A Particle Physics Tour with CompHEP

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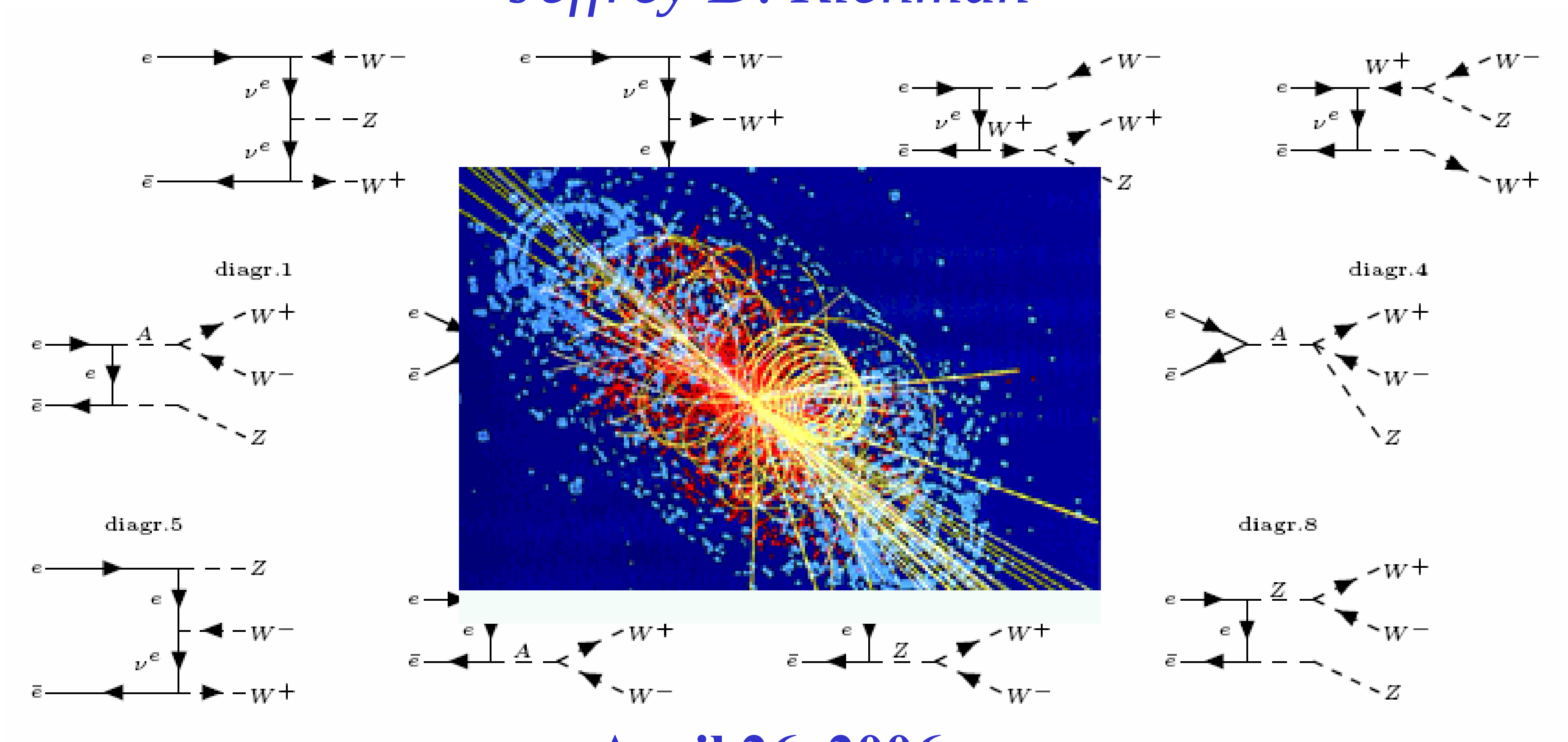


April 26, 2006

Outline

- **Introduction**
- **Getting, installing, and running CompHEP; references**
- **Using CompHEP; particle content in SM and SUSY; limitations of CompHEP; exclusive vs. inclusive processes; intermediate states**
- **“Observables” in particle physics: decay rates, cross sections,…**
- ***Z*-boson, *t*-quark, and Higgs decay in the SM**
- **Compton Scattering**
- **Muon decay and radiative corrections; *b*-quark decay**
- **$e^+ e^-$ scattering**
- **Structure functions**
- ***pp* and $p\bar{p}$ interactions: production of dijets, *t*-quarks, $t\bar{t}H$**
- **Conclusions**

A Tour of Particle Physics with CompHEP

$Z \to 2$ body	$t \to bW^+$	$\gamma + e^- \to \gamma + e^-$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$ $\mu^- \to e^- \overline{\nu}_e \nu_\mu \gamma$
$b \to c e^- \overline{\nu}_e$	$\overline{\nu}_e + e^- \to \overline{\nu}_\mu + \mu^-$	$e^+ e^- \to \gamma, Z \to \mu^+ \mu^-$ $e^+ e^- \to \gamma, Z \to b\overline{b}$	$e^+ + e^- \to W^+ + W^-$ $e^+ + e^- \to Z + Z$
$g + g \to g + g$	$g + g \to t + \overline{t}$ $q + \overline{q} \to t + \overline{t}$	$g + g \to t + \overline{t} + H$ $q + \overline{q} \to t + \overline{t} + H$ $g + g \to t + \overline{t} + b + \overline{b}$	$H \to q\overline{q},$ $\to W^+ W^-, ZZ$

Each one of these processes has a story to tell and could be investigated in much more depth…we will just scratch the surface.

Getting CompHEP and Other Generators

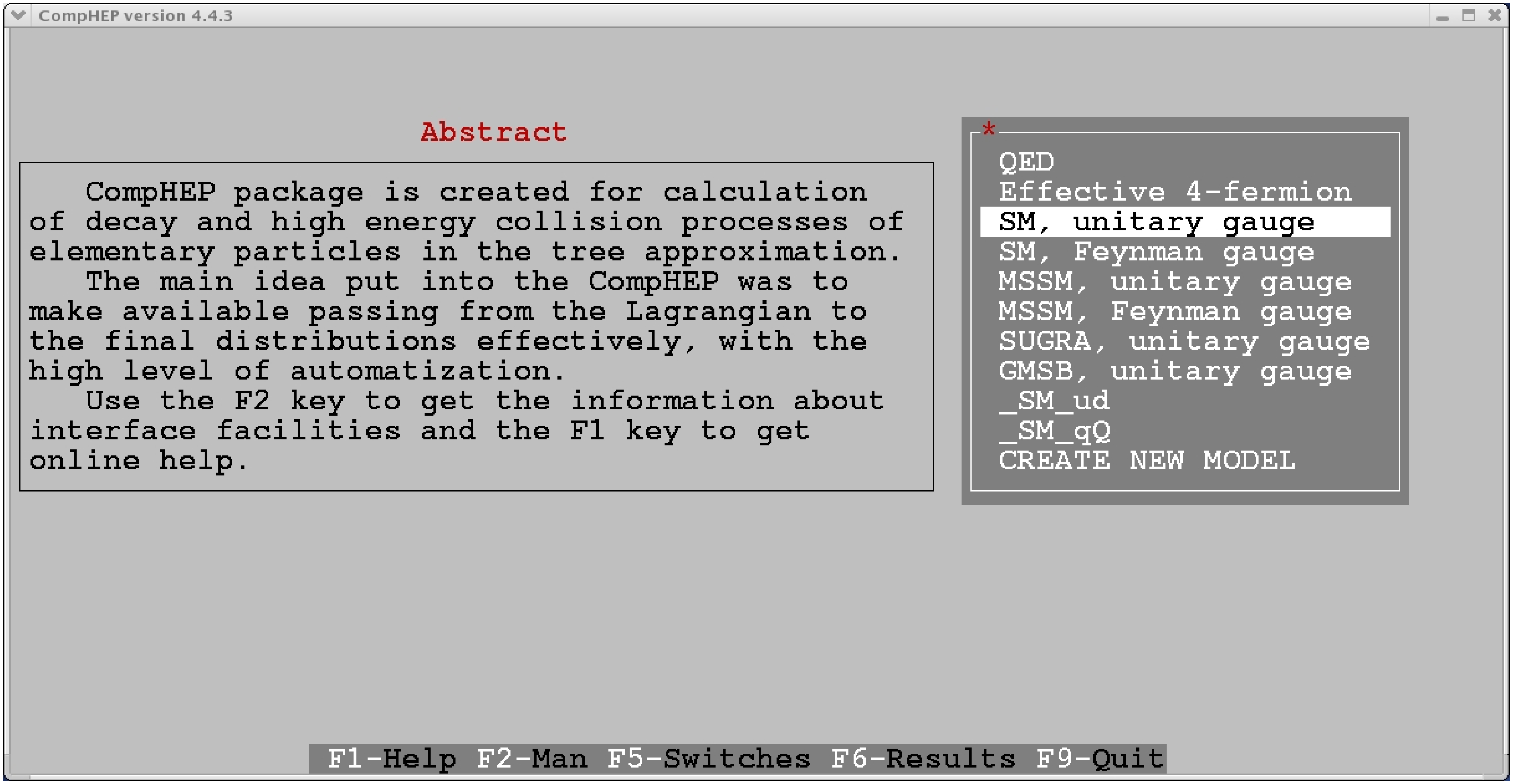
- **CompHEP is a tool for calculating observables for particle processes, both scattering and decays**
  - developed at Moscow State University
  - powerful, simple and fast to use, but has significant limitations
  - a good tool for learning particle physics
  - CompHEP home page: http://theory.sinp.msu.ru/comphep
  - latest version is comphep-4.4.3 (25/05/2004)
  - documentation: hep-ph/9908288, hep-ph/0403113.
- **Comprehensive set of links to other Monte Carlo generators for hadron-collider physics**
  - http://www.ippp.dur.ac.uk/montecarlo/BSM
  - Les Houches Guidebook to Monte Carlo Generators for Hadron Physics (hep-ph/0403045)

Note: all figures in this talk were made by the author using CompHEP, FeynDraw, ROOT,…

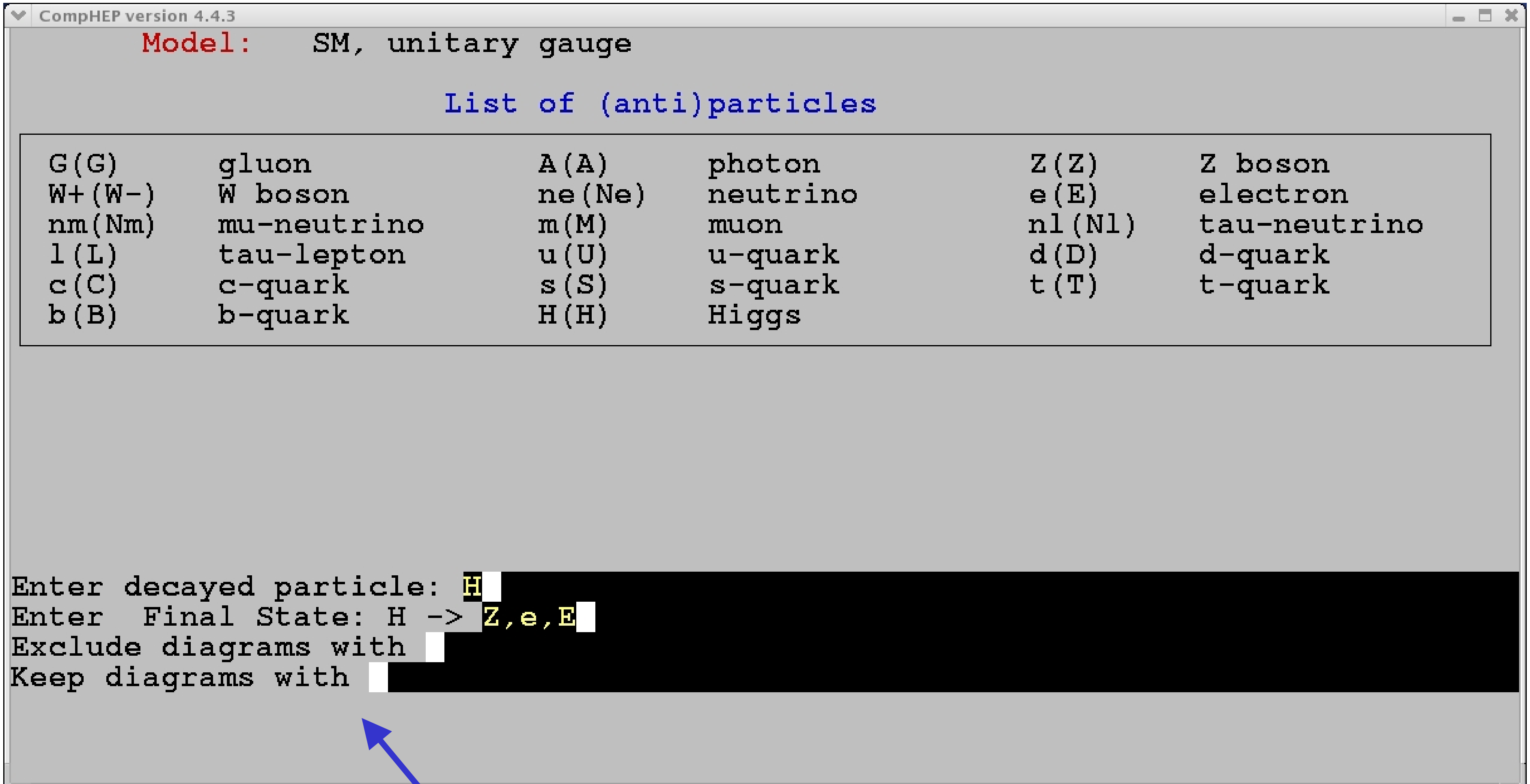
Installation for Linux

- **Installation of CompHEP**
  - **download archive file (comphep-4.4.3.tgz) to your directory**
  - **/home/richman/CompHEPSource**
  - **tar xzvf comphep-4.4.3.tgz**
  - **creates directory with name comphep-4.4.3**
  - **cd comphep-4.4.3**
  - **./configure**
    - Note: the configure script looks for CERNLIB. You may need to change the CERNLIB environment variable to point to the appropriate directory. CERNLIB is needed only for SUSY models.
  - **make**
  - **make setup WDIR=/home/richman/MyCompHEPWorkDir**
- **Running CompHEP**
  - **cd ~/MyCompHEPWorkDir**
  - **./comphep &**

CompHEP Model Selection



Particle Content of CompHEP: Standard Model



Can constrain possible intermediate-state particles; can be useful in reducing execution time when there are many possible Feynman diagrams and some have negligible amplitudes.

CompHEP Standard Model Parameters

CompHEP version 4.4.3

Variables 17

Clr Rest Del Size

Name	Value	Comment
EE	0.31345	Elementary charge (alpha=1/127.9, on-shell, MZ
GG	1.21358	Strong coupling constant (Z pnt, alp=0.1172pm0
SW	0.48076	sin of the Weinberg angle (MZ point -> MW=79.9
s12	0.2229	Parameter of C-K-M matrix (PDG2002)
s23	0.0412	Parameter of C-K-M matrix (PDG2002)
s13	0.0036	Parameter of C-K-M matrix (PDG2002)
MZ	91.1876	mass of Z boson
wZ	2.43631	width of Z boson
wW	2.02798	width of W boson
Mm	0.10566	mass of muon
Mtau	1.77699	mass of tau-lepton
Mc	1.65	mass of c-quark
Ms	0.117	mass of s-quark
Mtop	174.3	mass of t-quark
wtop	1.54688	width of t-quark
Mb	4.85	mass of b-quark
MH	115	mass of Higgs
wH	0.0061744	width of Higgs

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Also a separate menu of constraints, such as CKM unitarity relations.

Particle Content of CompHEP: Minimal SUSY

CompHEP version 4.4.3

Model: MSSM, unitary gauge

List of (anti)particles

A(A)	photon	Z(Z)	Z boson	W+(W-)	W boson
G(G)	gluon	e(E)	electron	m(M)	muon
ne(Ne)	e-neutrino	nm(Nm)	mu-neutrino	nl(Nl)	tau-neutrino
l(L)	tau-lepton	s(S)	s-quark	c(C)	c-quark
u(U)	u-quark	d(D)	d-quark	t(T)	t-quark
b(B)	b-quark	h(h)	Light Higgs	H(H)	Heavy higgs
H3(H3)	CP-odd Higgs	H+(H-)	Charged Higgs	~1+(~1-)	chargino 1
~2+(~2-)	chargino 2	~o1(~o1)	neutralino 1	~o2(~o2)	neutralino 2
~o3(~o3)	neutralino 3	~o4(~o4)	neutralino 4	~G(~G)	gluino
~eL(~EL)	selectron L	~eR(~ER)	selectron R	~mL(~ML)	smuon L
~mR(~MR)	smuon R	~l1(~L1)	stau 1	~l2(~L2)	stau 2
~ne(~Ne)	e-sneutrino	~nm(~Nm)	mu-sneutrino	~nl(~Nl)	tau-sneutrino

PgDn

Enter decayed particle: H
Enter Final State: H -> 2*x
Exclude diagrams with
Keep diagrams with

CompHEP version 4.4.3

Model: MSSM, unitary gauge

List of (anti)particles

PgUp

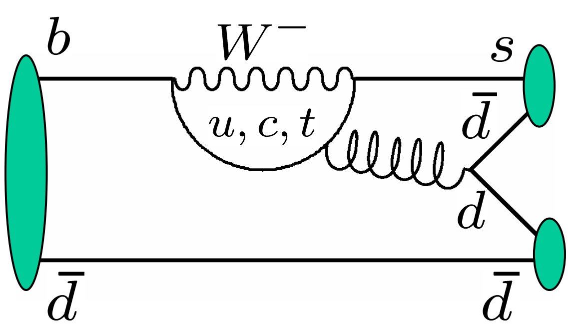
u(U)	u-quark	d(D)	d-quark	t(T)	t-quark
b(B)	b-quark	h(h)	Light Higgs	H(H)	Heavy higgs
H3(H3)	CP-odd Higgs	H+(H-)	Charged Higgs	~1+(~1-)	chargino 1
~2+(~2-)	chargino 2	~o1(~o1)	neutralino 1	~o2(~o2)	neutralino 2
~o3(~o3)	neutralino 3	~o4(~o4)	neutralino 4	~G(~G)	gluino
~eL(~EL)	selectron L	~eR(~ER)	selectron R	~mL(~ML)	smuon L
~mR(~MR)	smuon R	~l1(~L1)	stau 1	~l2(~L2)	stau 2
~ne(~Ne)	e-sneutrino	~nm(~Nm)	mu-sneutrino	~nl(~Nl)	tau-sneutrino
~uL(~UL)	u-squark L	~uR(~UR)	u-squark R	~cL(~CL)	c-squark L
~cR(~CR)	c-squark R	~t1(~T1)	t-squark 1	~t2(~T2)	t-squark 2
~dR(~DR)	d-squark R	~dL(~DL)	d-squark L	~sL(~SL)	s-squark L
~sR(~SR)	s-squark R	~b1(~B1)	b-squark 1	~b2(~B2)	b-squark 2

Some useful features of CompHEP

- You can restrict/specify the particles that enter in the intermediate state
- CompHEP provides a menu of structure functions, including the CTEQ6 series, which can be used to help compute *pp* scattering processes.
- You can apply cuts before computing cross sections; sometimes this is necessary to remove divergences.
- You can write out “events.”
- CompHEP can peform calculations in various SUSY models; this requires CERNLIB.

