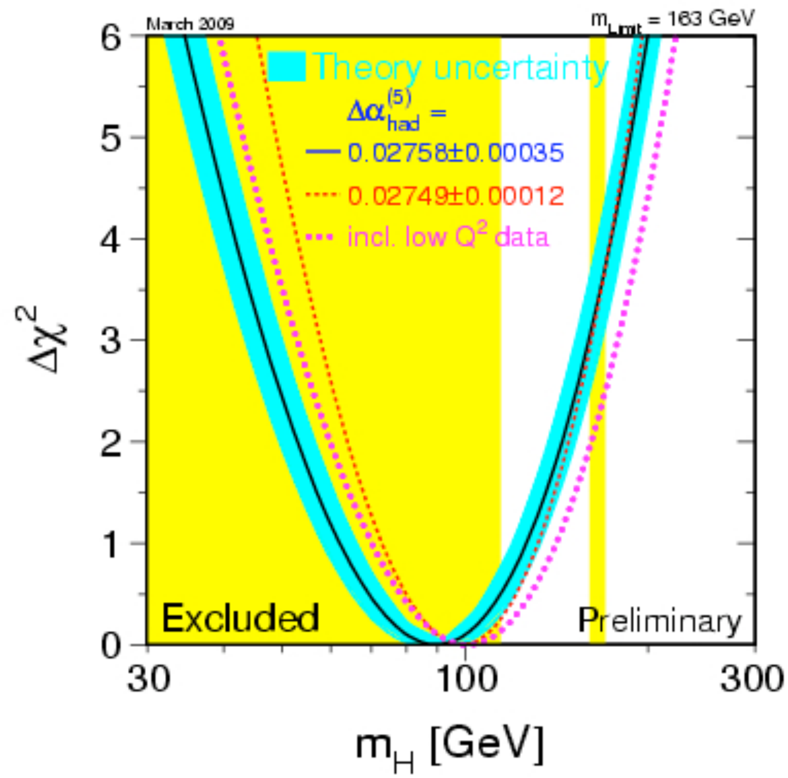
- Four Detectors: ALEPH, DELPHI, L3, OPAL
- Final results combined all detectors, all channels

boson and by those of the associated Z boson. The searches at LEP encompass the four-jet final state (H→b$\bar{b}$)(Z→q$\bar{q}$), the missing energy final state (H→b$\bar{b}$)(Z→$\nu\bar{\nu}$), the leptonic final state (H→b$\bar{b}$)(Z→$\ell^+\ell^-$) where ℓ denotes an electron or a muon, and the tau lepton final states (H→b$\bar{b}$)(Z→$\tau^+\tau^-$) and (H→$\tau^+\tau^-$)(Z→q$\bar{q}$).

- Complicated combination.

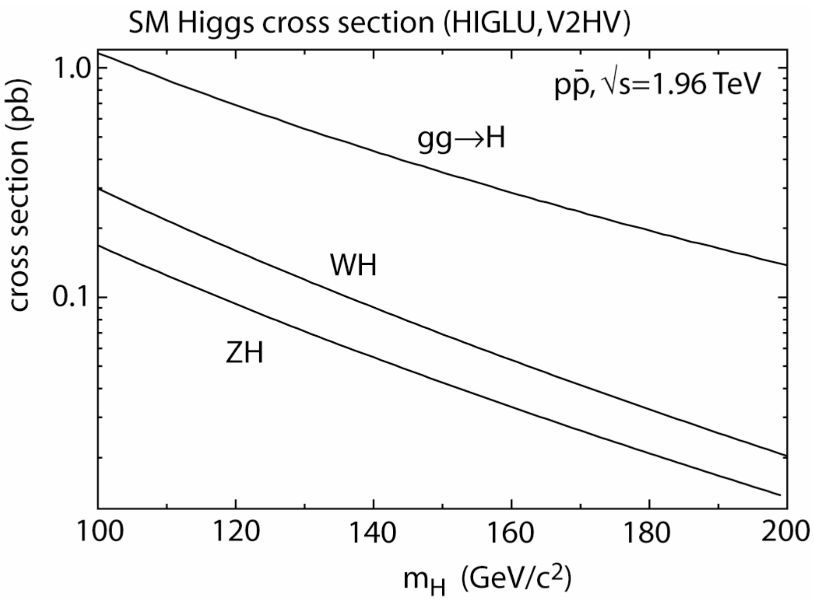
Higgs Searches - LEP

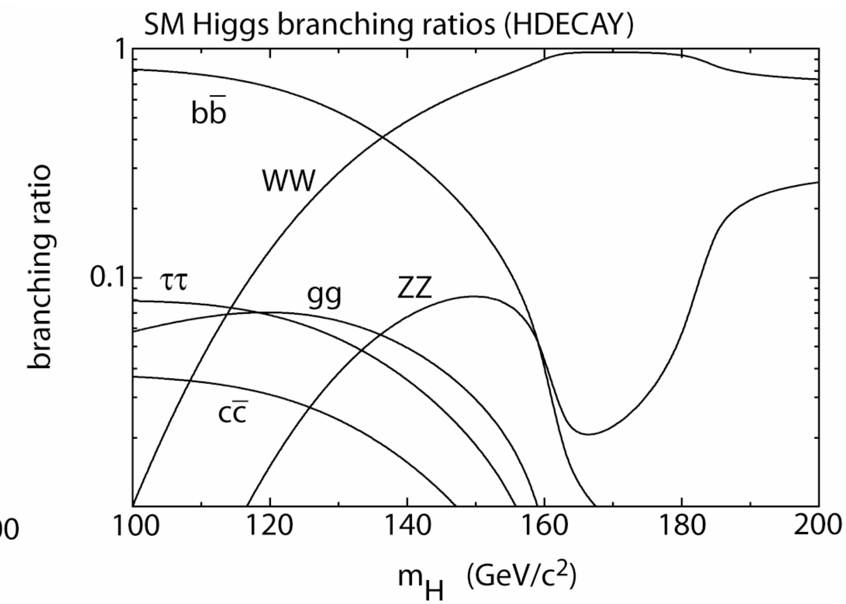




- Standard Model Higgs excluded for m_H < 114.4 GeV.
- Electroweak fit favors a light Higgs Boson.

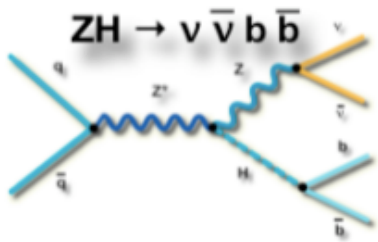
Higgs Boson Production and Decay (2 TeV, p p-bar)

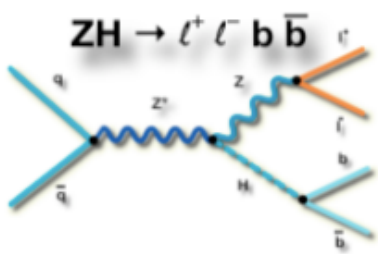


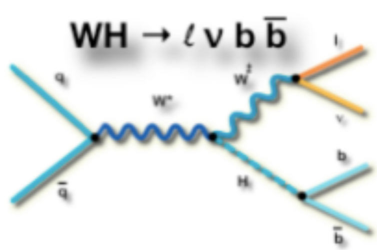


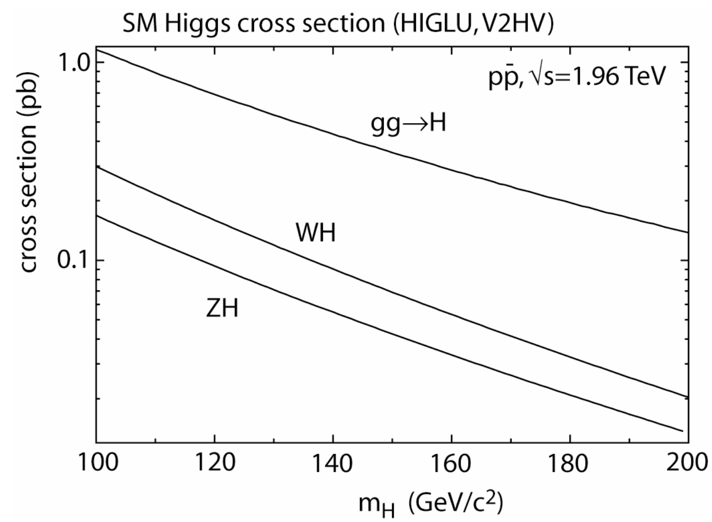
- High-Mass: Look for direct production, WW decays dominate
- Low-Mass: Look for associated production with a W or Z, bb decays dominate
- Hunting for Higgs at the Tevatron is hunting for Di-Bosons