CompHEP Limitations

- No hadronic bound states (mesons, baryons) and no hadronization of quarks and gluons into jets
- No loop/box diagrams
- All processes are averaged over allowed initial-state spin polarizations and summed over final-state polarizations.
- No neutrino oscillations
- CompHEP can be used to compute quasi-inclusive processes (e.g., $H\rightarrow 2*x$), but it is awkward to perform truly inclusive calculations.



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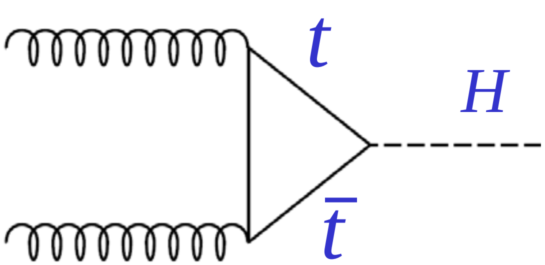
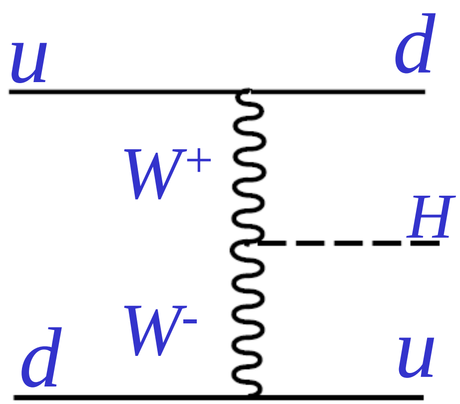


No



Yes

Procedure for computing results

1. Specify decay or scattering process
2. View Diagrams; can write Latex code; can Delete selected diagrams; Exit (escape key)
3. Square Diagrams (can View and escape)
4. Symbolic calculation
5. Write results
6. C code
7. C-Compiler (hit return in separate window after complete)
8. Go to new window for numerical calculations
9. Select subprocess if applicable
10. Define cuts if desired
11. Vegas (or Simpson if applicable)
12. Set distributions and ranges if desired
13. Integrate ($X^2<1$ for numerically consistent results)
14. View distributions
15. Generate events if desired

“Observables” in CompHEP

- **CompHEP allows us to compute the main “observables” that can be predicted by theories of particle physics.**
  - Decay rates of particles (and lifetimes)
  - Scattering cross sections
  - Differential distributions for both scattering and decays processes
  - Decay rates and asymmetries as a function of a parameter
- **Note that *none* of these quantities is directly measured with a detector!**
  - charged particles→ionization in detector→voltages/charges
  - neutral particles→generate EM or hadronic showers…
  - energy loss, multiple scattering, Cerenkov radiation, radiation damage,…
  - Particle interactions with the detector or not simulated by CompHEP, but they form the fundamental basis of our measurements!

Observables: Decay Rates

The total decay rate (Γ) of a particle measures

- the strength, range of the interactions governing the decay processes
- the number of accessible final states that the particle can decay into
- for a given final state, the possible effects of interference among different amplitudes

Exponential decay law: number of surviving particles

$$N(t) = N_0 e^{-t/\tau} = N_0 e^{-\Gamma t}$$

$$\Gamma = \sum_{f=1}^{m} \Gamma_f$$

Decays/sec summed over all distinguishable final states f

Normally write Γ in energy units:

$$\Gamma \left(\frac{\text{decays}}{\text{sec}} \right) \rightarrow (\hbar\Gamma)(\text{Energy})$$

$$\tau = \frac{\hbar}{\Gamma} \cong \frac{65.8 \text{ MeV} \cdot 10^{-23} \text{ s}}{\Gamma}$$

Observables: Decay Rates

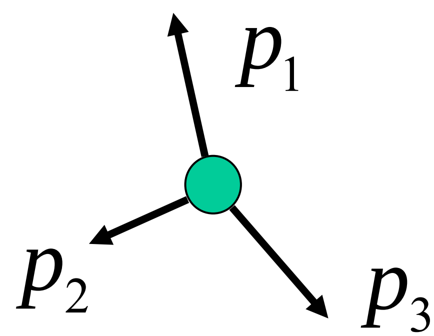
Branching fractions (B_f)

$$1 = \sum_{f=1}^{m} \frac{\Gamma_f}{\Gamma} = \sum_{f=1}^{m} B_f$$

Each mode i corresponds to a distinguishable set of final-state particles and is called a "subprocess" in CompHEP.

Differential decay rate for mode *i* (in diff. region of phase space)

$$d\Gamma_f = \frac{(2\pi)^4}{2M} \left|\mathcal{M}_f\right|^2 d\Phi_n(P; p_1, \ldots, p_n)$$



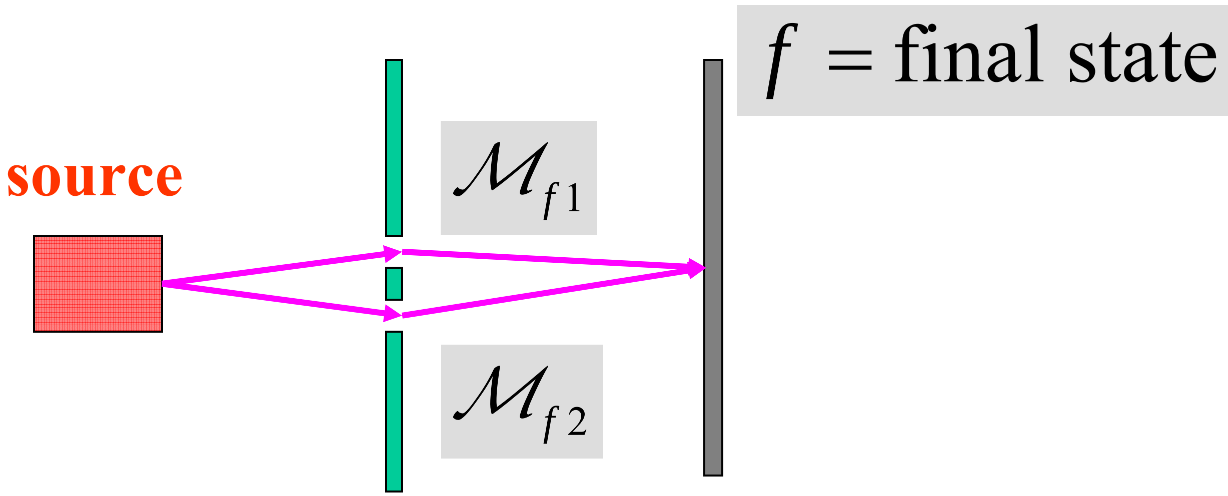
sum of amplitudes for specified final state

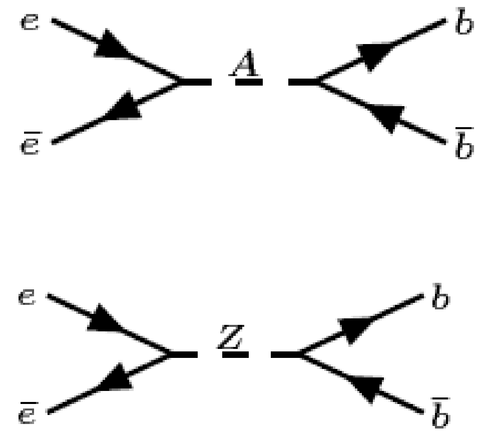
$$\mathcal{M}_f = \mathcal{M}_{f1} + \mathcal{M}_{f2} + \ldots$$

*phase space factor: integrate it over kinematic configurations consistent with (E,**p**) conservation*

$$d\Phi_n(P; p_1, \ldots, p_n) = \delta^4(P - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 (2E_i)}$$

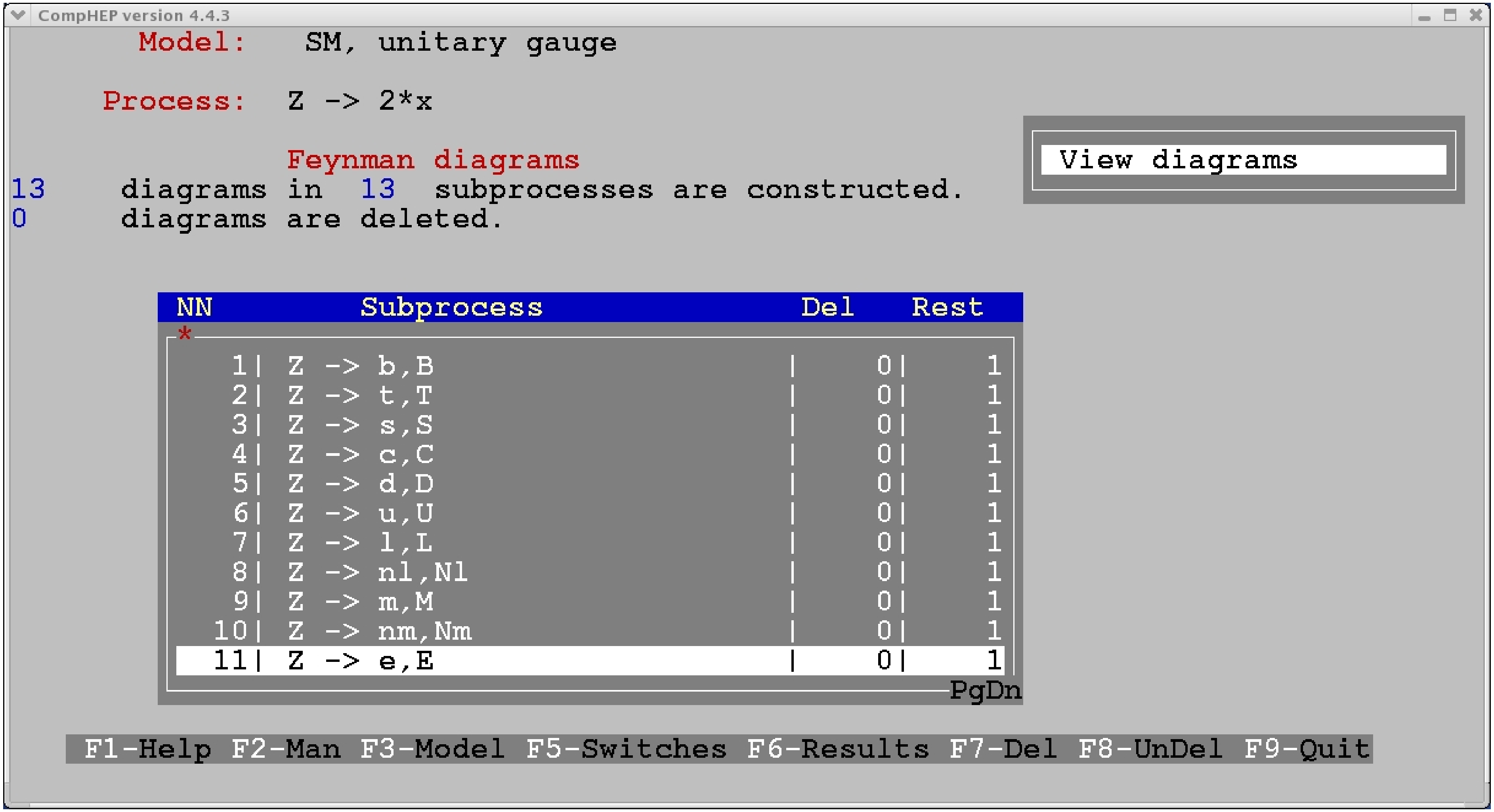
Initial states, intermediate states, and final states





- Sum the rate over final states (they are distinguishable)
- Sum the amplitudes over intermediate states (they are not distinguishable)
- Average the resulting rate over possible initial states
- Interference pattern allows us to infer that there is more than one intermediate state!

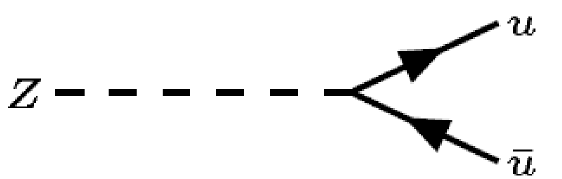
CompHEP: $Z \rightarrow 2*x$ subprocesses

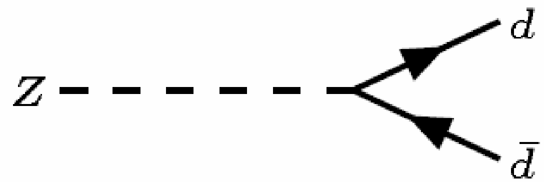


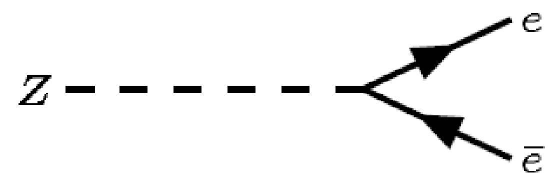
Each subprocess corresponds to a distinguishable final state; we need to add the rates for the subprocesses, not the amplitudes.

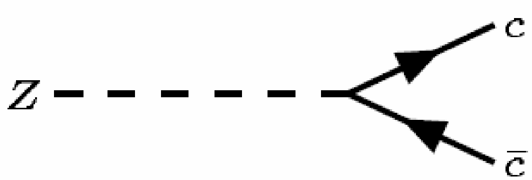
CompHEP Diagrams for $Z \rightarrow 2*x$

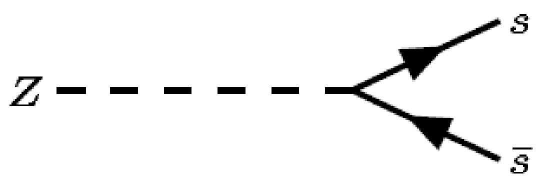
These diagrams are distinct subprocesses: no interference.

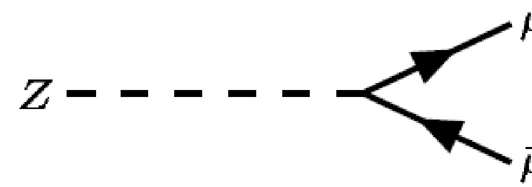


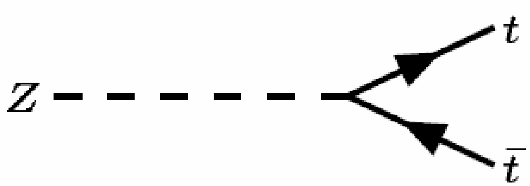


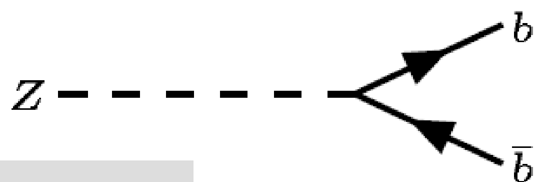


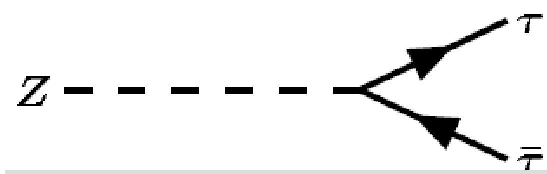






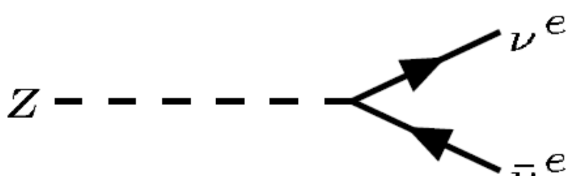


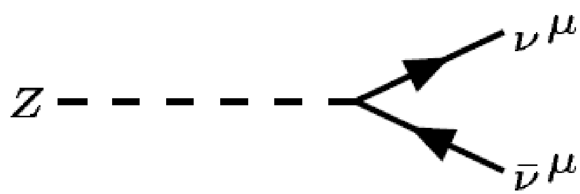


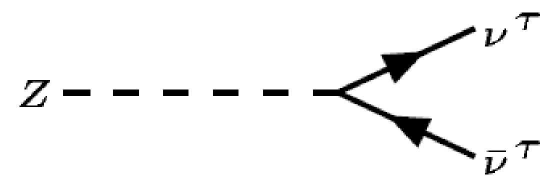


Note: kinematically forbidden diagram.

in CompHEP menus, τ is l







Left out $Z \rightarrow W^+W^-$ diagram, also kinematically forbidden.

Examples

*CompHEP results for Z → 2*x*

```
 Total width :  2.436309E+00 GeV
 Modes and fractions :          d D -       15%                          s S -        15%
b B -        15%                u U -       12%                          c C -        12%
nl Nl -        6.9%             nm Nm -       6.9%                       ne Ne -        6.9%
e E -       3.5%                m M -       3.5%                         l L -        3.4%
t T -         0%                W+ W- -          0%
```

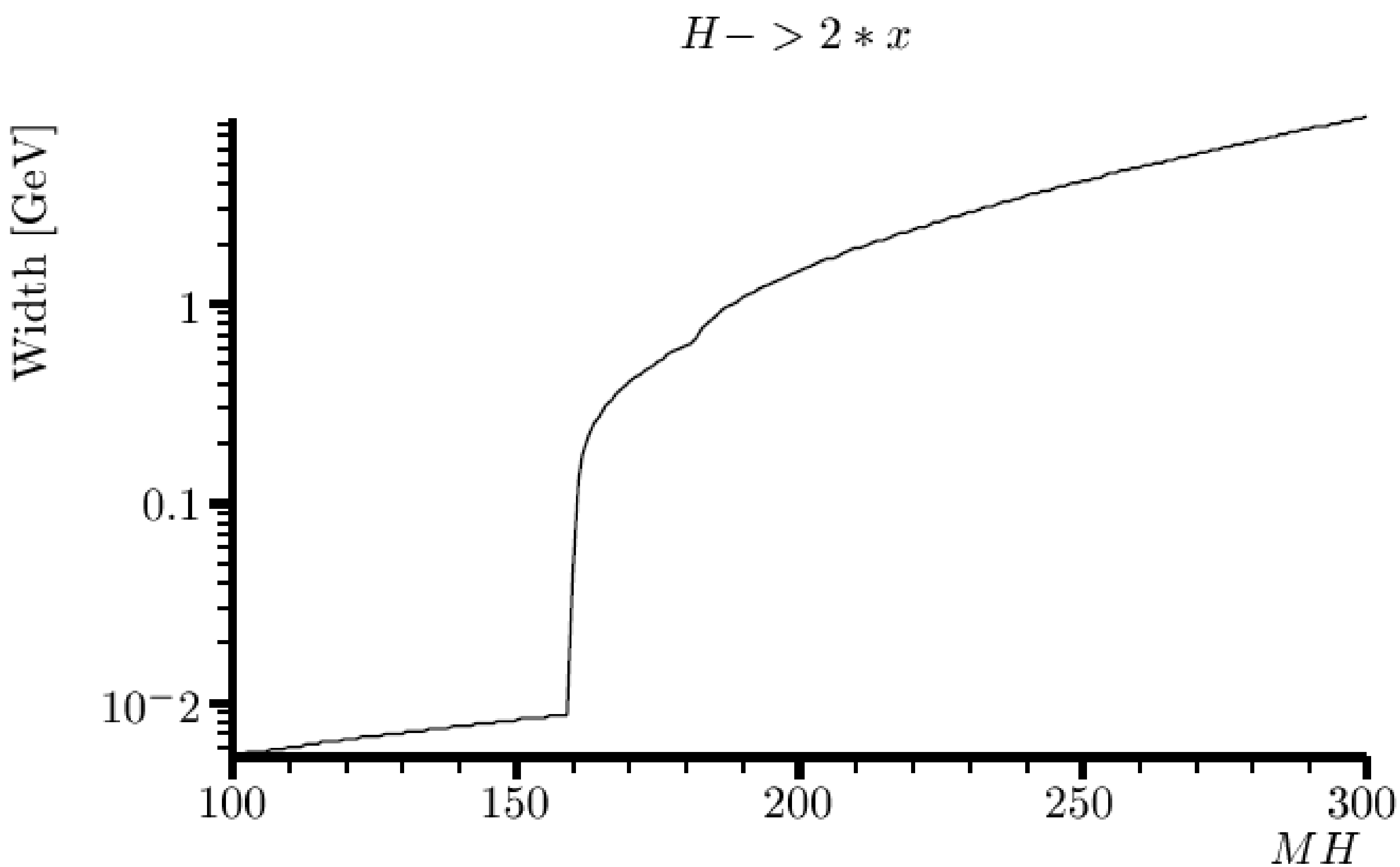
*CompHEP results for t → 2*x*

```
 Total width :  1.546882E+00 GeV
 Modes and fractions :          W+ b -     1E+02%                        W+ s -      0.17%
W+ d -     0.0032%
```

$$\tau_t \simeq \frac{65.8 \text{ MeV} \times 10^{-23} \text{ s}}{1.55 \text{ GeV}} \simeq 4.4 \times 10^{-25} \text{ s}$$

The top quark decays before it has time to form a hadronic bound state!