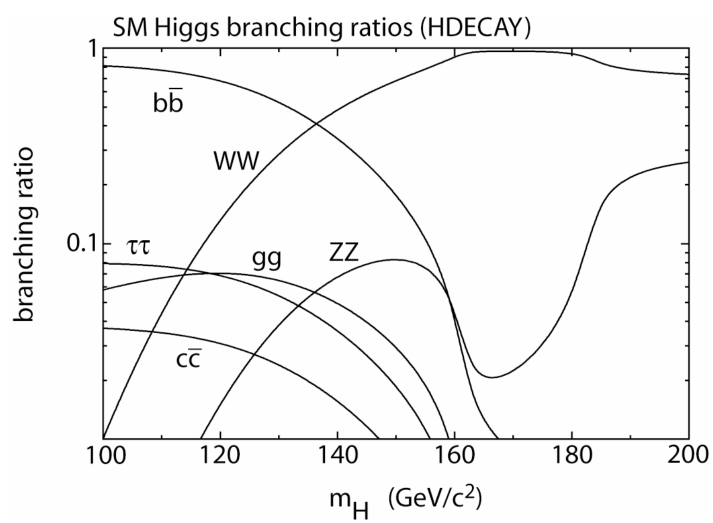
Higgs Boson Searches -- Tevatron

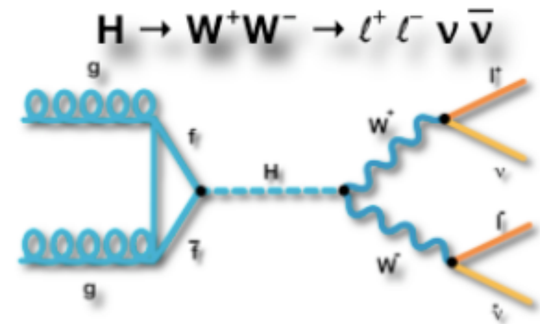






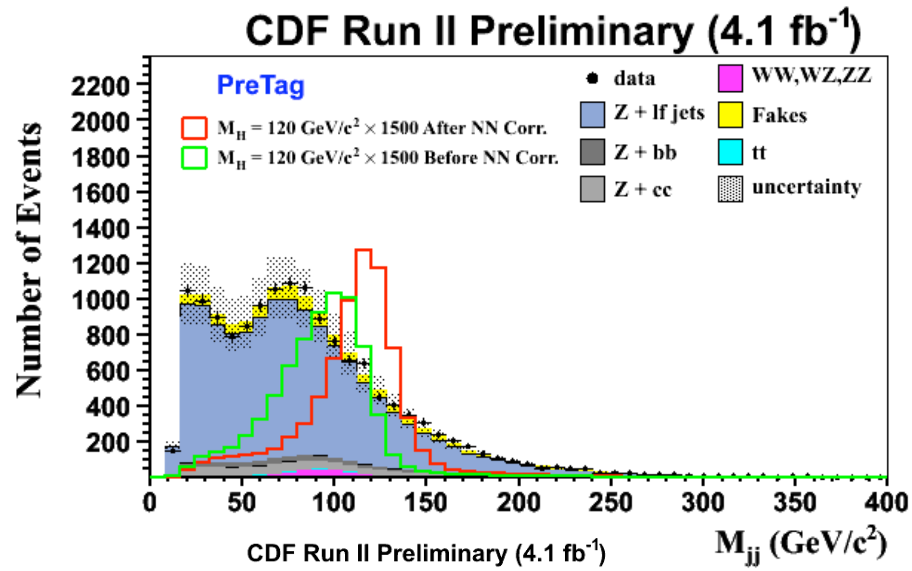


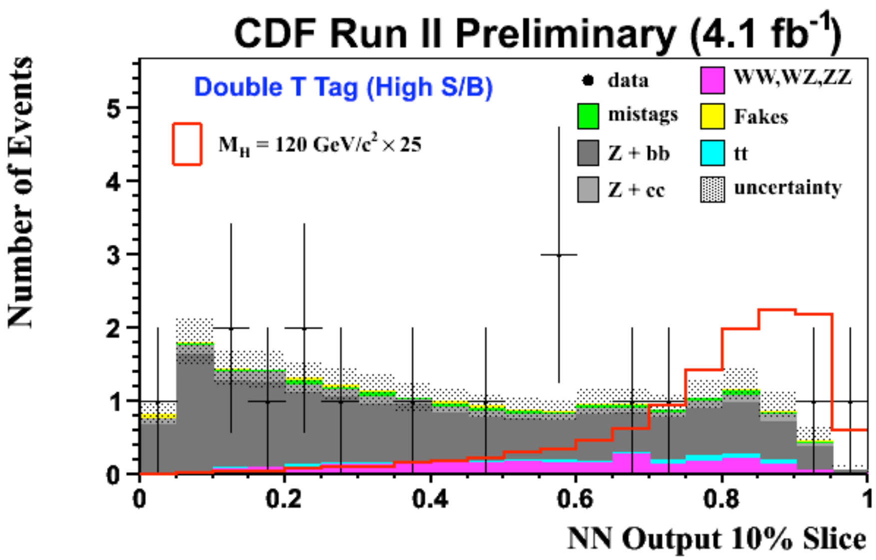


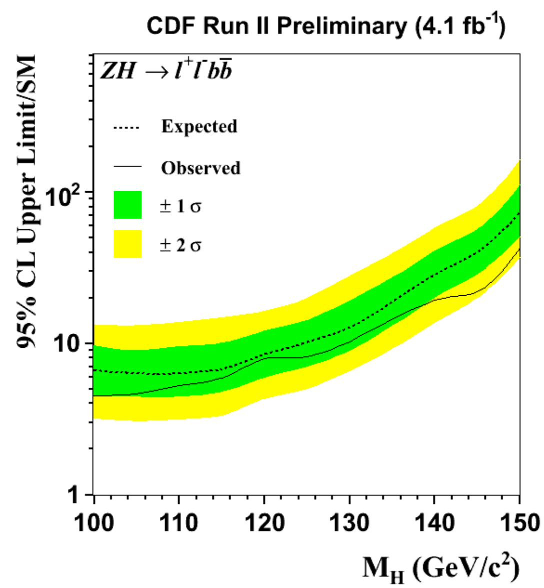


Higgs Search: Low-Mass ZH and WH

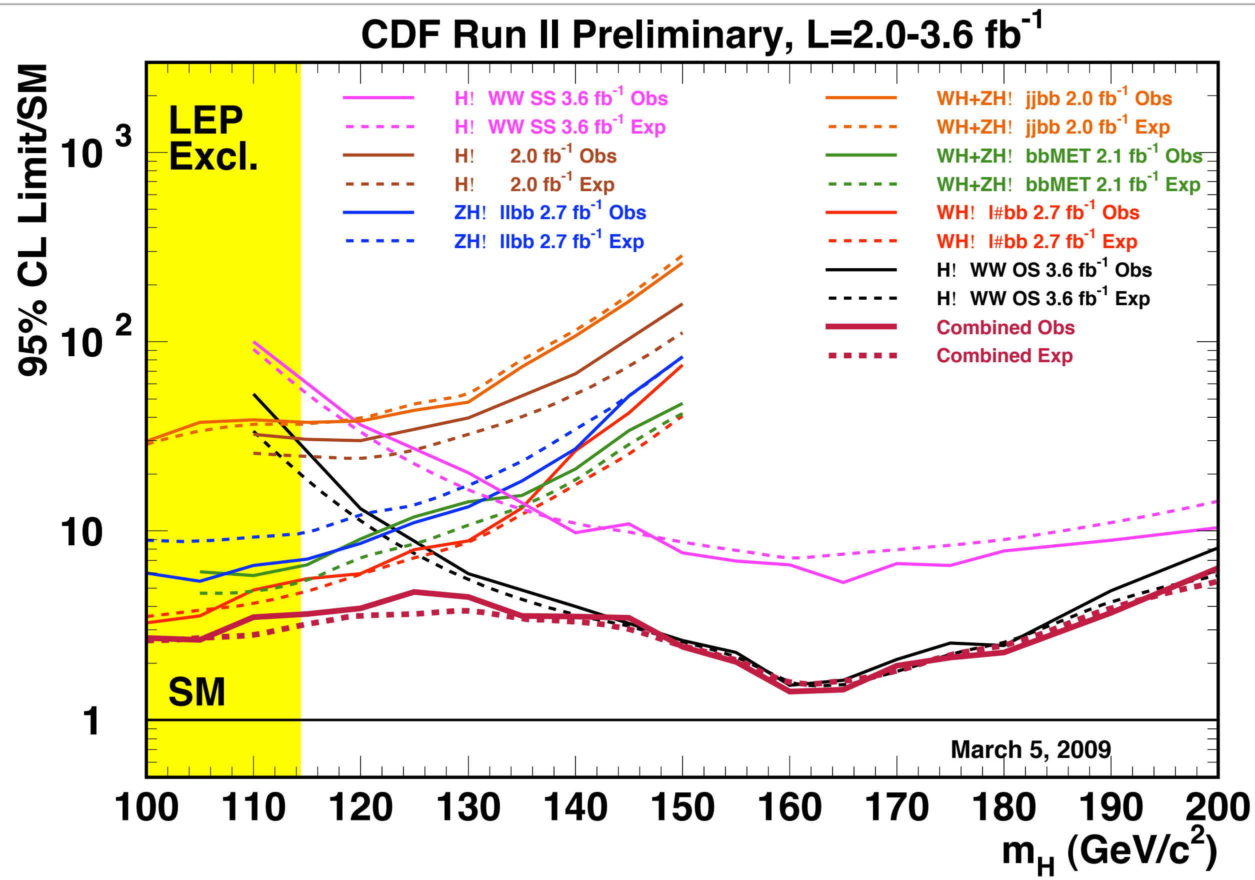
- Reconstruct Z-> ll, Require 2 jets.
- Require one jet have a b-tag
- Jet energies are corrected with a NN
- 2-dimensional NN trained to discriminate from Z+jets, ttbar