SM Higgs Decay H→2*x

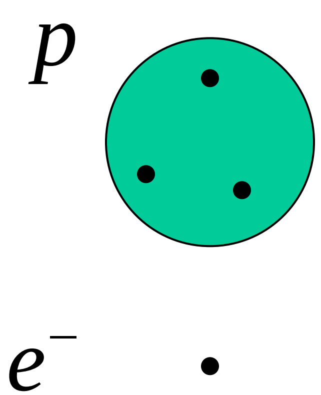


Observables: Scattering Cross Sections

The scattering cross section (σ) of two particles measures

- the strength and range of the interactions governing the scattering processes
- the number of accessible final states that the particles can scatter into
- for a given final state, the possible effects of interference among different amplitudes

imagine a particle coming directly at you…



If interaction is short range, and particle has finite extent, then the cross section roughly corresponds to the geometric area of the particle.

If interaction is long range, and/or particle has no finite extent, the cross section does not correspond to a geometrical area.

$$1 \text{ barn} = 10^{-24} \text{ cm}^2$$

pp̄ and pp cross sections

pp cross sections (LHC)

$$\sigma_{tot} \simeq 100 \text{ mb}$$

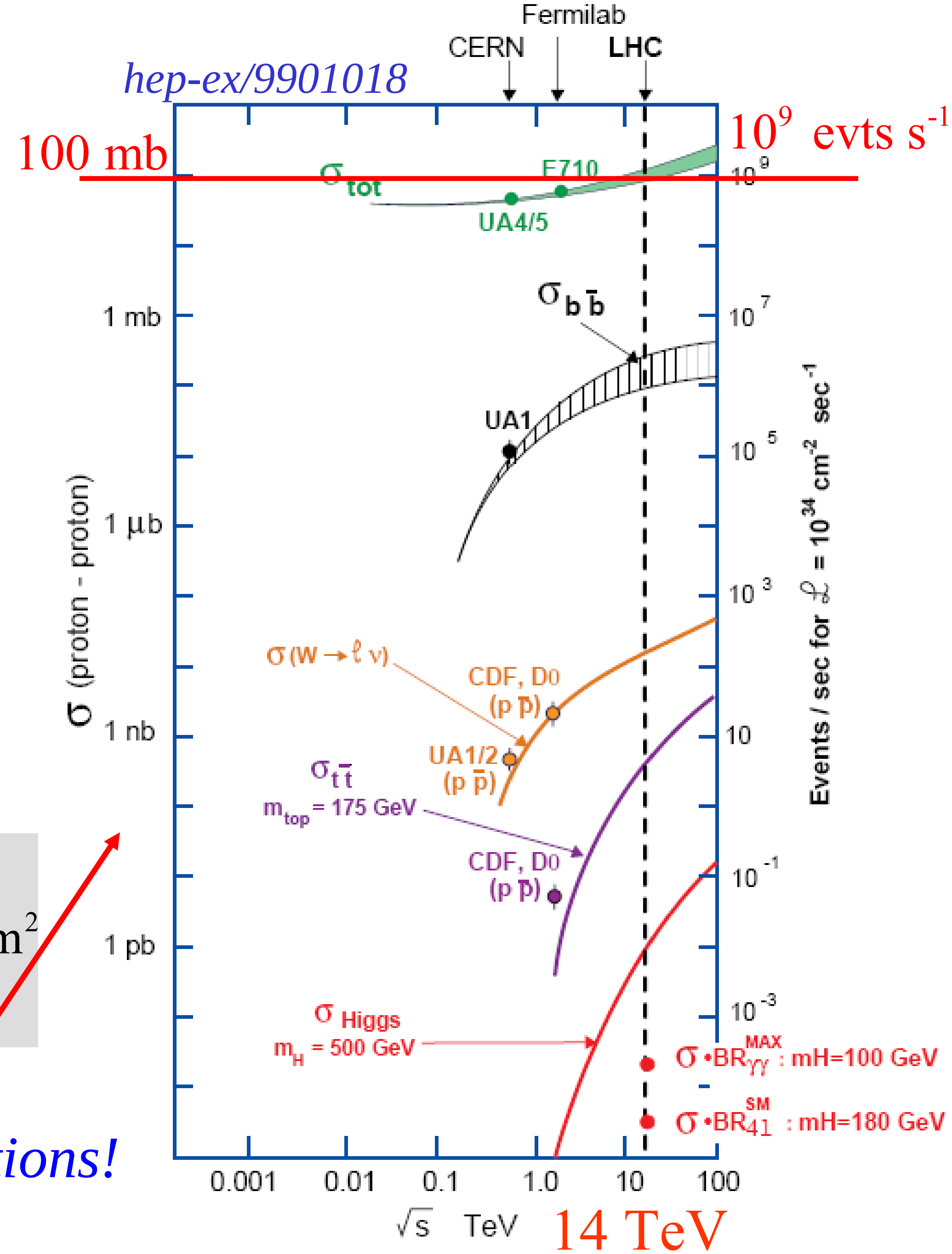
$$\sigma_{inelastic} \simeq 80 \text{ mb}$$

$$\sigma_{elastic} \simeq 20 \text{ mb}$$

Geometric cross section (very naïve)

$$\sigma(NN) \approx \pi r_{nucleus}^2 \approx \pi (1.2 \text{ fm } A^{1/3})^2$$
$$\approx \pi (1.2 \times 10^{-13} \text{ cm})^2 \cdot A^{2/3} \cdot 10^{24} \text{ barn/cm}^2$$
$$\approx 30 \text{ mb } (pp)$$

Huge range of cross sections!



Observables: Scattering Cross Sections

$$N(t) = N_0 e^{-x/\lambda}$$

$$\lambda = \frac{1}{n\sigma}$$

scattering from a fixed target with
n = #scattering objects/volume

$$\lambda^{-1}_{\text{nucl int}}(\text{Fe}) = n\sigma \approx (25\text{ cm})^{-1}$$

$$N_{\text{interactions}} = \left(\int dt\, L(t)\right)\cdot\sigma$$

colliding-beam experiment
$L(t)$=instantaneous luminosity
($\text{cm}^{-2}\text{s}^{-1}$)

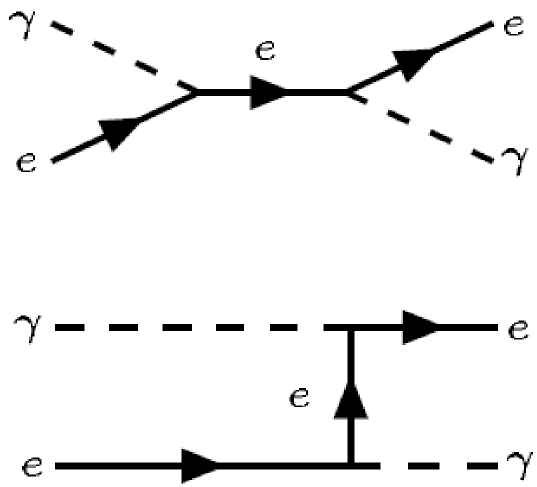
$$L(t) = \frac{N_1 N_2 n_B f}{A}$$

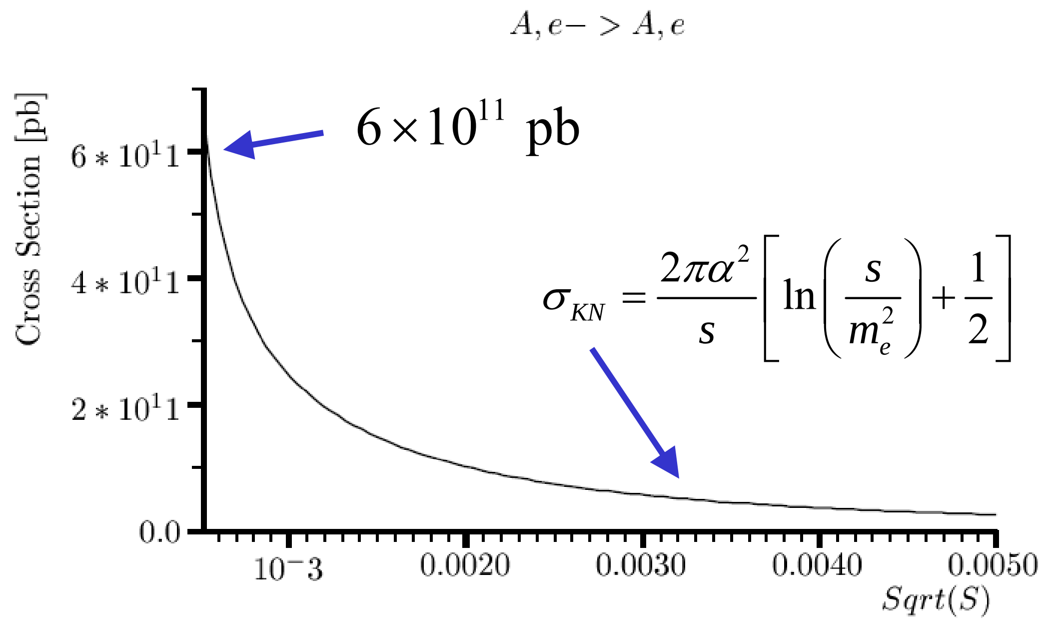
$$d\sigma_f = \frac{(2\pi)^4}{4\sqrt{(p_1\cdot p_2)^2 - m_1^2 m_2^2}} \left|\mathcal{M}_f\right|^2 d\Phi_n(p_1 + p_2; p_3, \dots, p_{n+2})$$

$$\mathcal{M}_f = \mathcal{M}_{f,1} + \mathcal{M}_{f,2} + \dots$$

$$d\Phi_n(P; p_1, \dots, p_n) = \delta^4(P - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 (2E_i)}$$

γ + e⁻ → γ + e⁻ (Compton Scattering)





$$\sigma(\gamma + e^- \rightarrow \gamma + e^-) = \frac{\pi\alpha^2(1-v)}{m_e^2 v^3} \times \left[\frac{4v}{1+v} + (v^2 + 2v - 2)\ln\left(\frac{1+v}{1-v}\right) - \frac{2v^3(1+2v)}{(1+v)^2}\right]$$

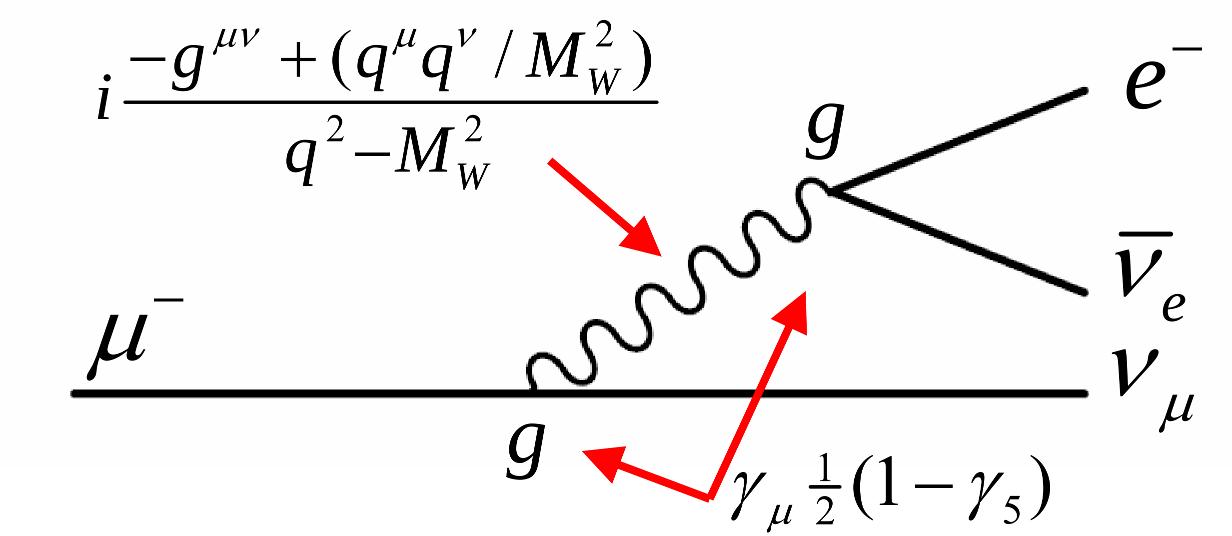
$$v = \frac{s - m_e^2}{s + m_e^2}$$

Thomson scattering

$$v \rightarrow 0 \;\Rightarrow\; \sigma \rightarrow \frac{8\pi\alpha^2}{3m_e^2} = \frac{8\pi\left(\frac{1}{137}\right)^2 (1973\times10^{-6}\ \text{MeV}\cdot 10^{-8}\ \text{cm})^2}{3(0.511\ \text{MeV})^2} \simeq 0.67\times10^{-24}\ \text{cm}^2$$

Muon decay: a prototype low-energy weak decay

W-mediated *b*-quark transitions have several key features in common with muon decay.



$$q^2 \le m_\mu^2 \ll M_W^2$$

Very strong dependence of decay rate on mass!

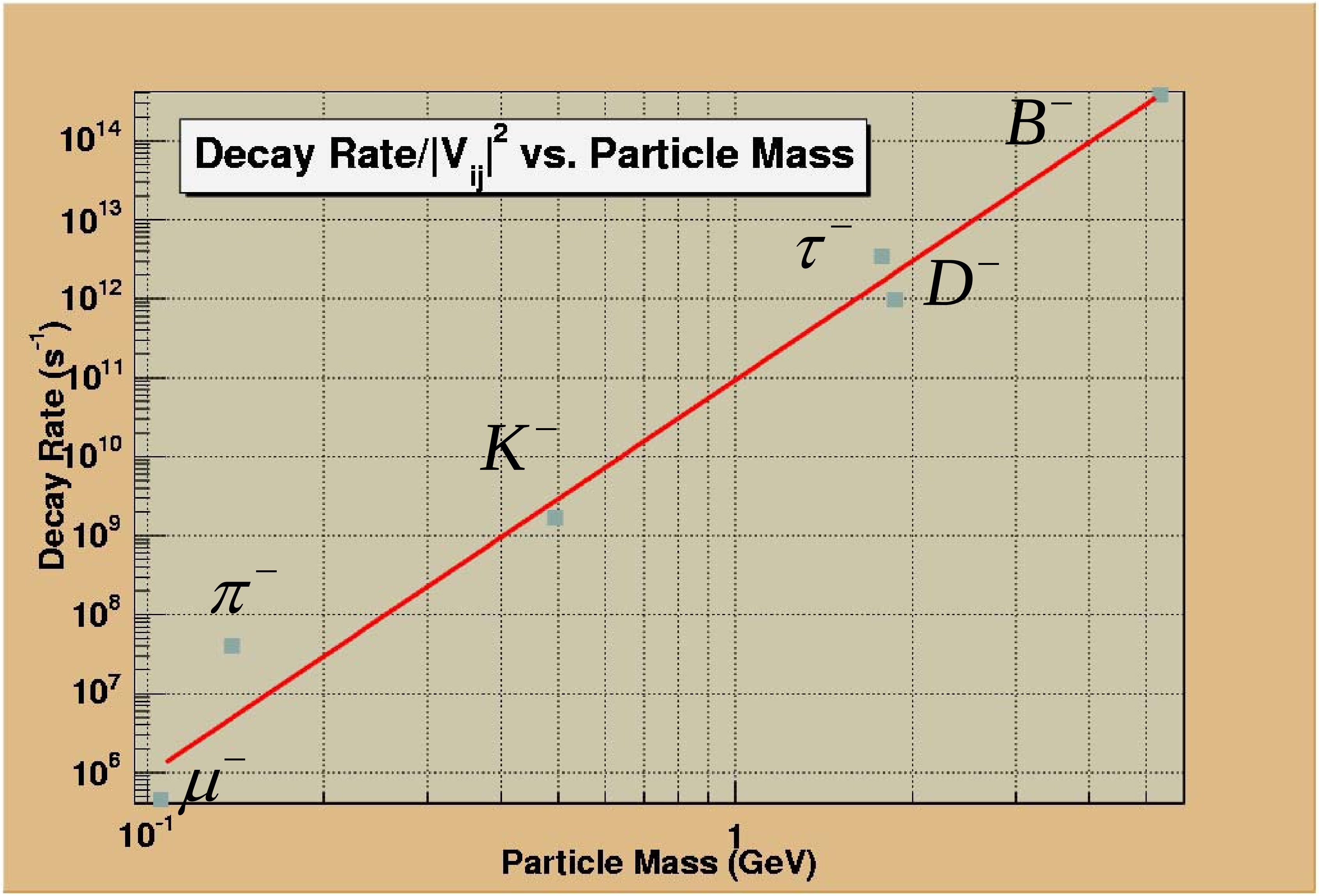
$$\frac{G_F}{\sqrt{2}} \equiv \frac{g^2}{8M_W^2}$$

$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}\cdot(1-8x+8x^3-x^4-12x^2\ln x)$$

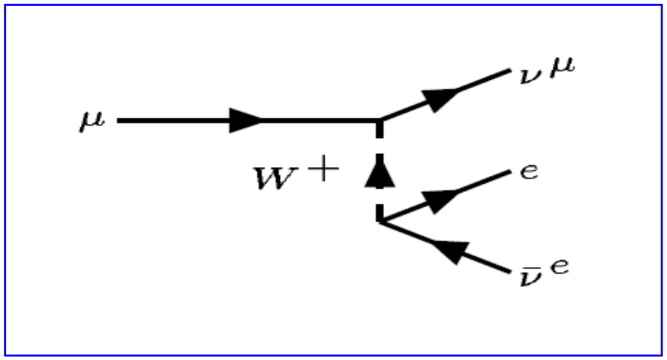
(ignoring QED radiative corrections)

$$x \equiv \frac{m_e^2}{m_\mu^2}$$

Mass dependence of weak decay rates (correcting for CKM elements)