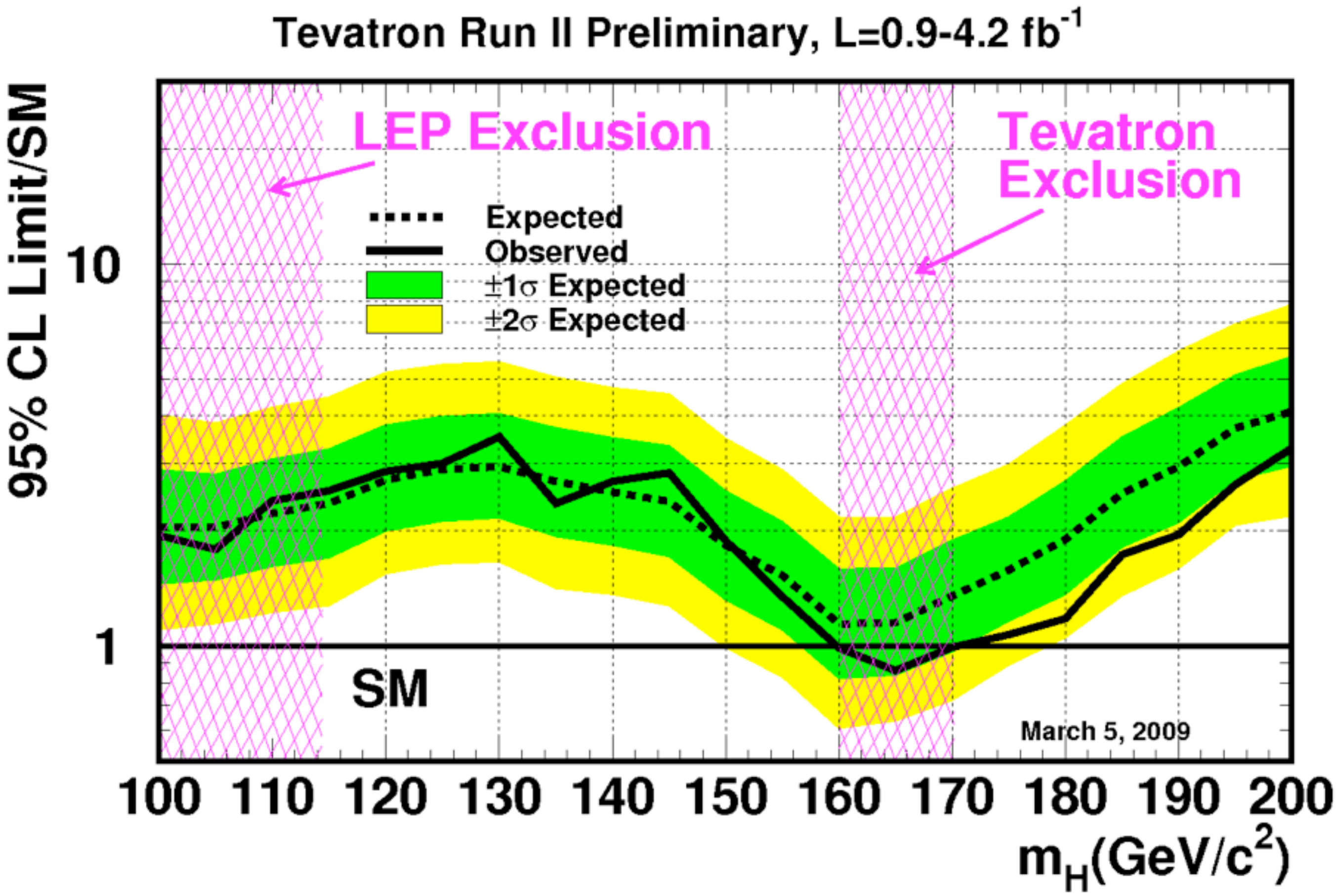


CDF Relative Sensitivity of Channels



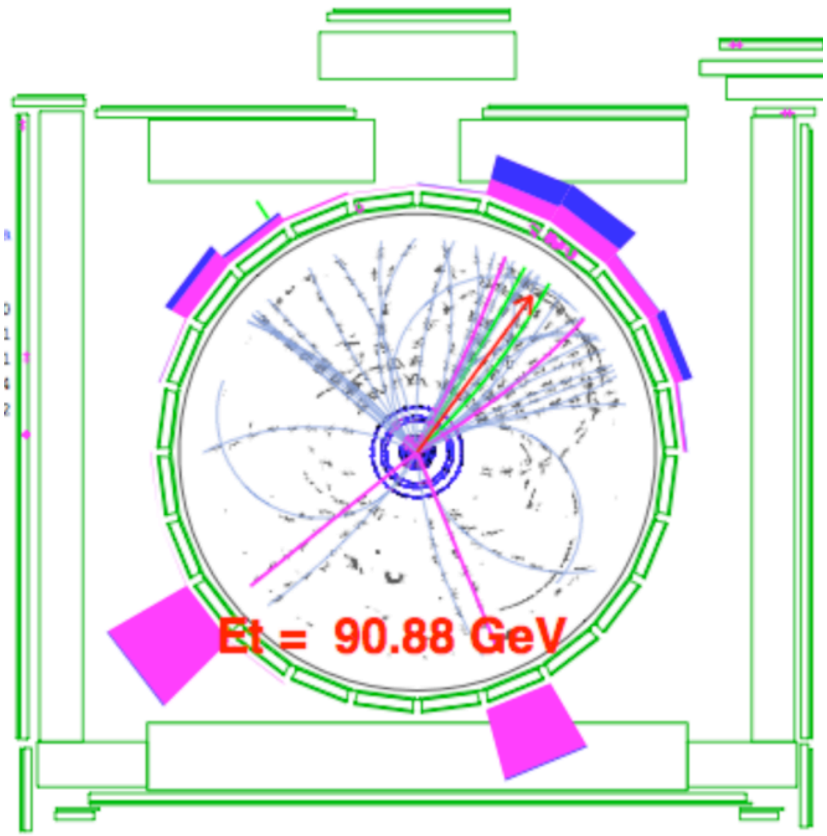
- Favored low-mass region most difficult: Many channels needed.
- Within a factor of 3 of SM over most of mass range.
- D0 results are very similar.

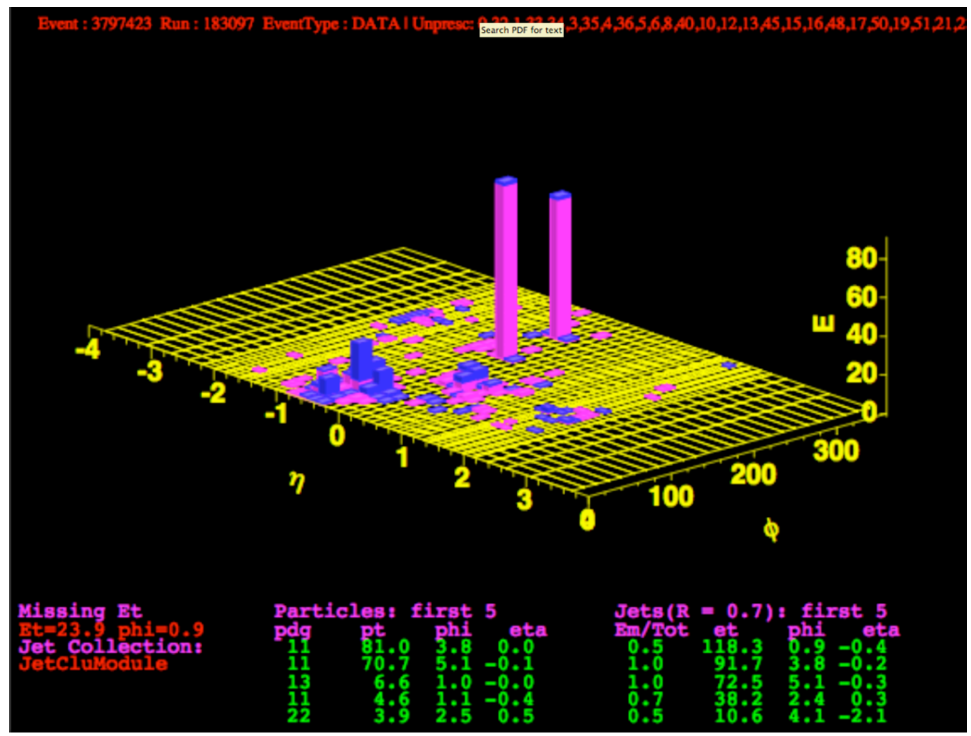
Higgs Limits - Tevatron Combination



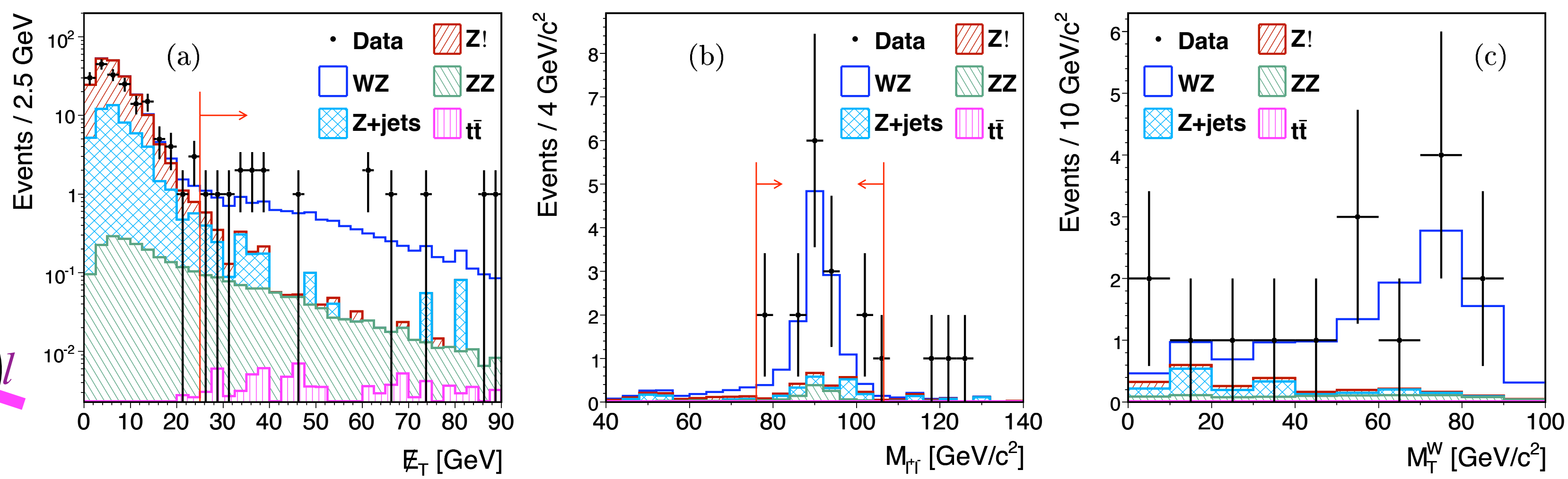
- Expect an update soon with more data

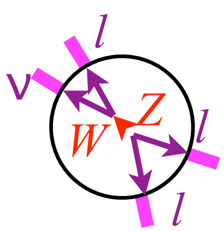
Event Display: A CDF ZH Candidate Event





Other Di-Boson searches: WZ → llν

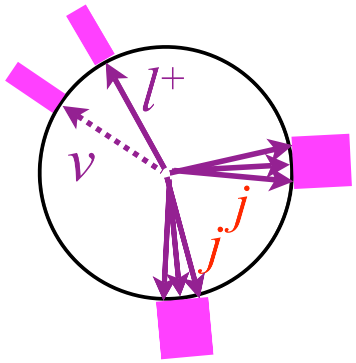




- If we hope to see Higgs, we should be able to see other SM diboson production (higher rates)
- WZ Observation at CDF is a milestone towards Higgs
- Significant improvements in lepton acceptance
- Other diboson milestones underway