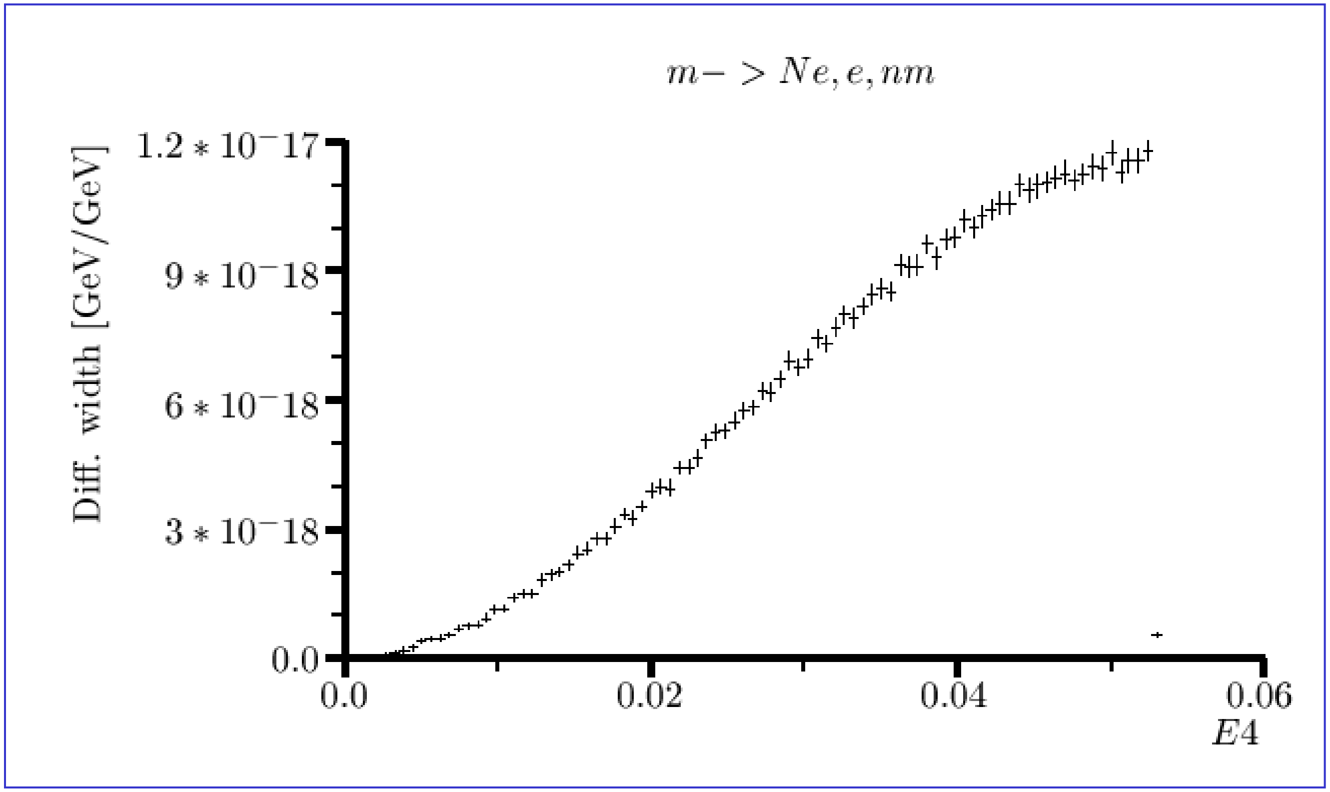


μ Decay Rate and Distributions



$$\Gamma(\mu^- \to e^- \nu_\mu \bar{\nu}_e) = (3.05 \times 10^{-19})\ \text{GeV}$$

$$\Rightarrow \quad \tau = \frac{\hbar}{\Gamma_{tot}} \cong 2.16 \times 10^{-6}\ \text{s}$$

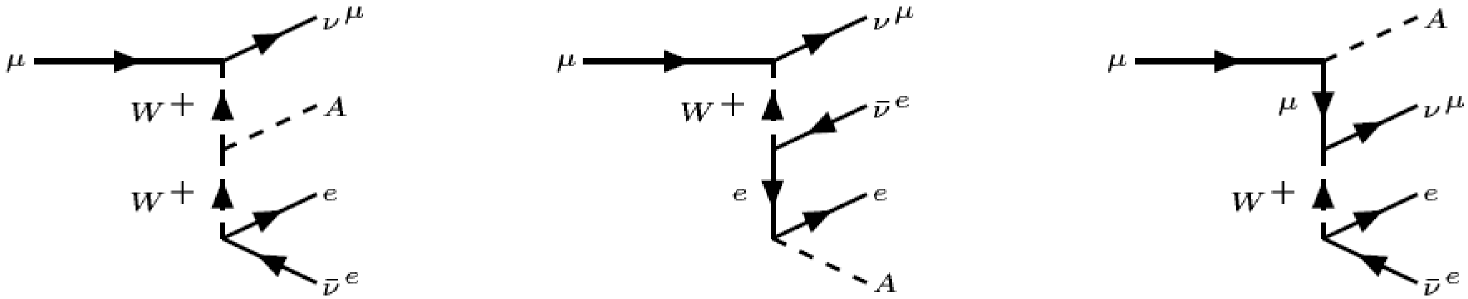


Electron energy spectrum
→ coupling is
V, A comb.
(excludes T,S,P)

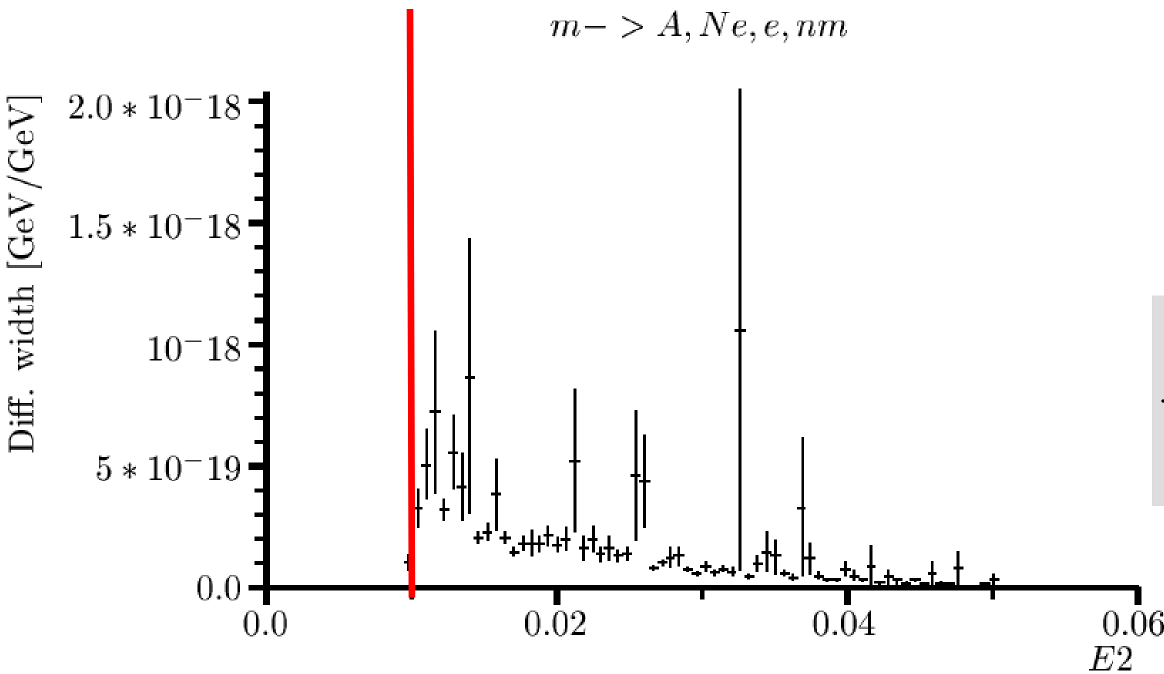
$$\frac{d\Gamma}{dx} = \frac{G_F^2 m_\mu^5}{96\pi^3} x^2 (3-2x)$$

$$x \equiv \frac{2E_e}{m_\mu}$$

μ Decay with Radiative Corrections



γ energy spectrum: E_γ>10 MeV

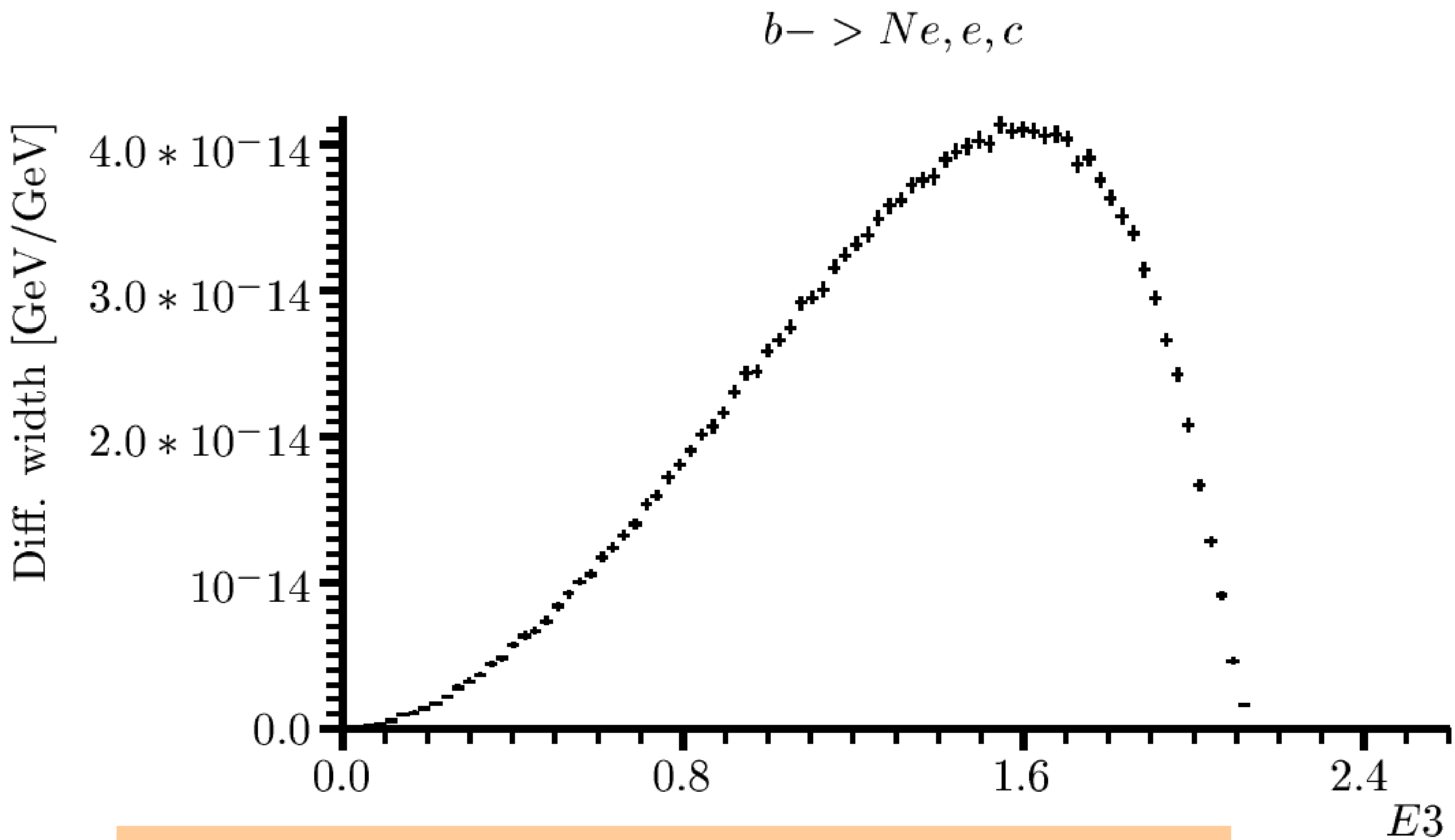


$$\Gamma(\mu^- \to e^- \nu_\mu \bar{\nu}_e \gamma) = (5.0 \times 10^{-21})\ \text{GeV} \qquad E_\gamma > 10\ \text{MeV}$$

$$\frac{\Gamma(\mu^- \to e^- \nu_\mu \bar{\nu}_e \gamma)}{\Gamma(\mu^- \to e^- \nu_\mu \bar{\nu}_e)} \simeq 1.7\%$$

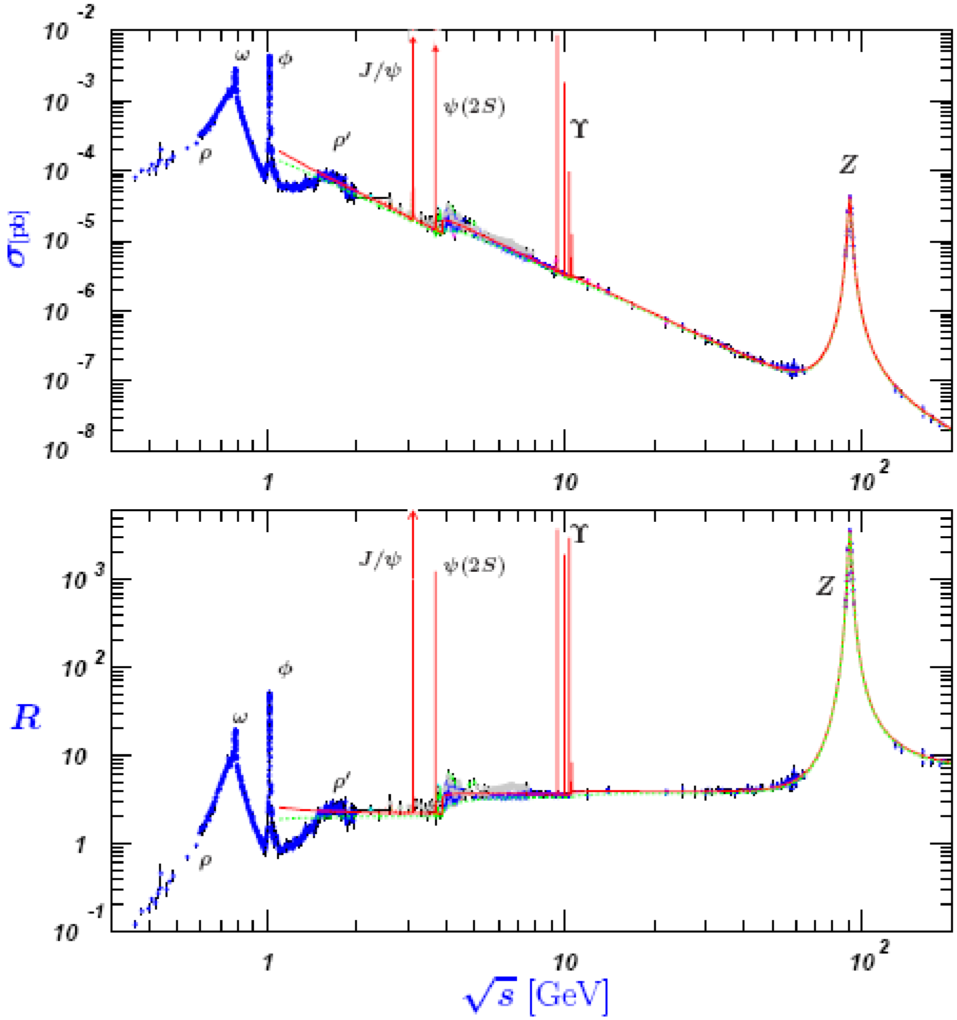
b-quark decay in CompHEP

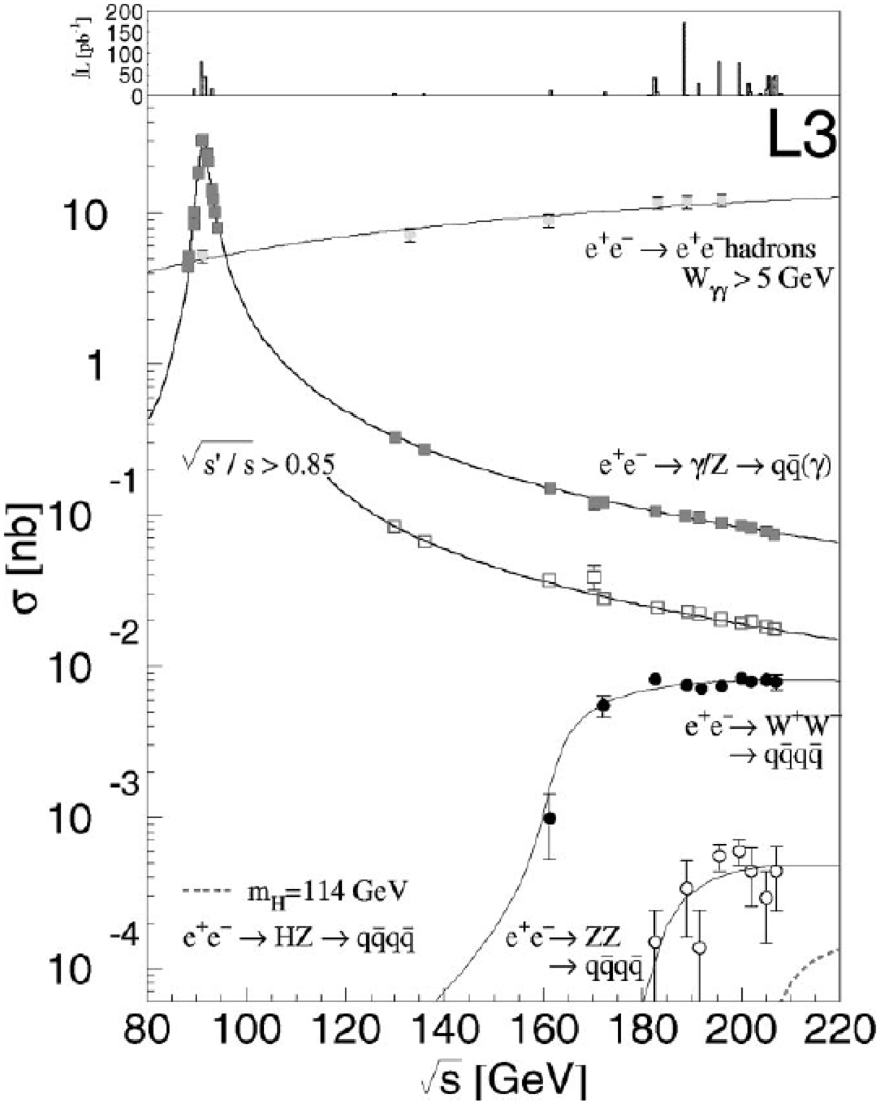
Electron energy spectrum in $b \rightarrow c\, e\, \nu$



Used to measure V_{cb}, m_b, and m_c…a long story!