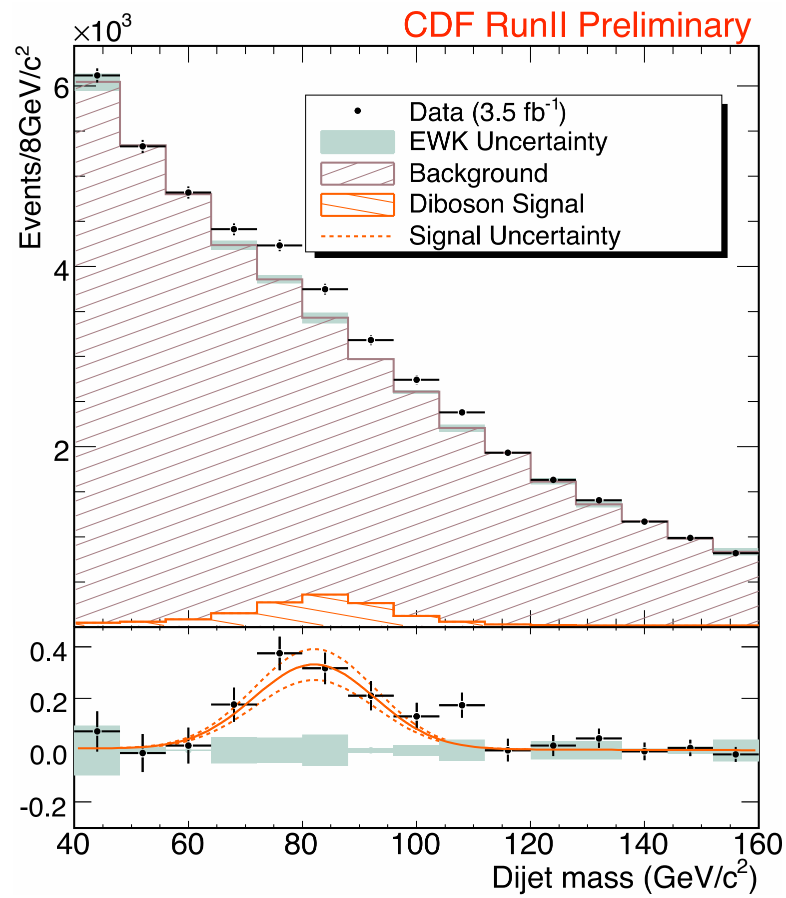
Source	Expectation ± Stat ± Syst ± Lumi
Z+jets	1.21 ± 0.27 ± 0.28 ± –
ZZ	0.88 ± 0.01 ± 0.09 ± 0.05
$Z\gamma$	0.44 ± 0.05 ± 0.15 ± 0.03
$t\bar{t}$	0.12 ± 0.01 ± 0.02 ± 0.01
Total Background	2.65 ± 0.28 ± 0.33 ± 0.09
WZ	9.75 ± 0.03 ± 0.31 ± 0.59
Total Expected	12.41 ± 0.28 ± 0.45 ± 0.67
Observed	16

Milestone on the road to the Higgs: Standard Model EWK DiBosons with Jets

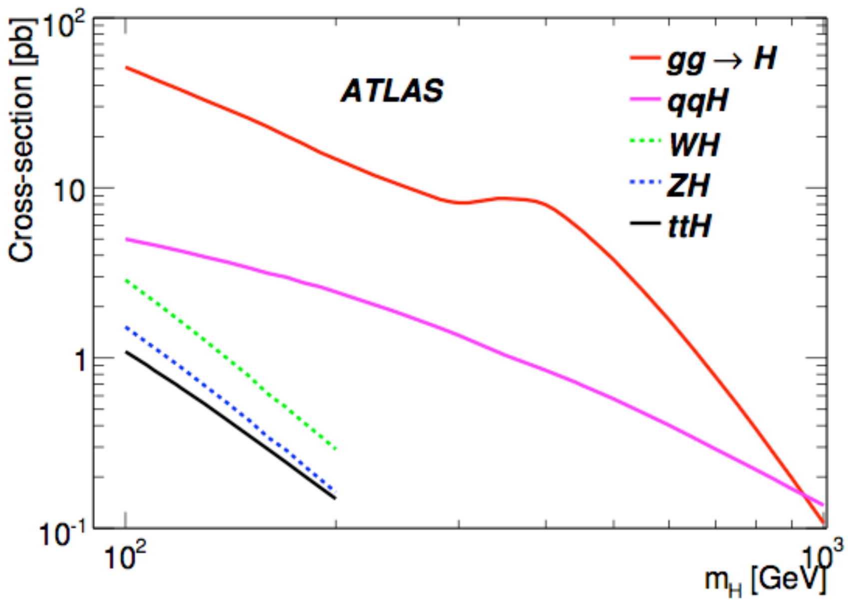


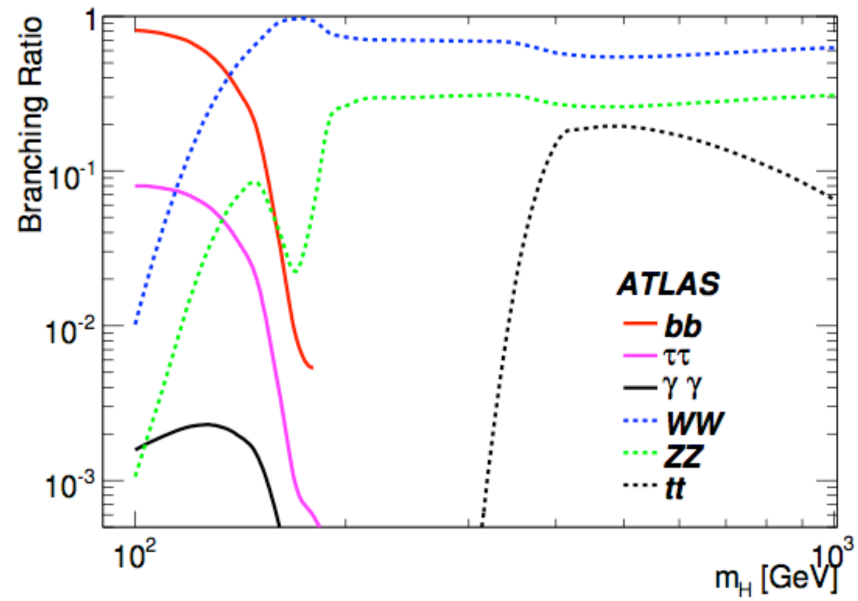
- Electroweak production of WW and WZ, observed in lepton + MET + jet + jet
- Detailed MET model used to reject events with mis-measured MET
- 5.3σ Observation
- Cross section consistent with SM

σ(ppbar→ VV+X) =18±2.8(stat)±2.4(syst)±1.1(lumi) pb



Higgs Production and Decay (14 TeV, pp)

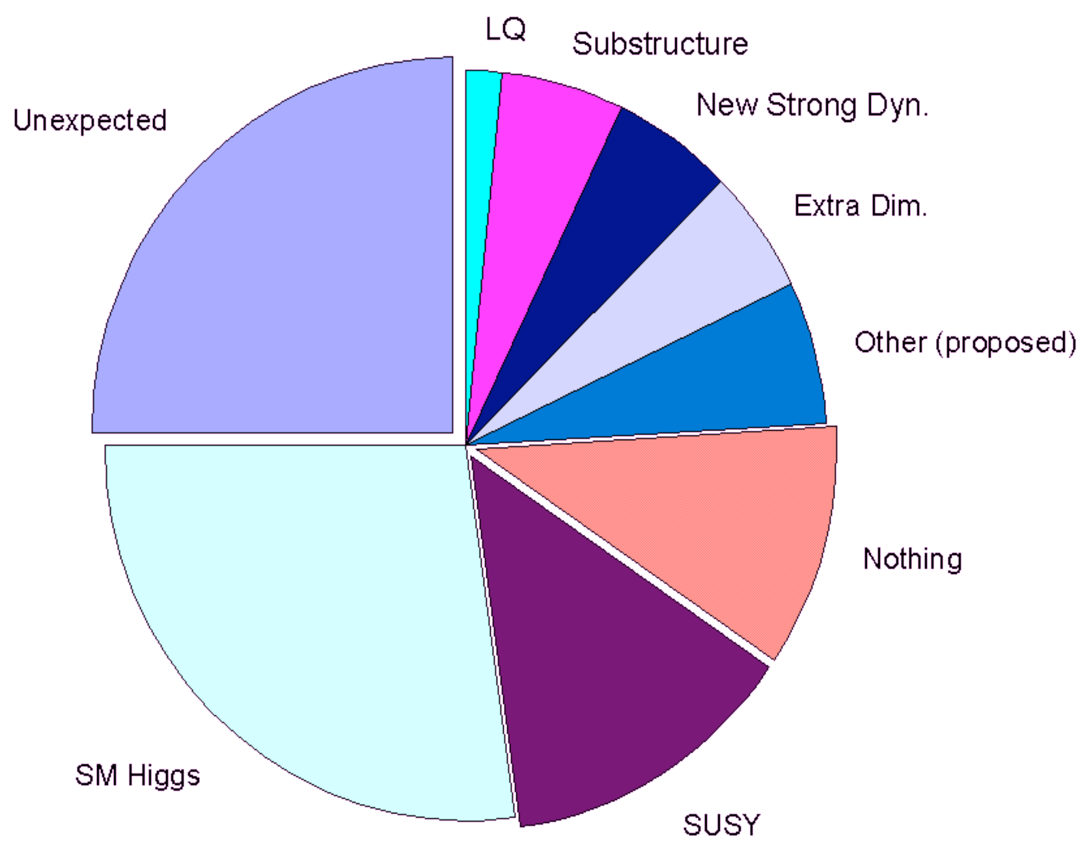




- High Mass: WW and ZZ most promising
- Low Mass: bb is very tough. γγ is clean but requires a lot of data.

"What kind of new physics do you expect to be discovered at the LHC?"

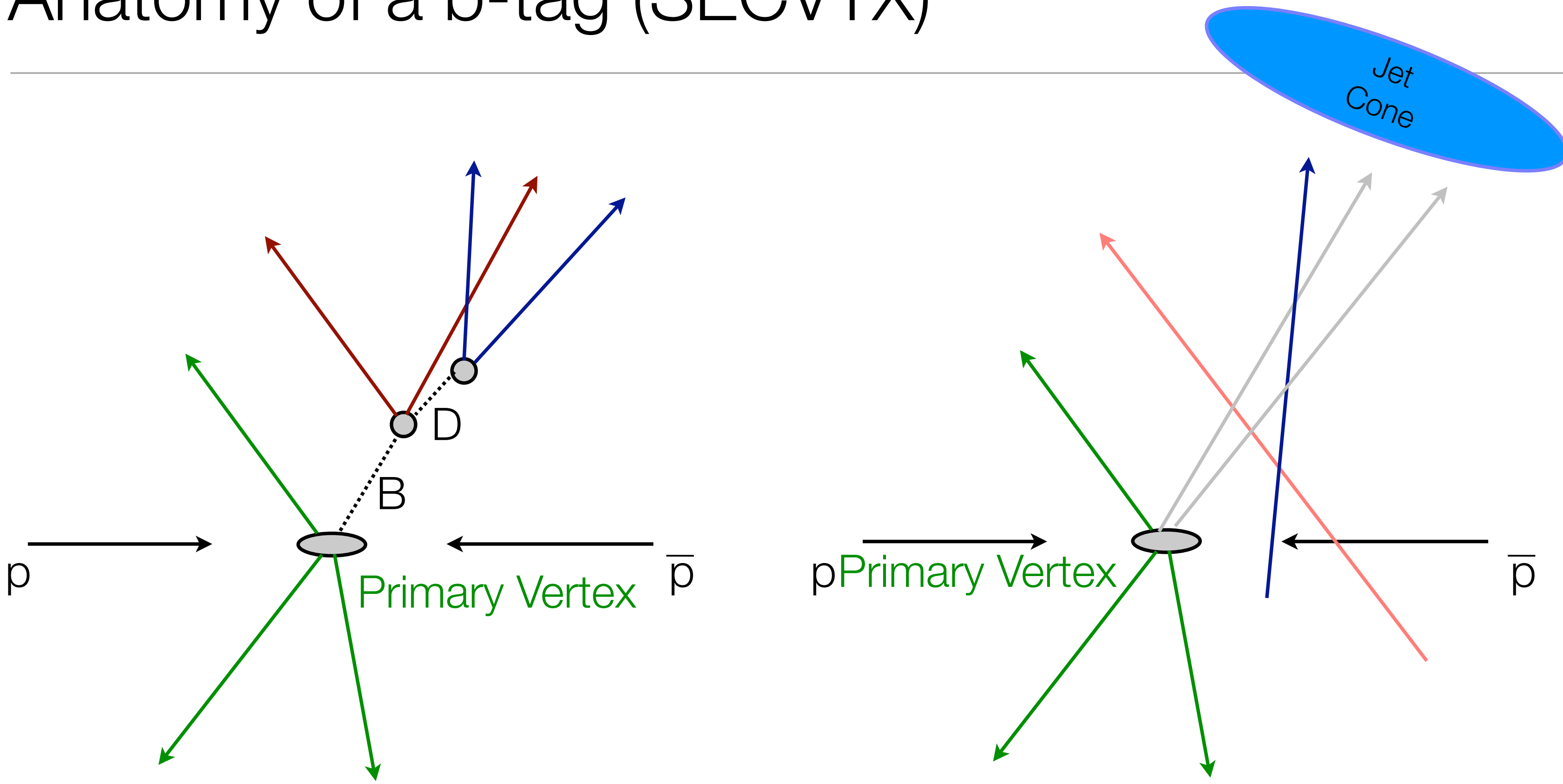
- Poll of 300 people at Fermilab (G. Choudalakis)
- Largest group said: "Higgs"
- Next largest said: "Something we haven't thought of yet"
- Symmetry magazine February 2007
- We expect something
- We don't know what to expect



Summary

- The Tevatron is searching for hints new phenomena in its data.
- The LHC is waiting eagerly for first collision data to explore a new energy regime.
  (and waiting and waiting...)

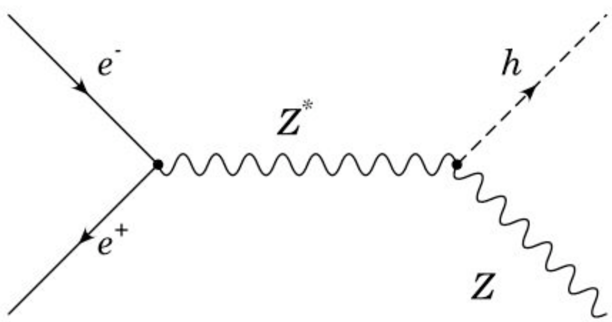
Anatomy of a b-tag (SECVTX)

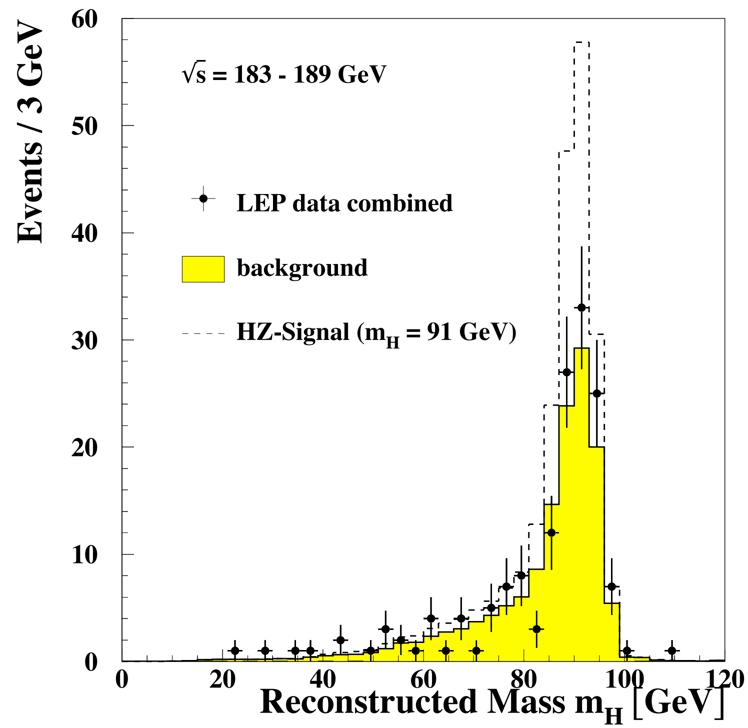


- Efficiency depends on jet E_T, nTracks, cone size, etc.