e^+e^- Scattering



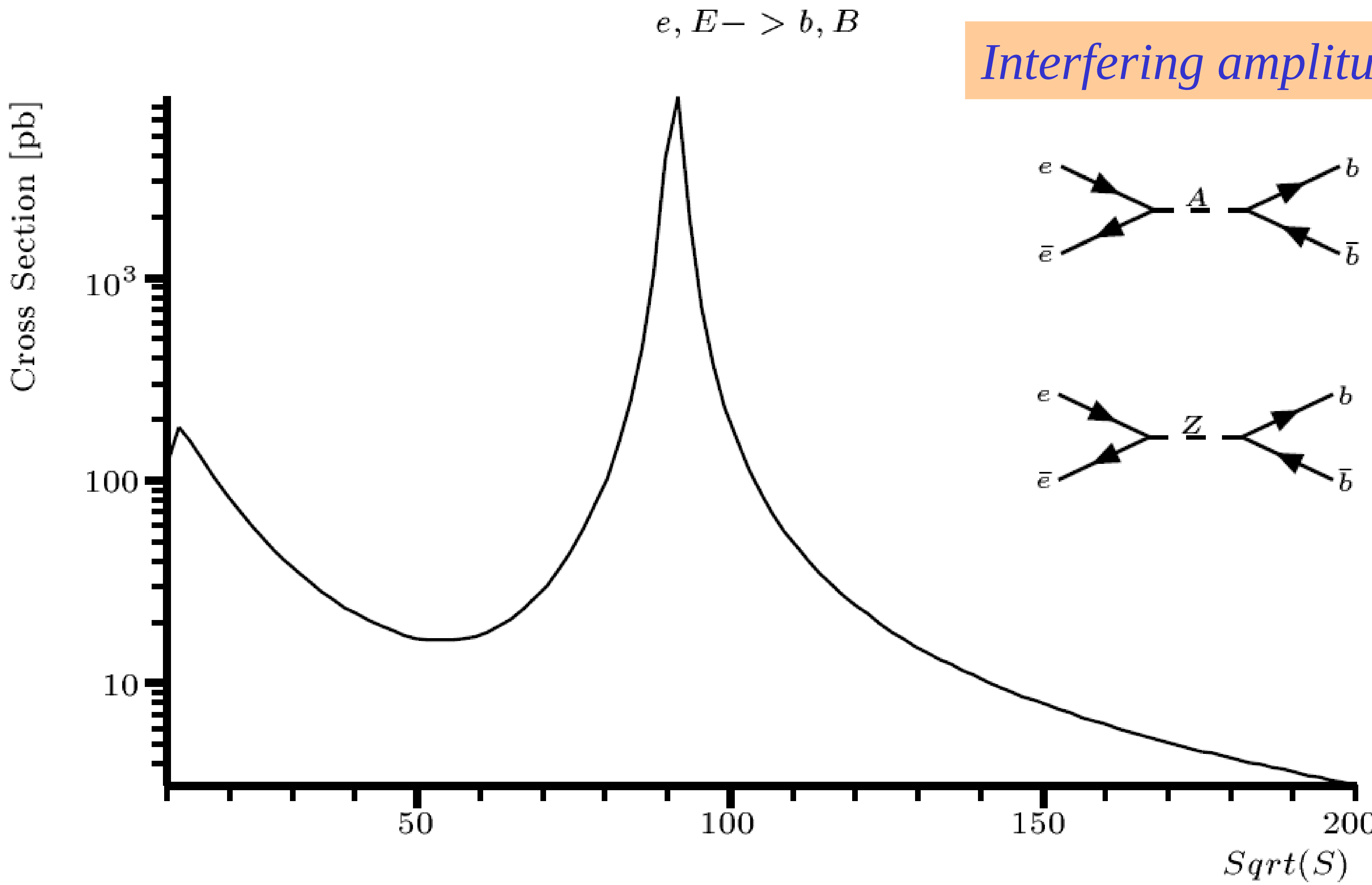


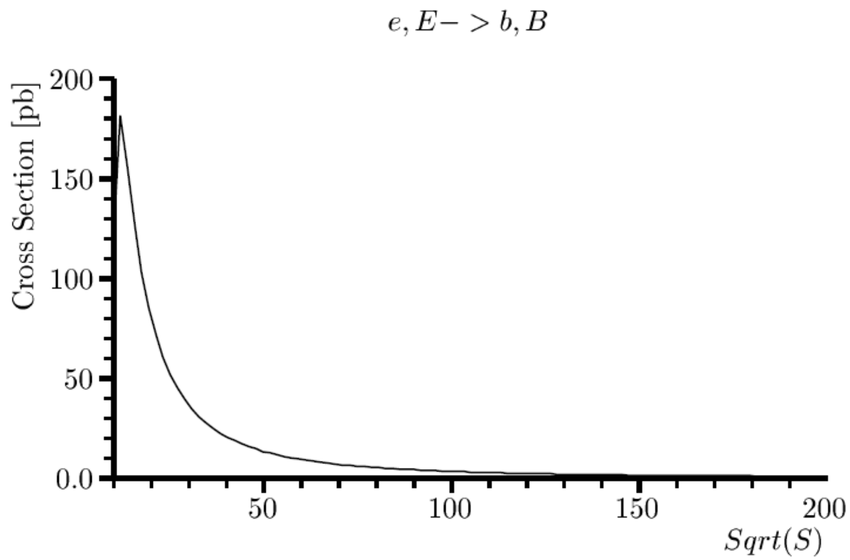
PDG 2005

M.M. Kado and C.G. Tully, Ann. Rev. Nucl. Part. Phys., Vol 52 (2002)

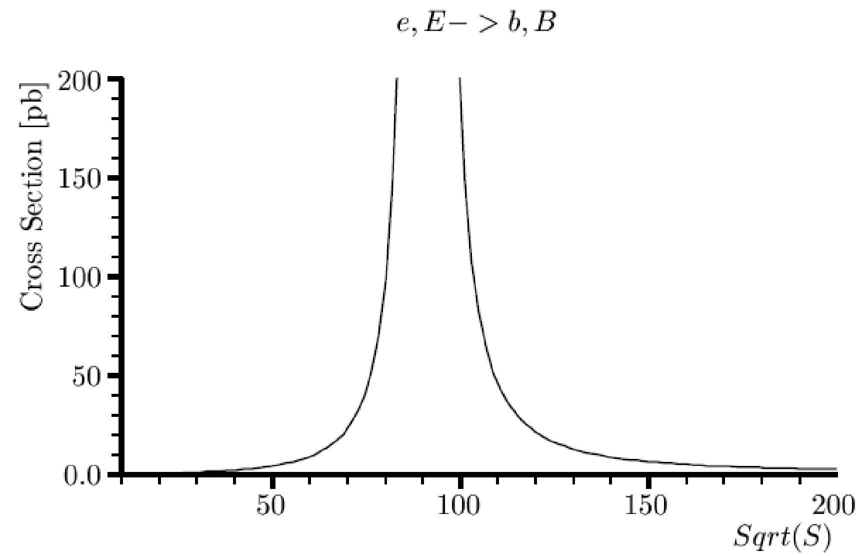
Cross section vs. CM energy for $e^+e^- \rightarrow b\bar{b}$

Interfering amplitudes

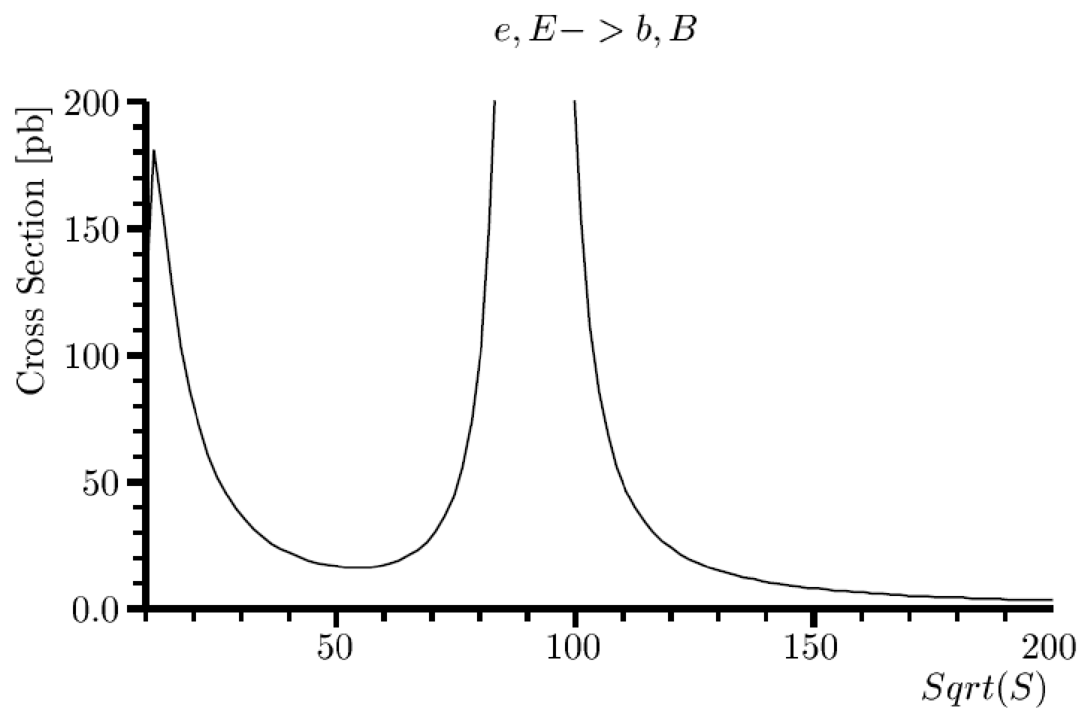




e, E−>b, B
Cross Section [pb]
0.0
50
100
150
200
50
100
150
200
Sqrt(S)

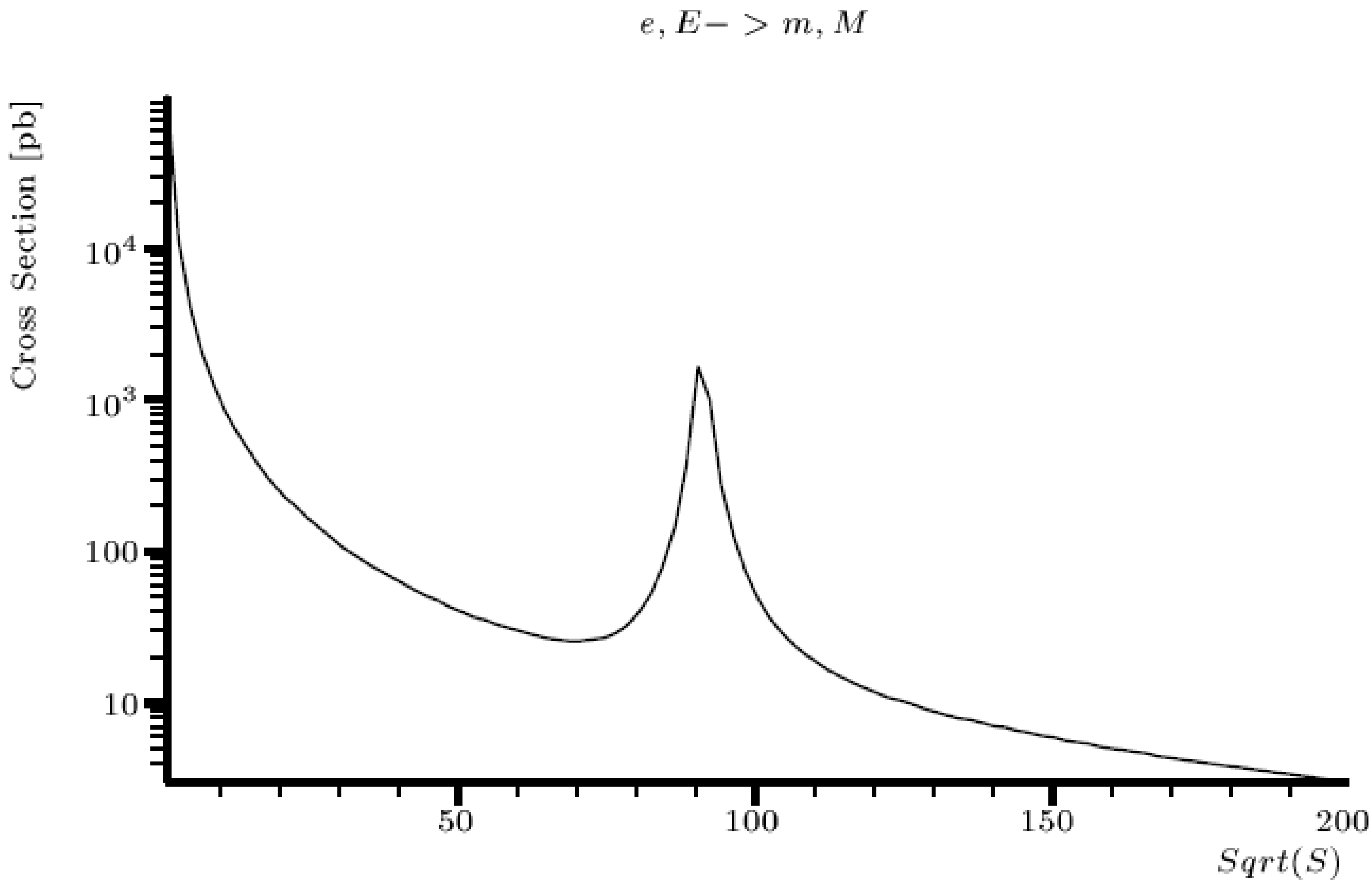


e, E−>b, B
Cross Section [pb]
0.0
50
100
150
200
50
100
150
200
Sqrt(S)



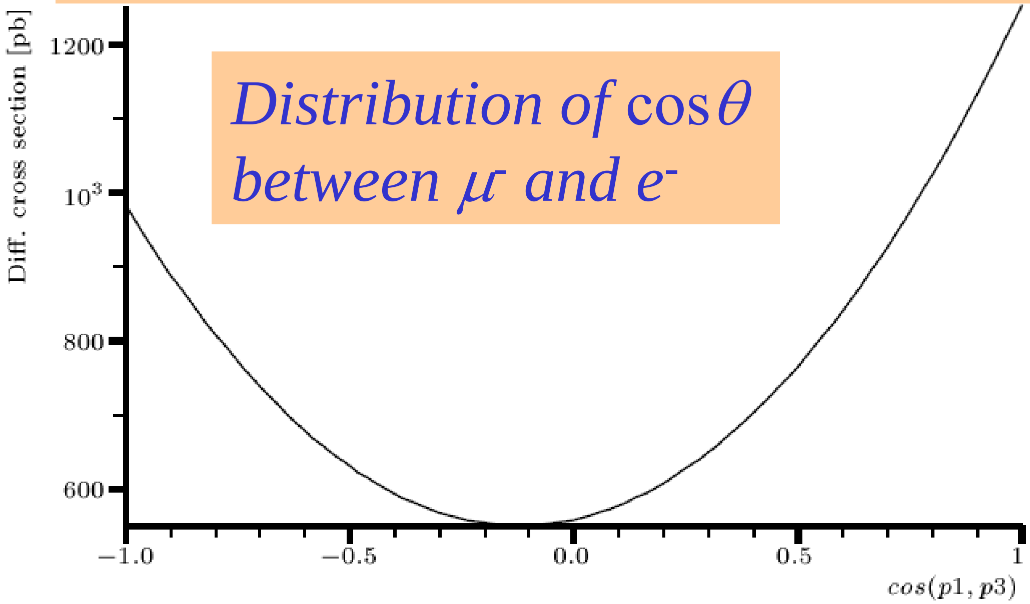
e, E−>b, B
Cross Section [pb]
0.0
50
100
150
200
50
100
150
200
Sqrt(S)

Cross section vs. CM energy for $e^+e^- \rightarrow \mu^+\mu^-$

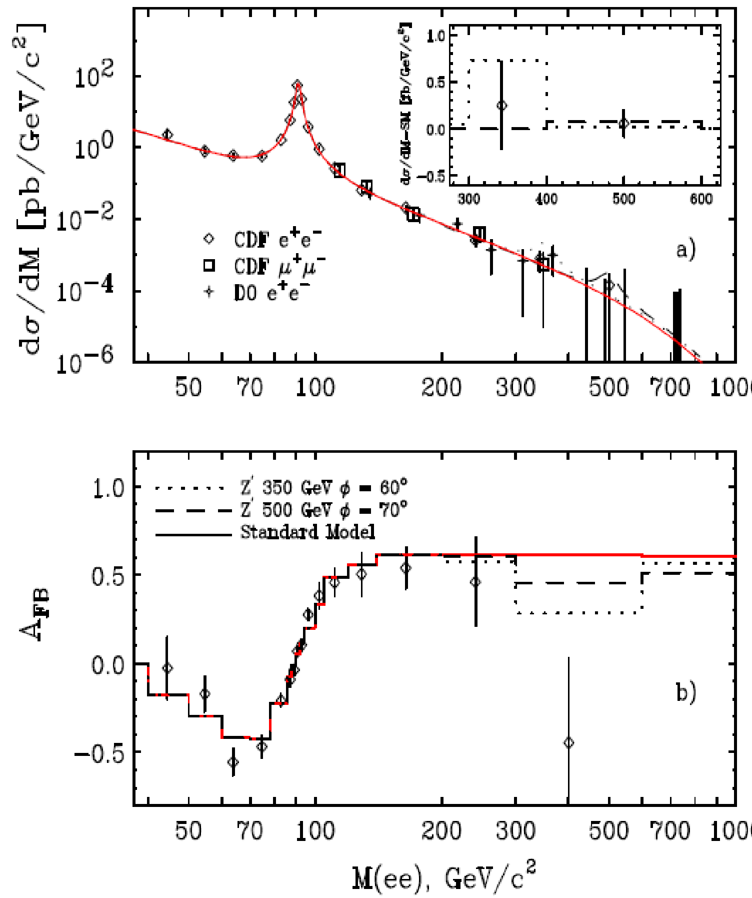


$e^+e^- \rightarrow \mu^+ \mu^-$ angular distribution and forward-backward asymmetry

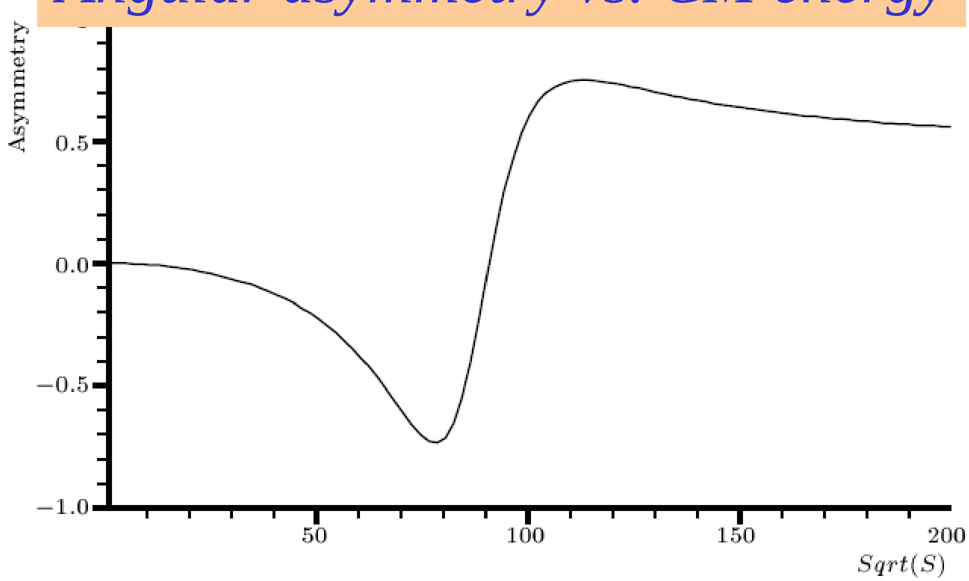
Distribution of cosθ between μ^- and e^-



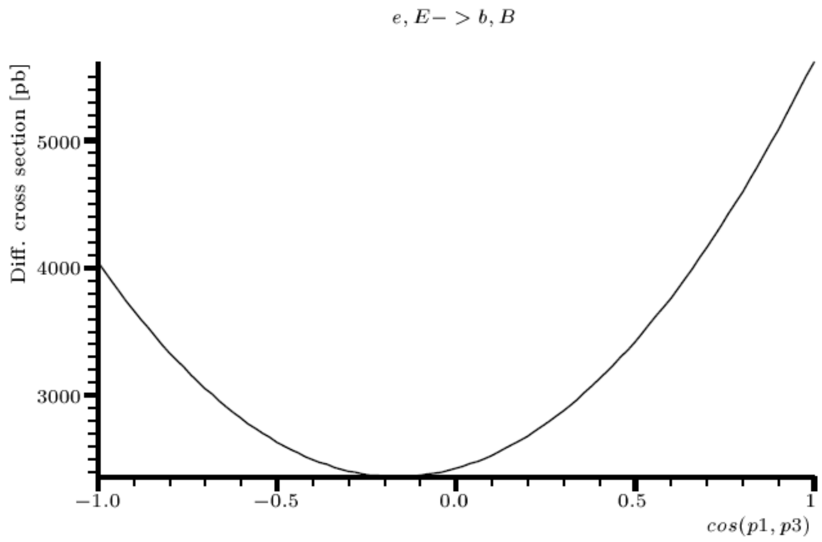
Measurement was done at the Tevatron too! (hep-ex/0106047)