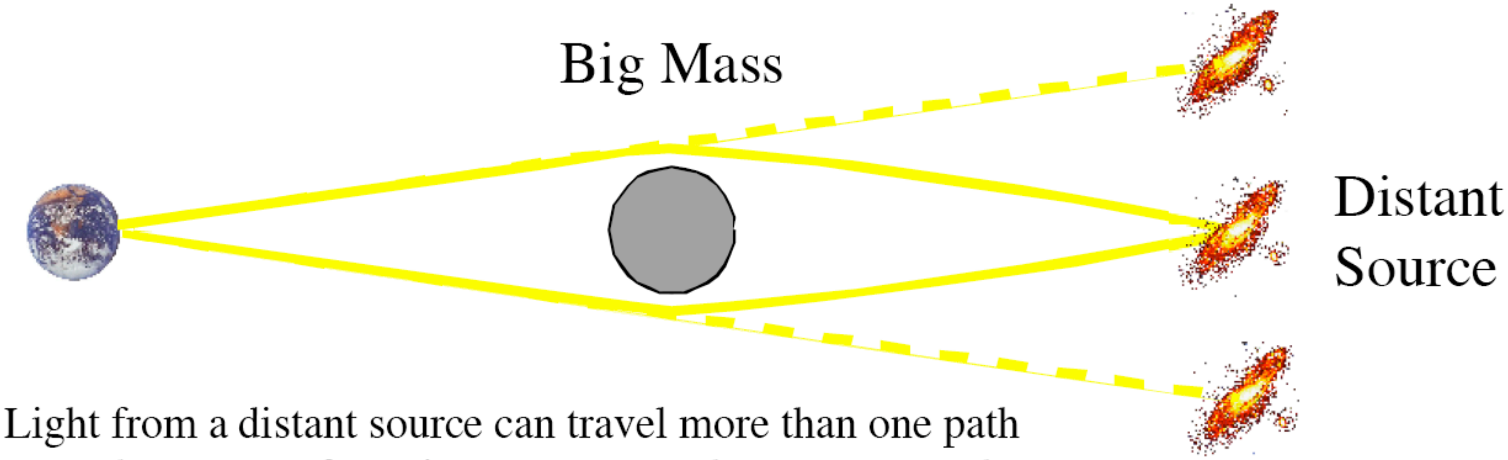
Could the Higgs hide under the Z?

- Nope.





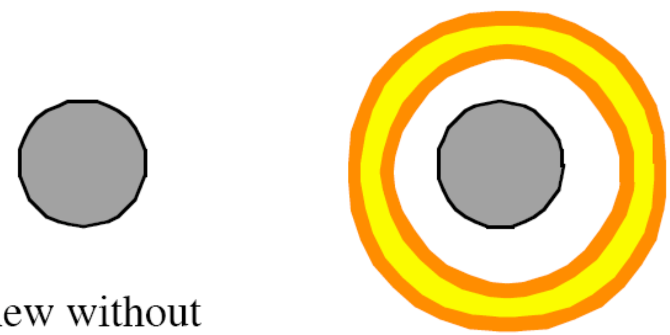
Gravitational Lenses



Light from a distant source can travel more than one path around a source of gravity to get to an observer on Earth.

There appears to be more than one source, or the source is distorted.

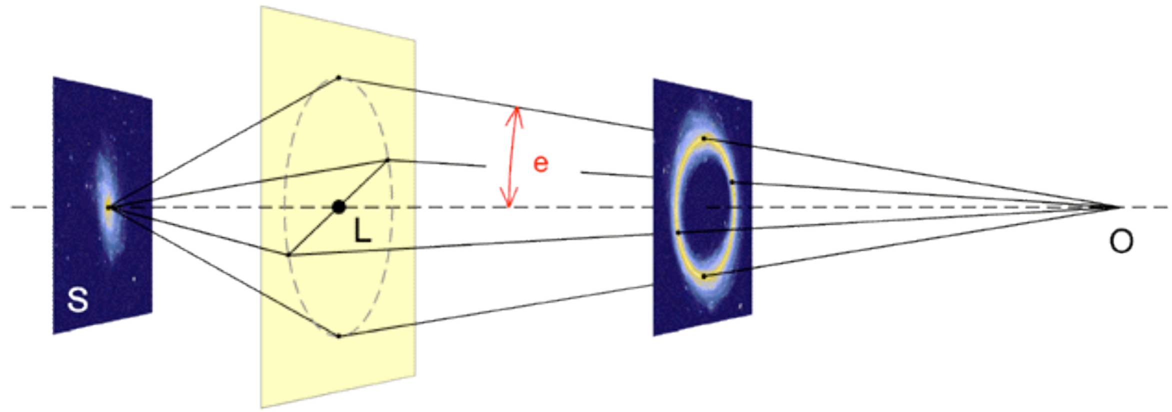
If the source, mass and Earth are all exactly in line the source will appear to be spread into a ring.



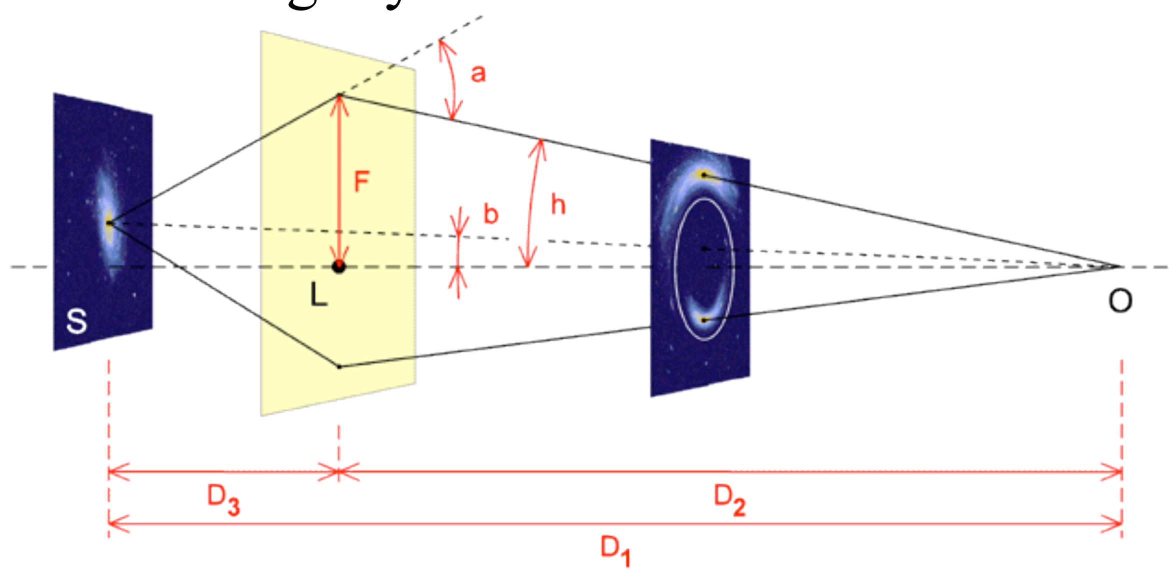
View without gravity.