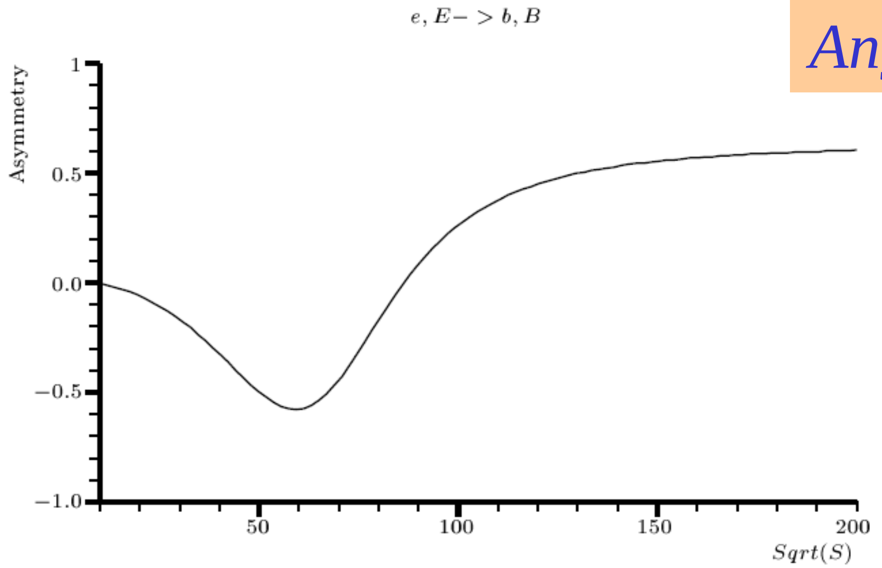
Angular asymmetry vs. CM energy



$e^+e^- \rightarrow b\,\bar{b}$ angular distribution and forward-backward asymmetry

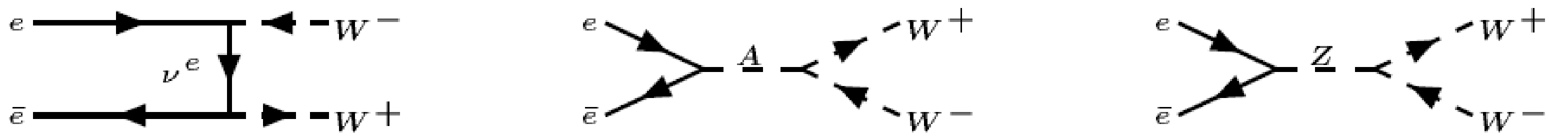


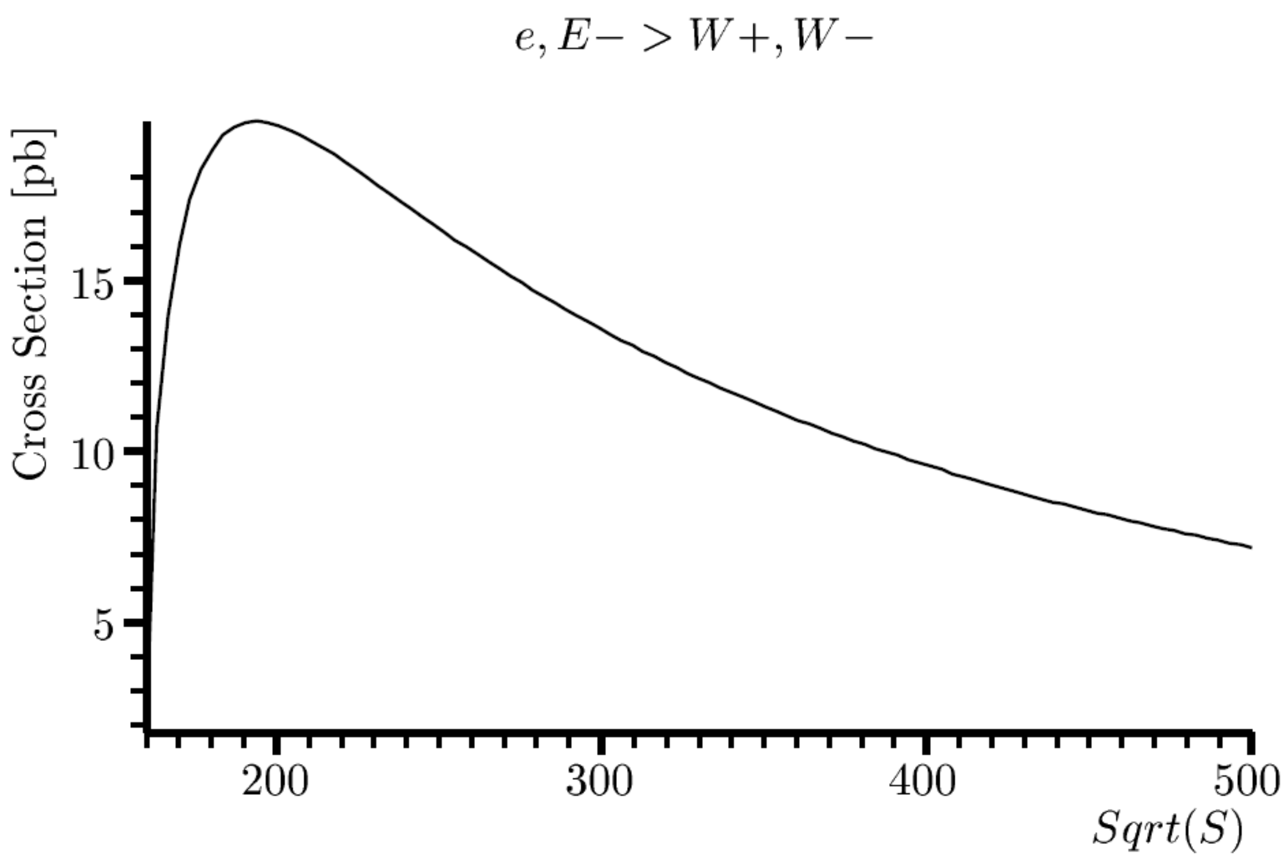
Distribution of $\cos\theta$ *between b and* e^-



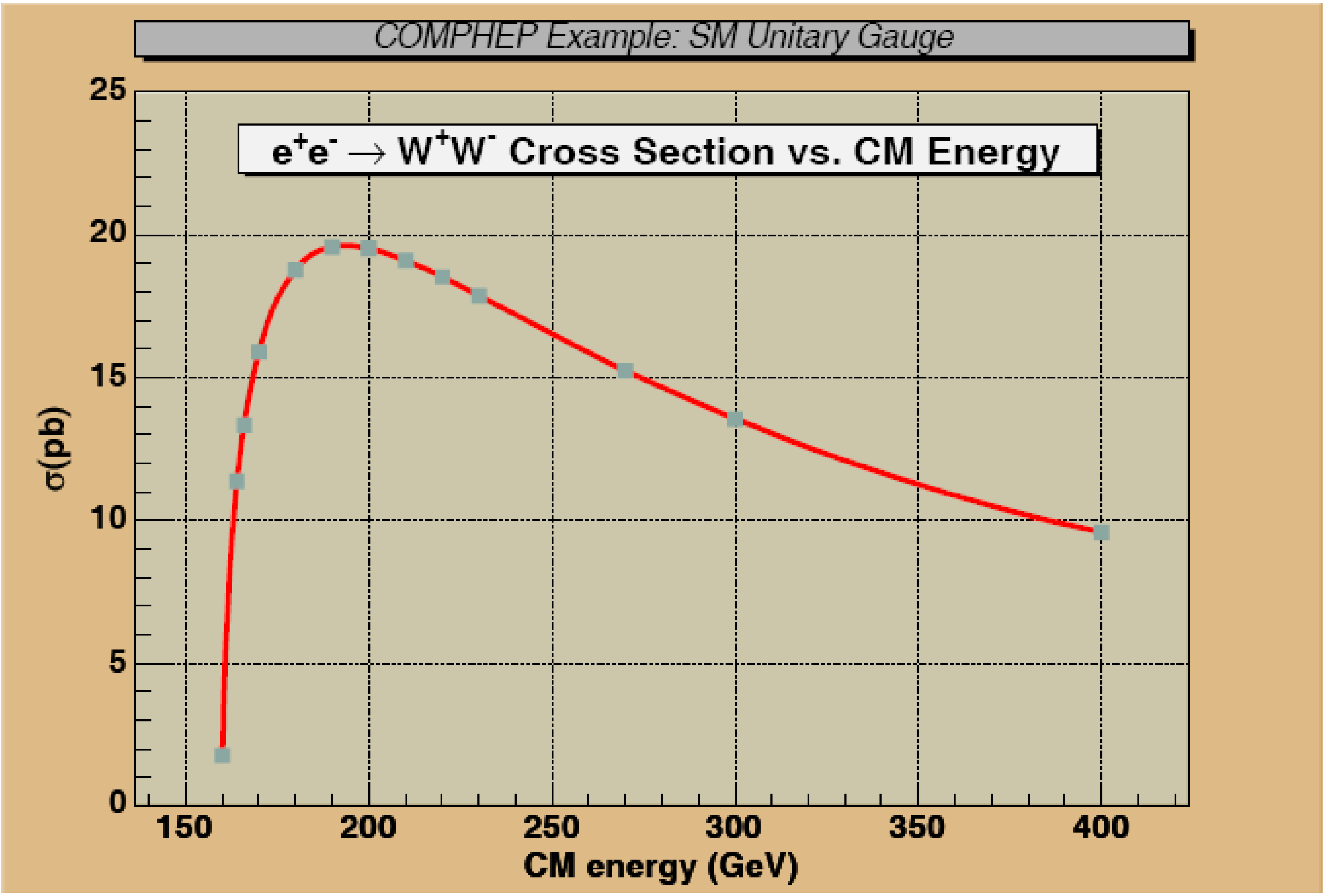
Angular asymmetry vs. CM energy

Cross section vs. CM energy for $e^+e^-\rightarrow W^+W^-$

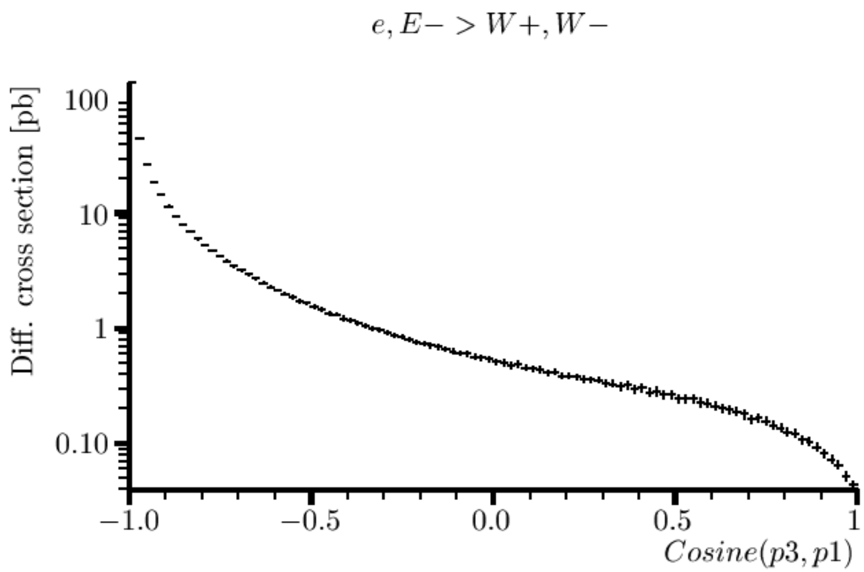


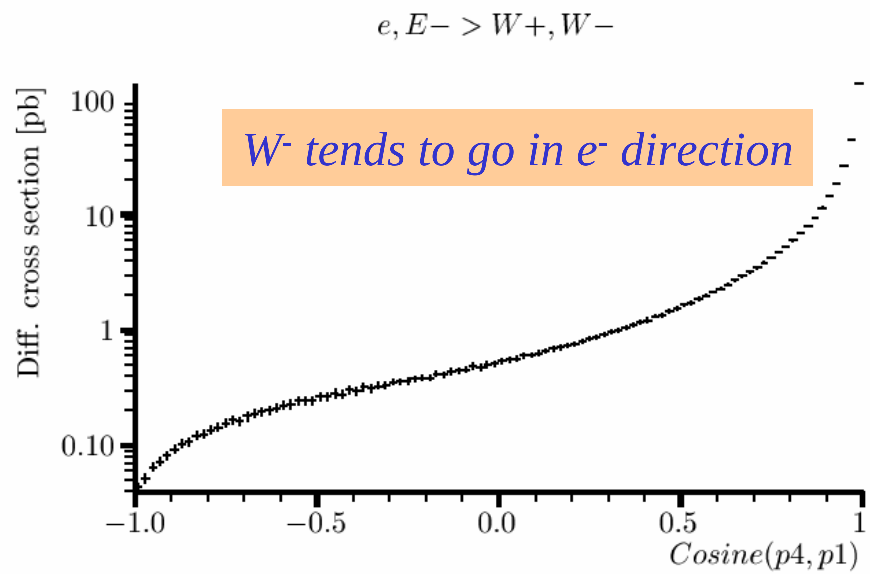


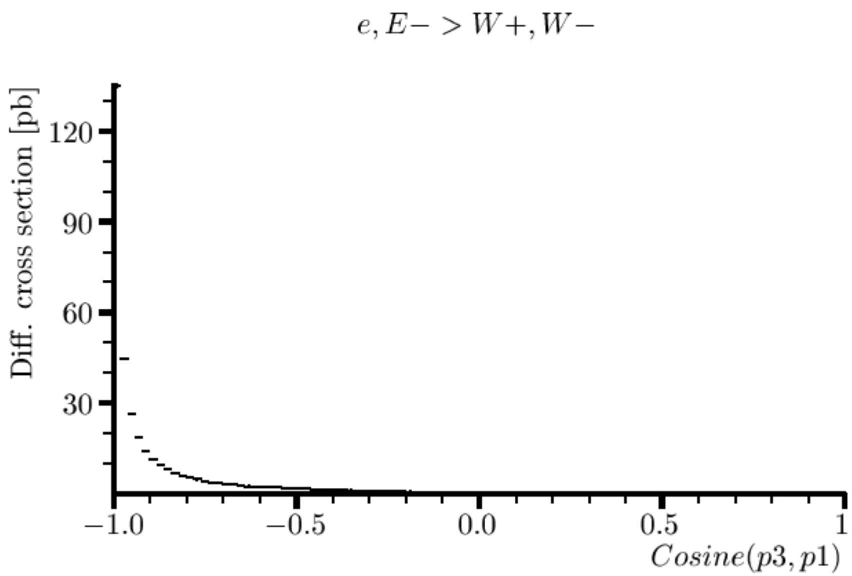
$e^+ + e^- \rightarrow W^+ + W^-$

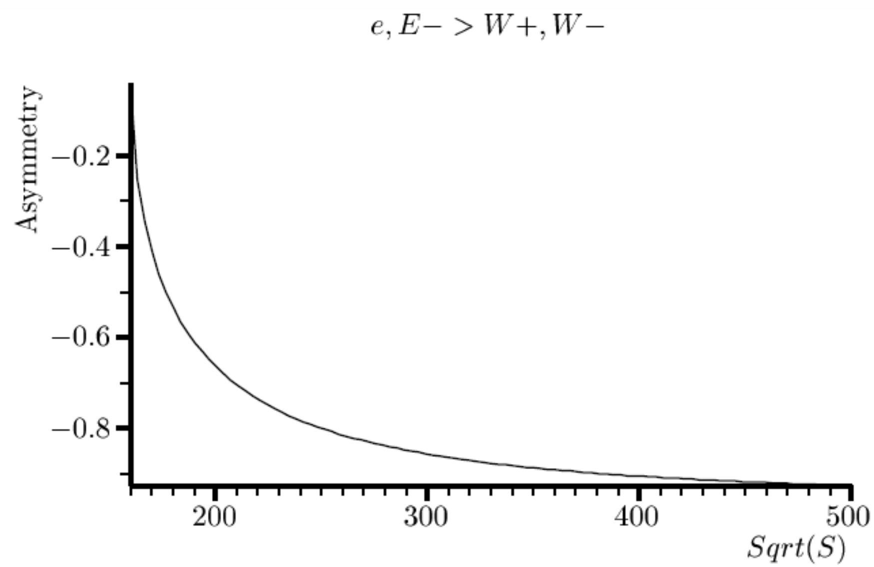


Angular Distributions and Asymmetry for $e^+e^- \rightarrow W^+W^-$

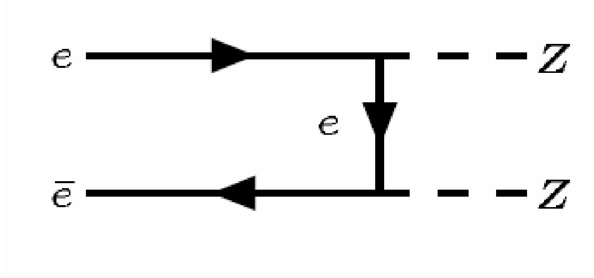


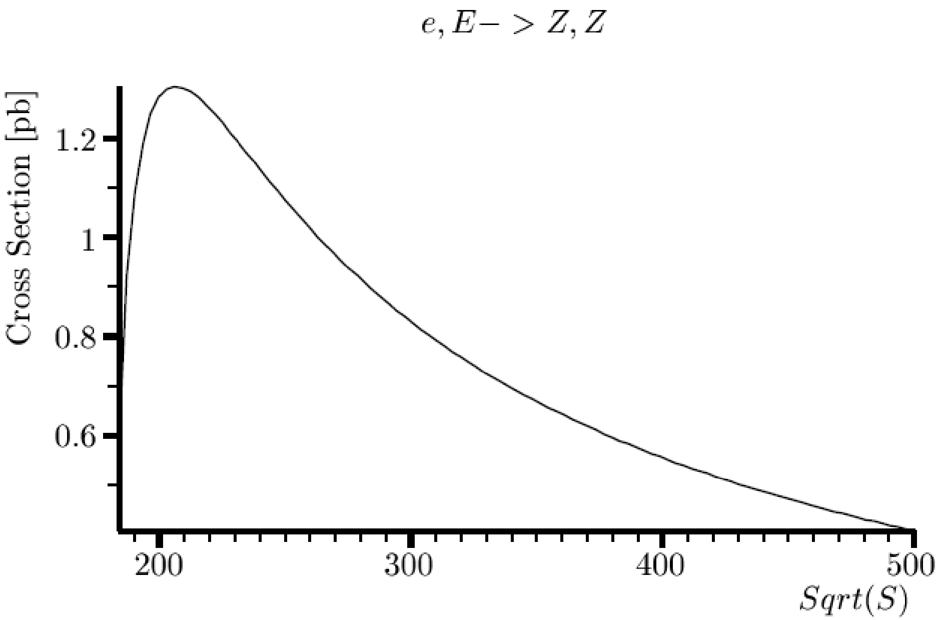


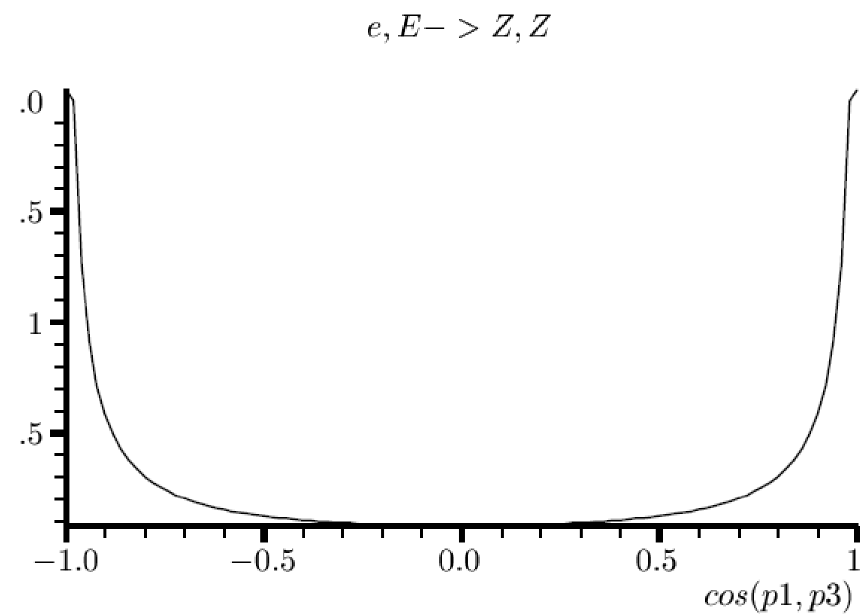




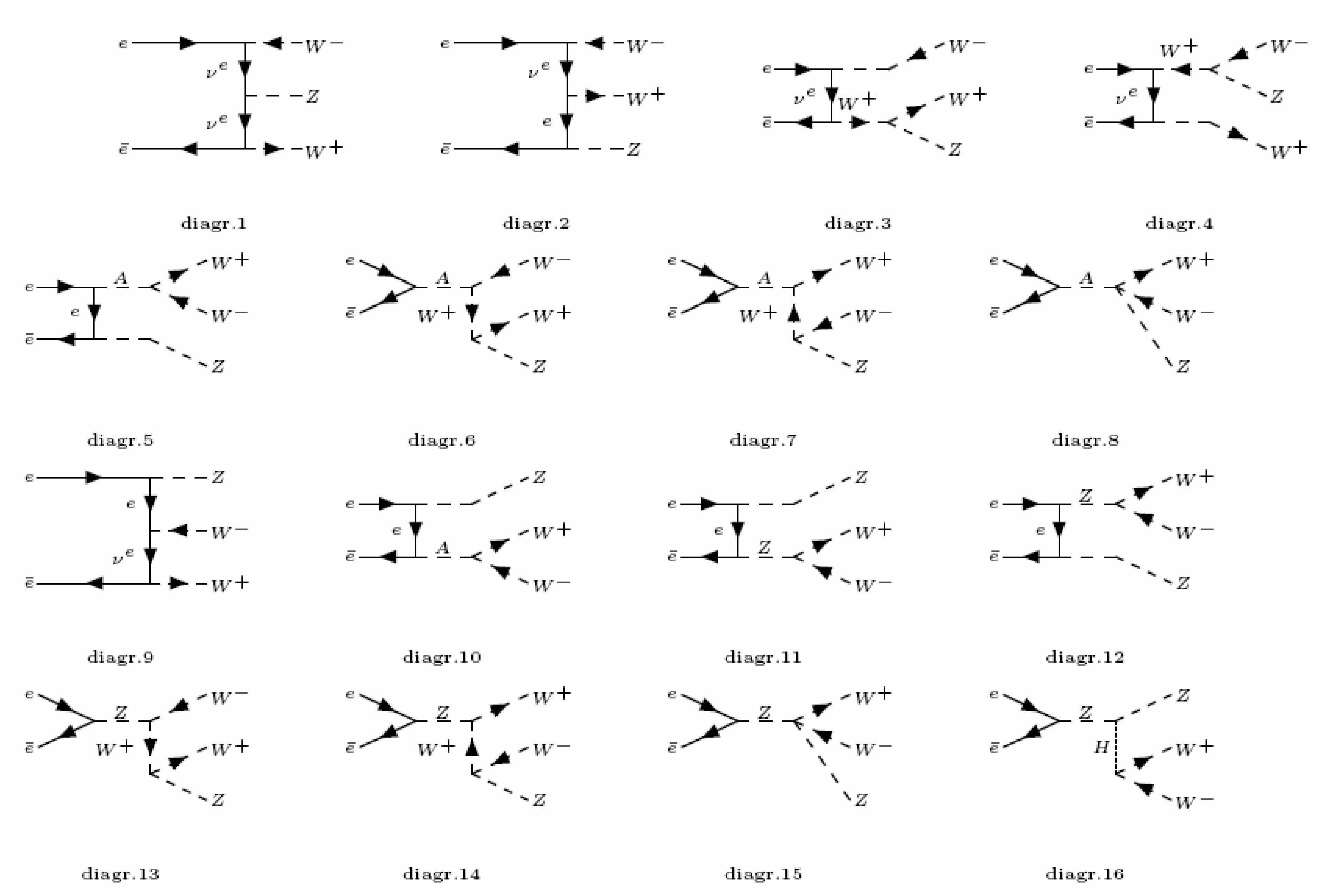
$e^{+} + e^{-} \rightarrow Z + Z$







CompHEP Diagrams for $e^+e^- \rightarrow W^+W^-Z$



pp Scattering Cross Sections

from talk by A. Sobol at US CMS meeting, April 7, 2006:

PYTHIA6.205/PHOJET1.12 predictions for cross sections at sqrt(s)=14 TeV

$\sigma_{tot}\,(101.5/119\,mb) \rightarrow \sigma_{elas}\,(22.2/34.4\,mb)$

$\sigma_{tot}\,(101.5/119\,mb) \rightarrow \sigma_{inelas}\,(79.3/84.5\,mb)$

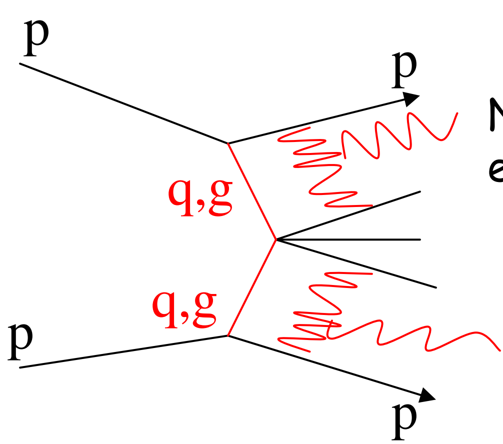
$\sigma_{inelas}\,(79.3/84.5\,mb) \rightarrow \sigma_{mb}\,(55.2/68\,mb)$

$\sigma_{inelas}\,(79.3/84.5\,mb) \rightarrow \sigma_{diff}\,(24.1/16.5\,mb)$

$\sigma_{diff}\,(24.1/16.5\,mb) \rightarrow \sigma_{sd}\,(14.3/11\,mb)$

$\sigma_{diff}\,(24.1/16.5\,mb) \rightarrow \sigma_{dd}\,(9.8/4.1\,mb)$

$\sigma_{diff}\,(24.1/16.5\,mb) \rightarrow \sigma_{cd}\,(\sim 1.4\,mb)$

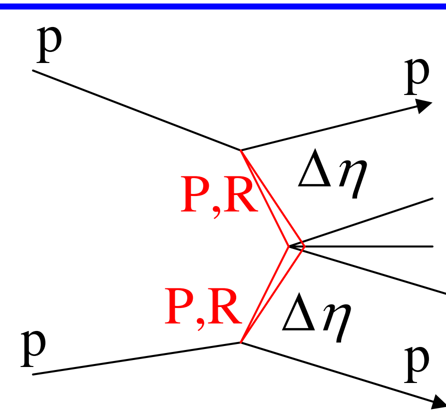


Non-Diffractive event

Exchange of color triplets, octets

- **exponential suppression of rapidity gaps**

(gaps filled by color exchange in hadronization)



Diffractive (central) event

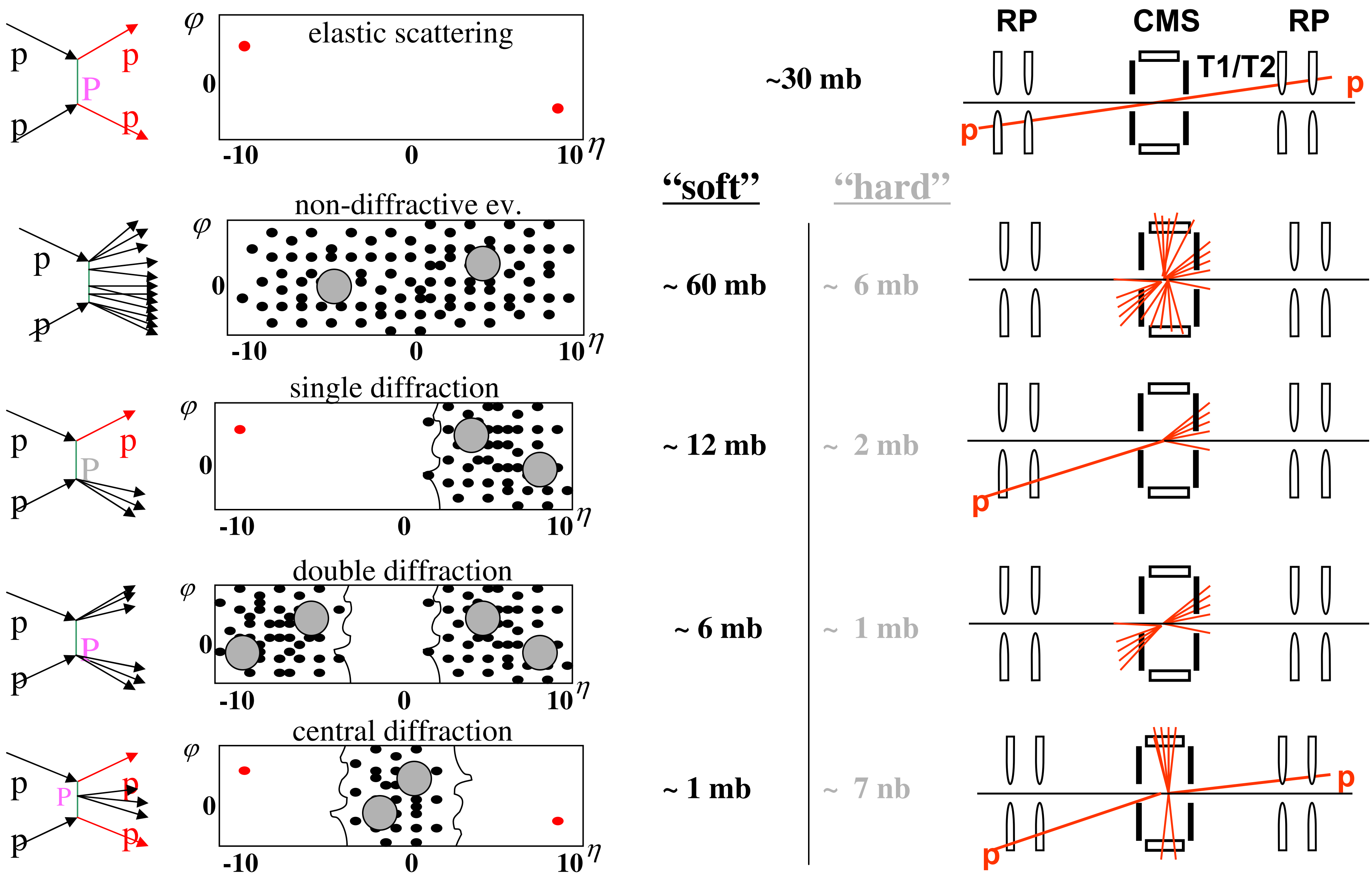
Exchange of color singlets: Reggeons, Pomerons

- **rapidity gaps** $\Delta\eta > 3-4$
- **momentum loss of the leading protons**

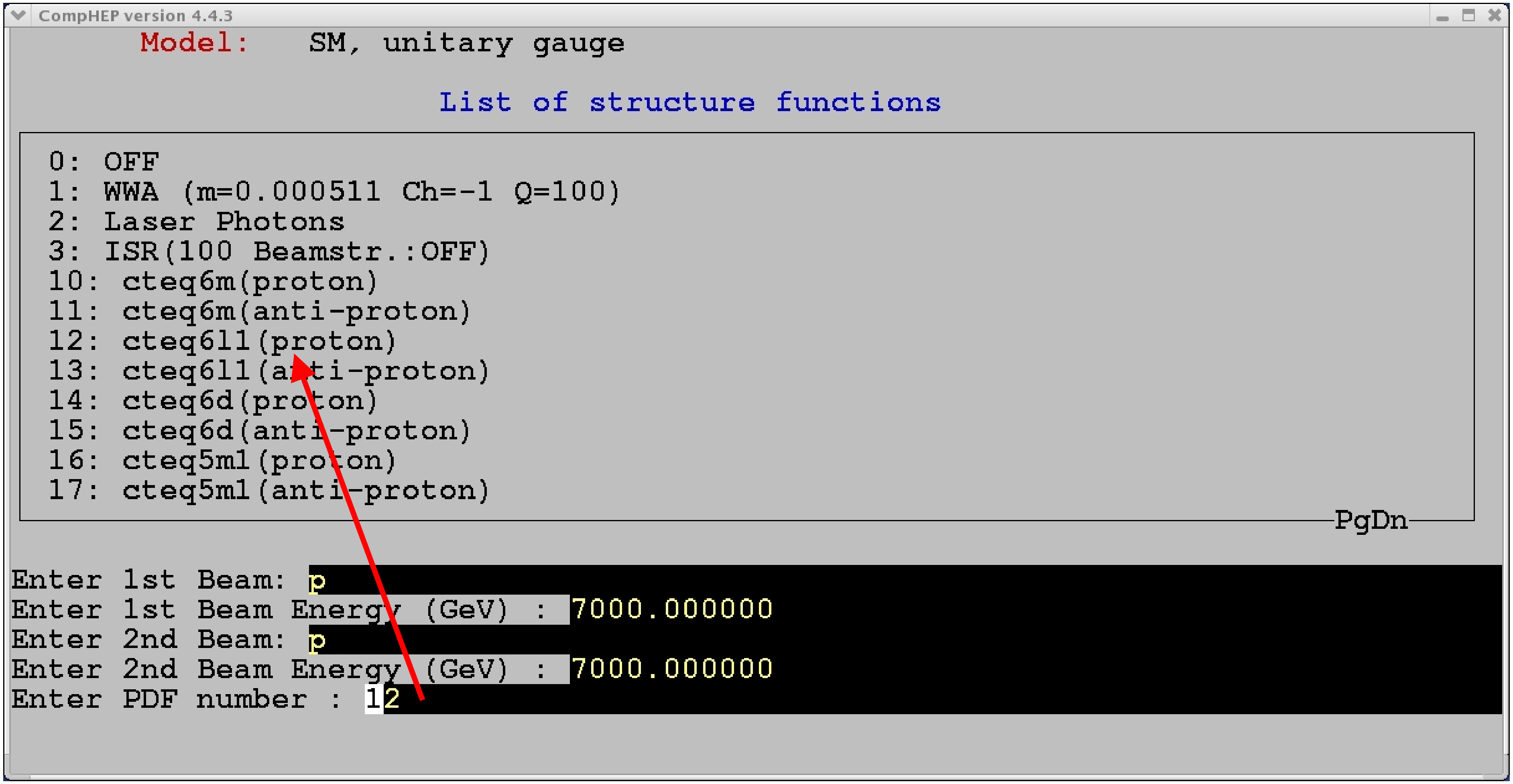
$$\xi = \frac{\Delta p}{p} < 0.05-0.1$$

Diffraction: events topologies

from talk by A. Sobol, US CMS meeting, April 7, 2006

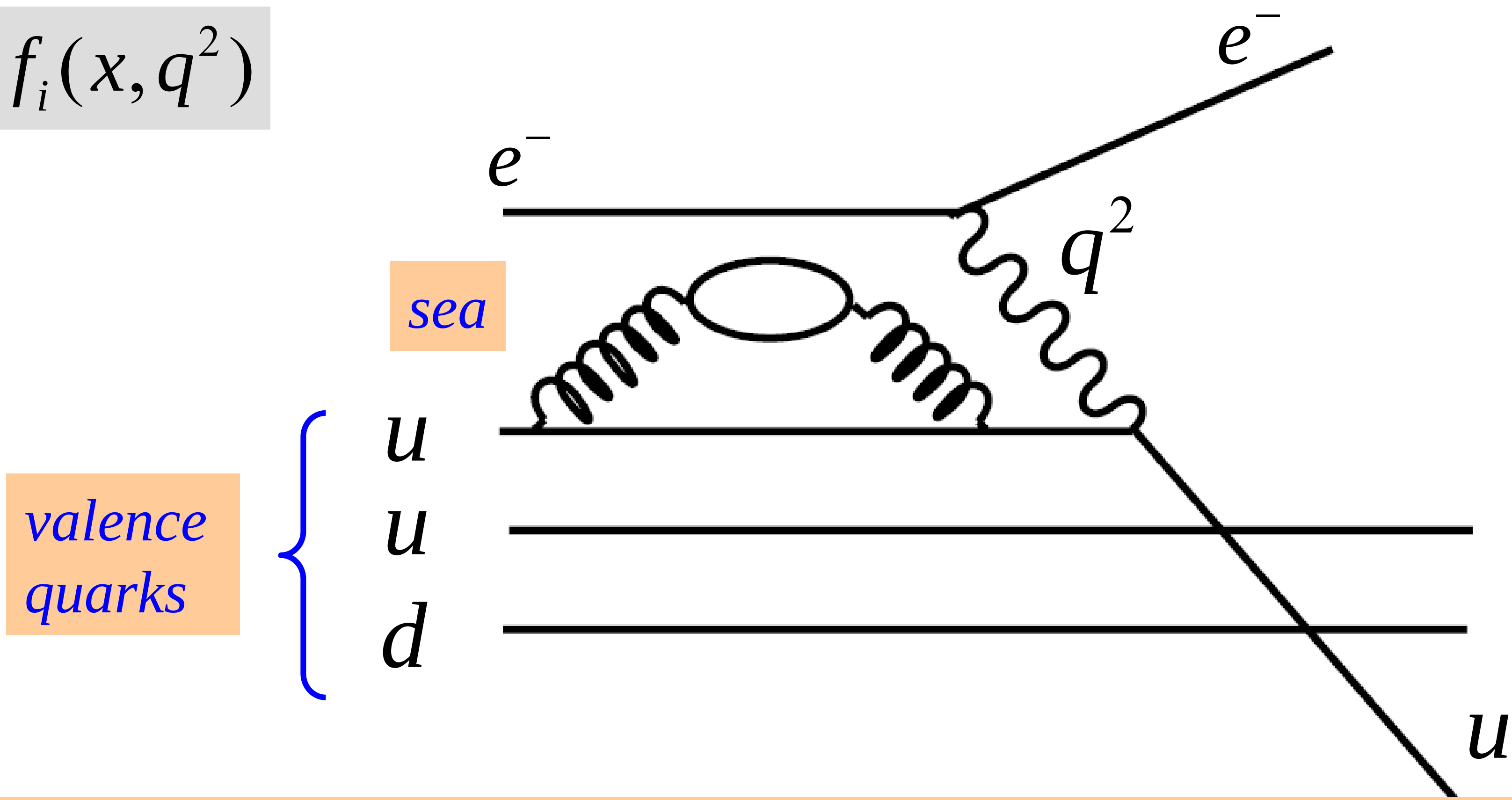


CompHEP: $p + p$ Scattering



Proton Structure Functions

$f_i(x, q^2)$

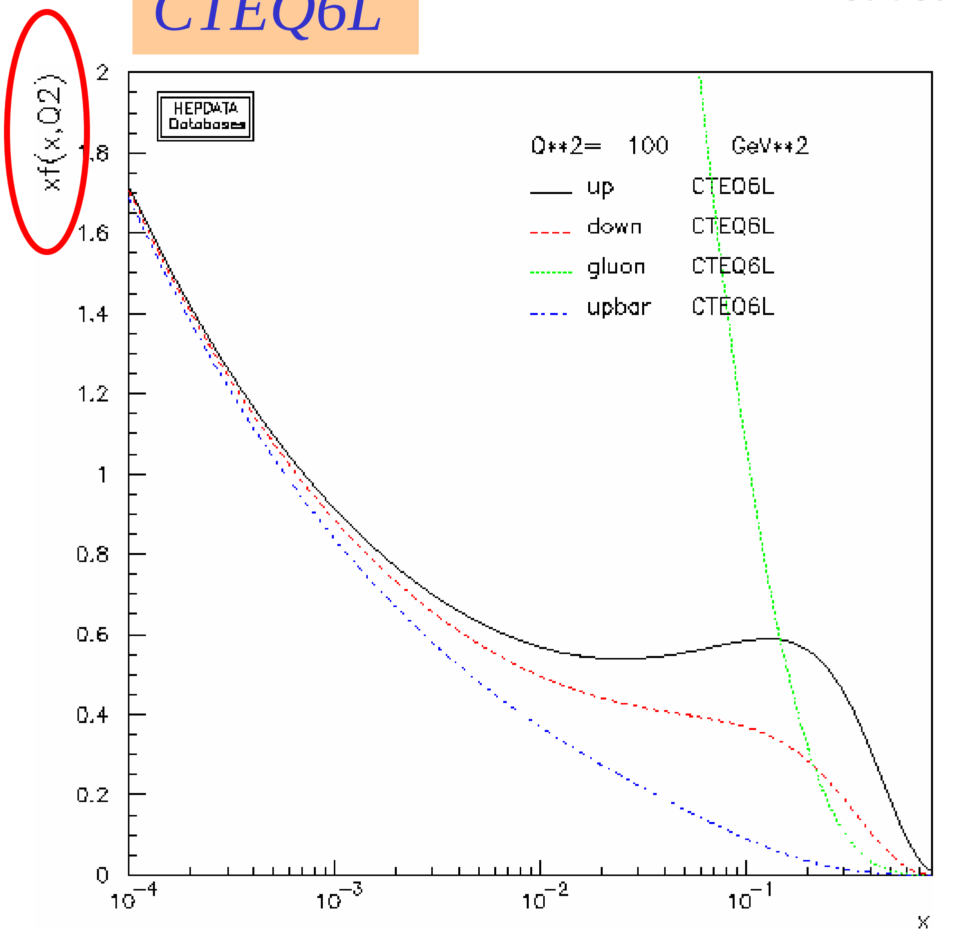


Prob to find a parton of type i carrying a fraction of the proton's longitudinal momentum $x = p^i_L / p_L$