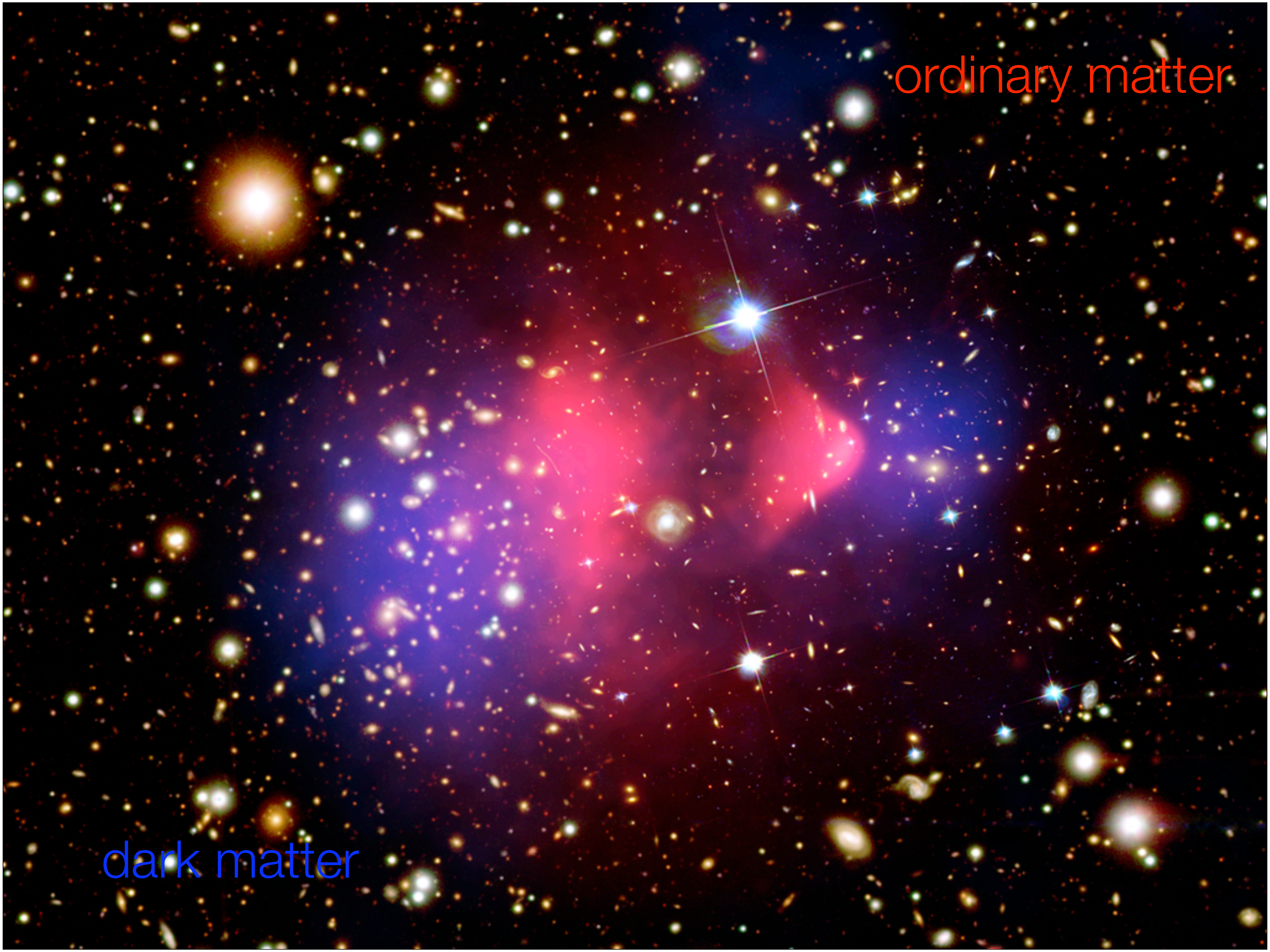
View with gravity.

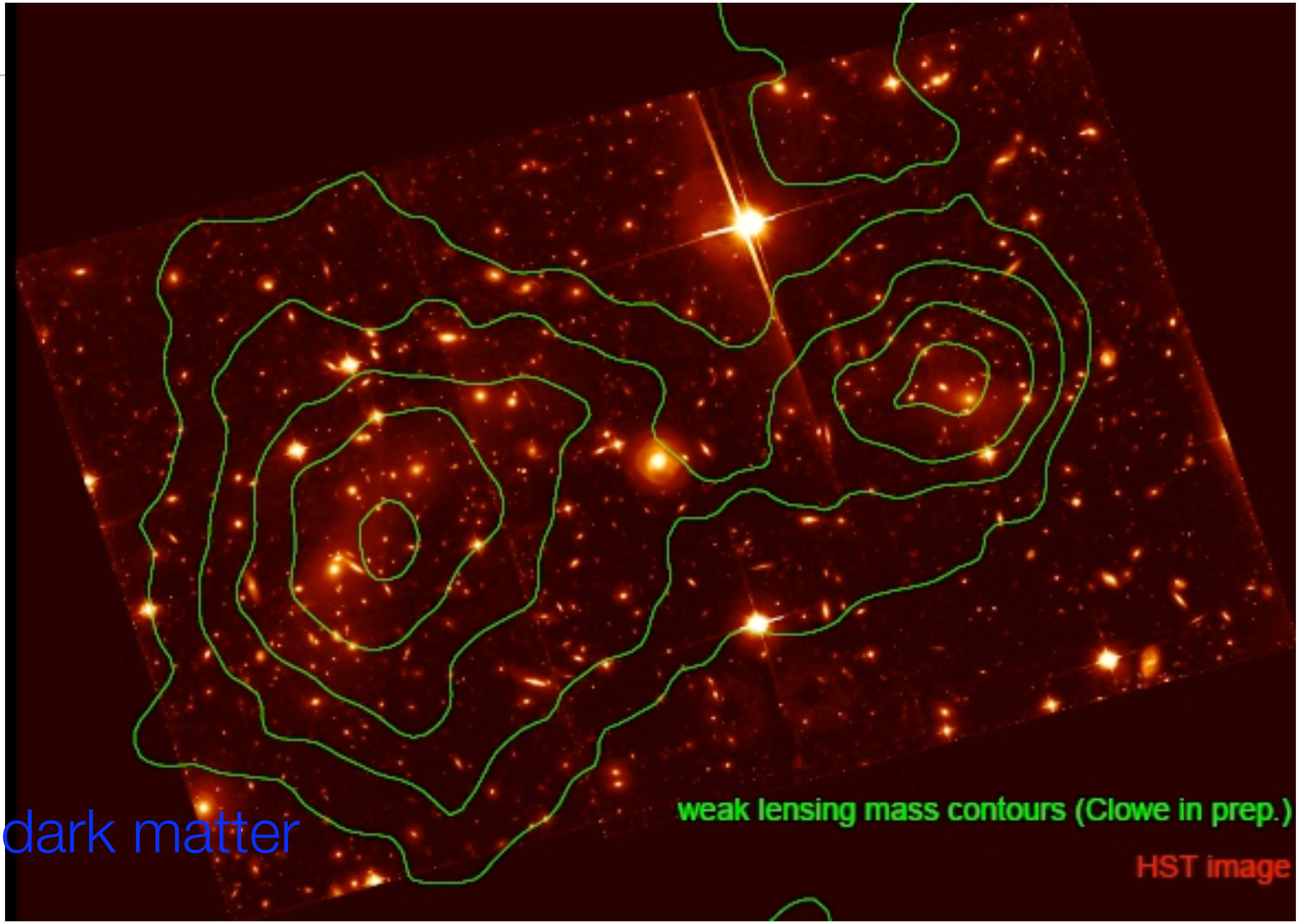
Source, mass, and observer lined up:



Source slightly off axis of mass and observer:




ordinary matter
dark matter



dark matter