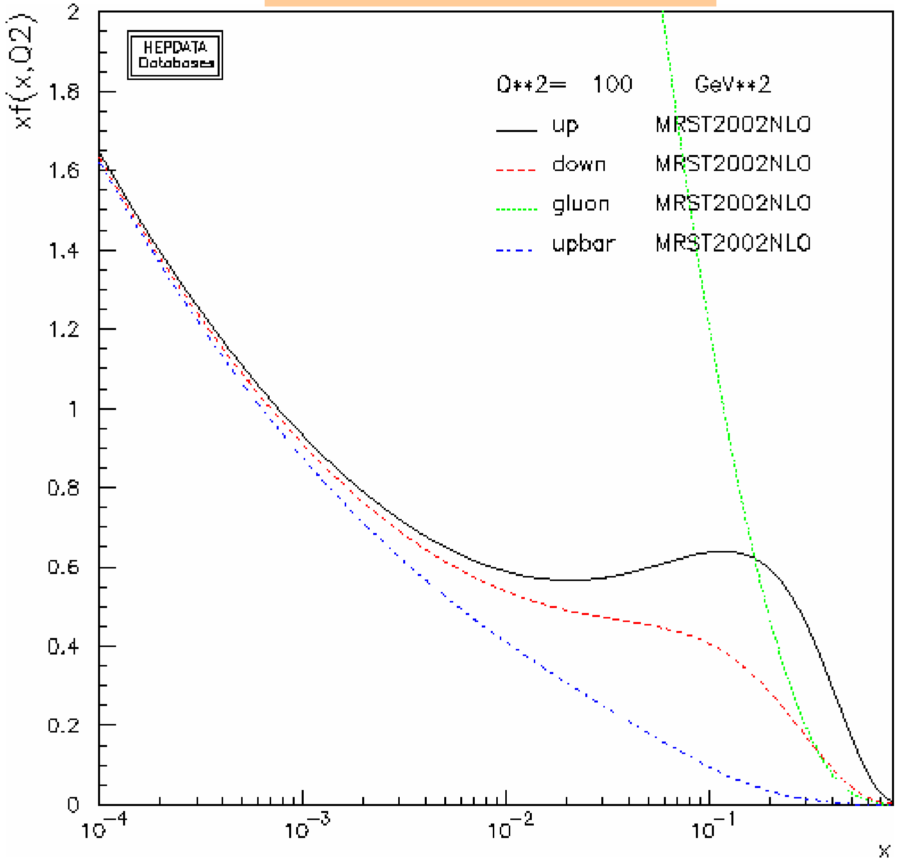
Cannot be calculated from 1st principles: extracted from data.

Structure functions from Durham HEP Database

CTEQ6L



MRST2002NLO

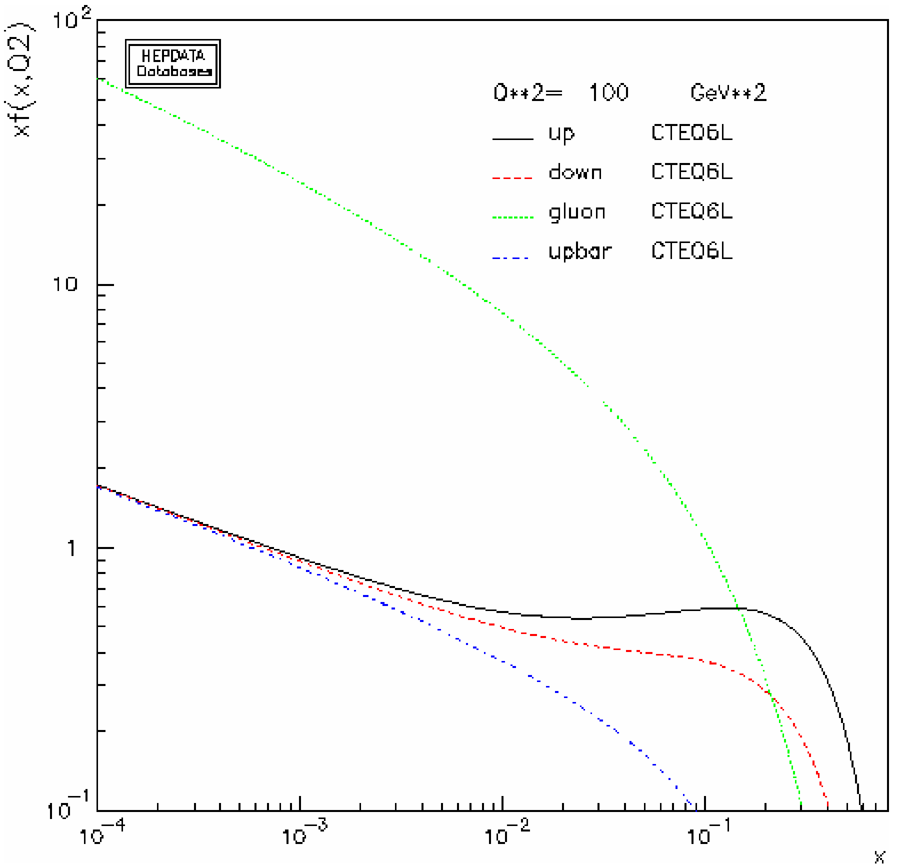


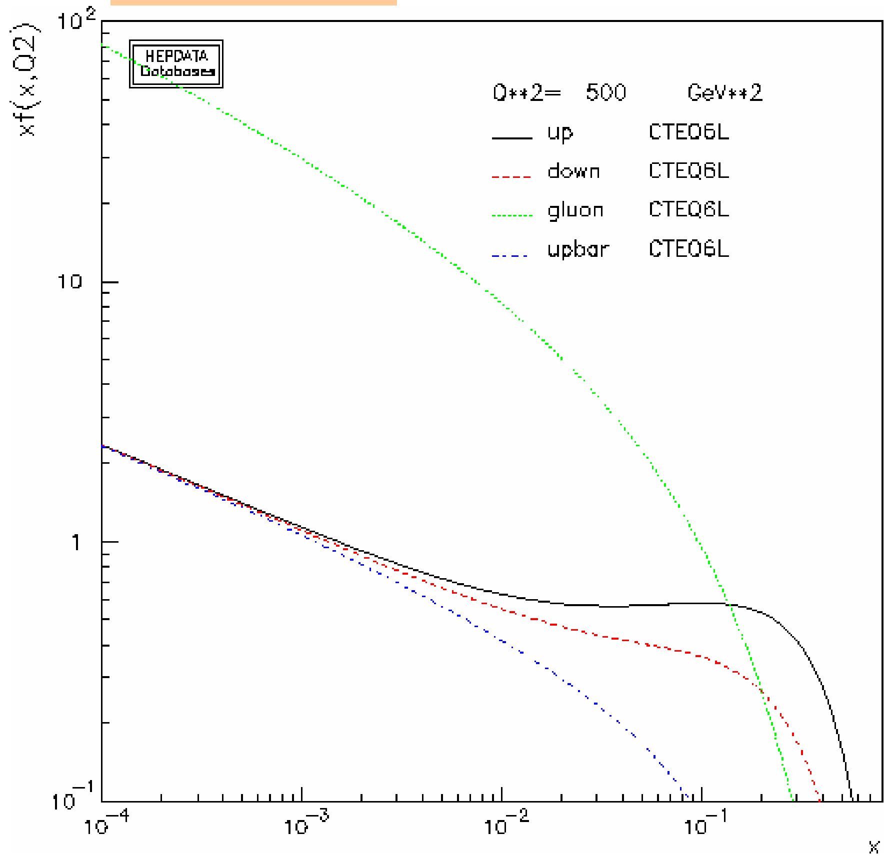
http://durpdg.dur.ac.uk/HEPDATA

Structure functions (Durham HEP database)

CTEQ6L $Q^2 = 100\ \text{GeV}^2$

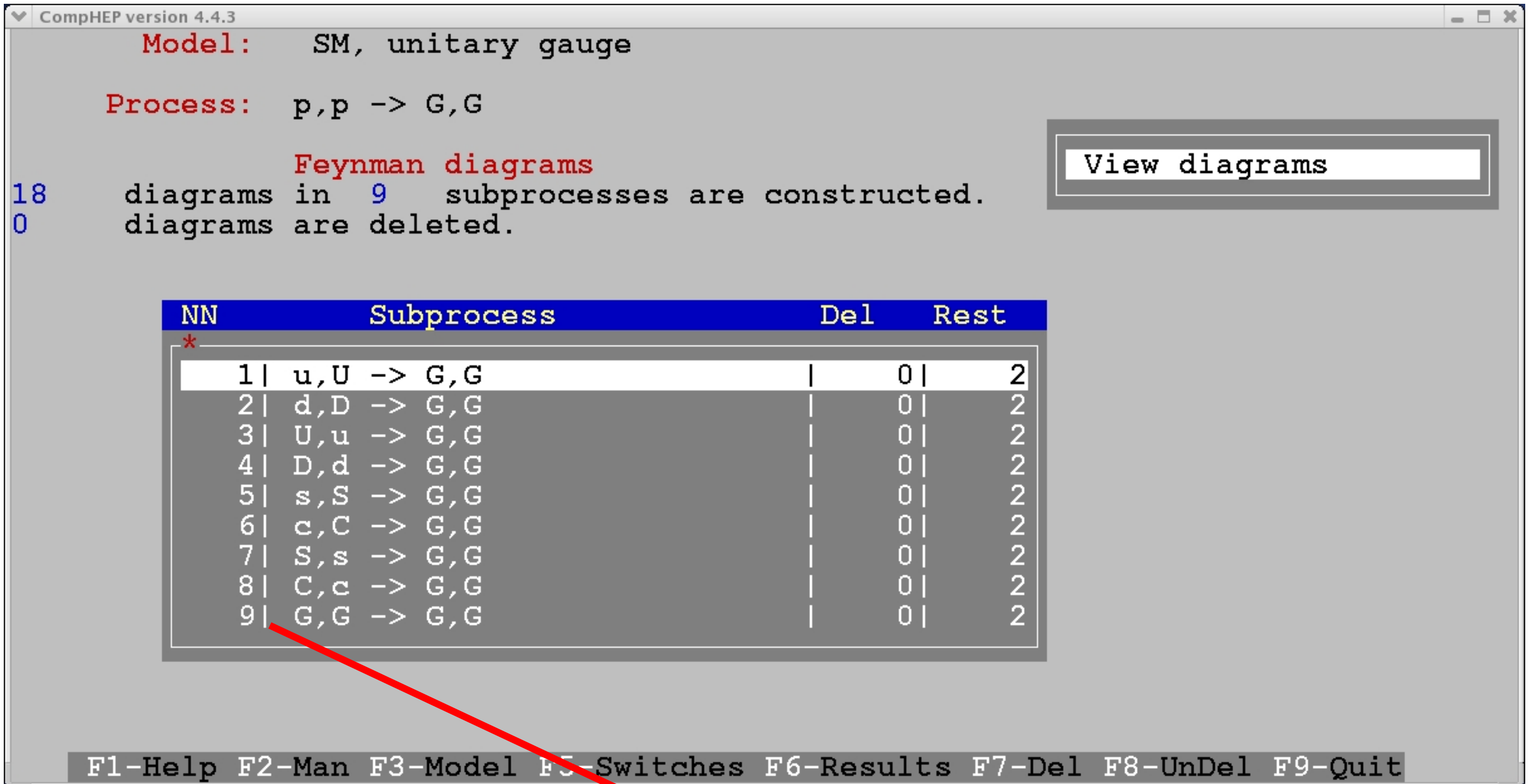
CTEQ6L $Q^2 = 500\ \text{GeV}^2$

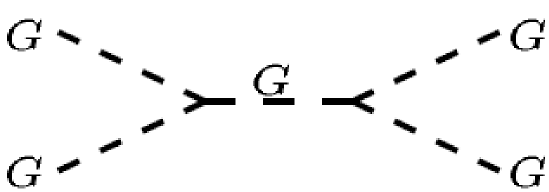


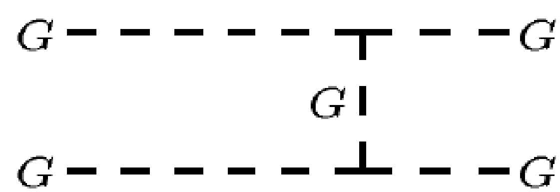


http://durpdg.dur.ac.uk/HEPDATA

$p + p \rightarrow G + G$ at 14 TeV

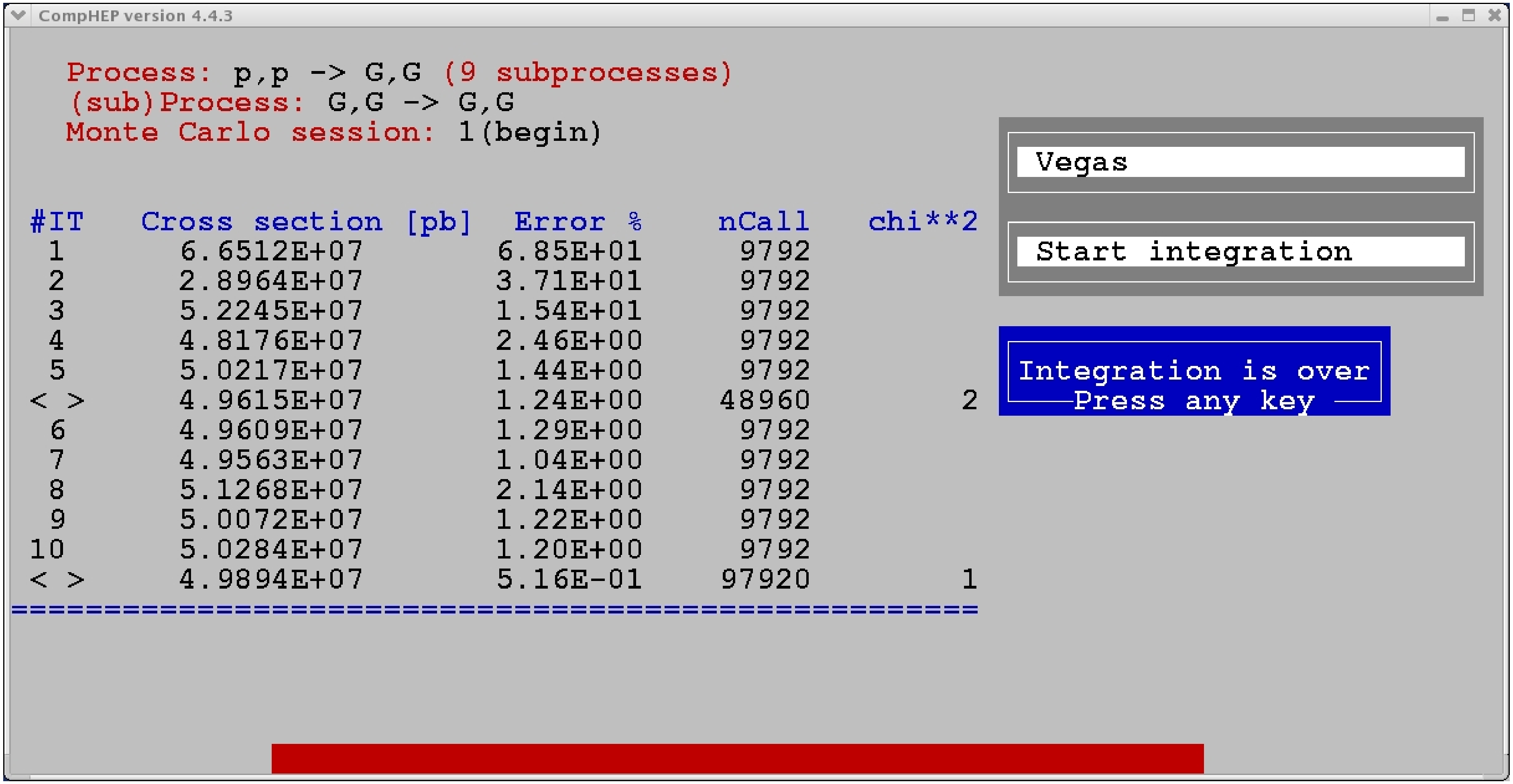






Apply cut before computing cross section: $p_t(G) > 35$ GeV

$p + p \rightarrow G + G$ at 14 TeV


CompHEP version 4.4.3

Process: p,p -> G,G (9 subprocesses)
(sub)Process: G,G -> G,G
Monte Carlo session: 1(begin)

#IT	Cross section [pb]	Error %	nCall	chi**2
1	6.6512E+07	6.85E+01	9792	
2	2.8964E+07	3.71E+01	9792	
3	5.2245E+07	1.54E+01	9792	
4	4.8176E+07	2.46E+00	9792	
5	5.0217E+07	1.44E+00	9792	
< >	4.9615E+07	1.24E+00	48960	2
6	4.9609E+07	1.29E+00	9792	
7	4.9563E+07	1.04E+00	9792	
8	5.1268E+07	2.14E+00	9792	
9	5.0072E+07	1.22E+00	9792	
10	5.0284E+07	1.20E+00	9792	
< >	4.9894E+07	5.16E-01	97920	1

Vegas

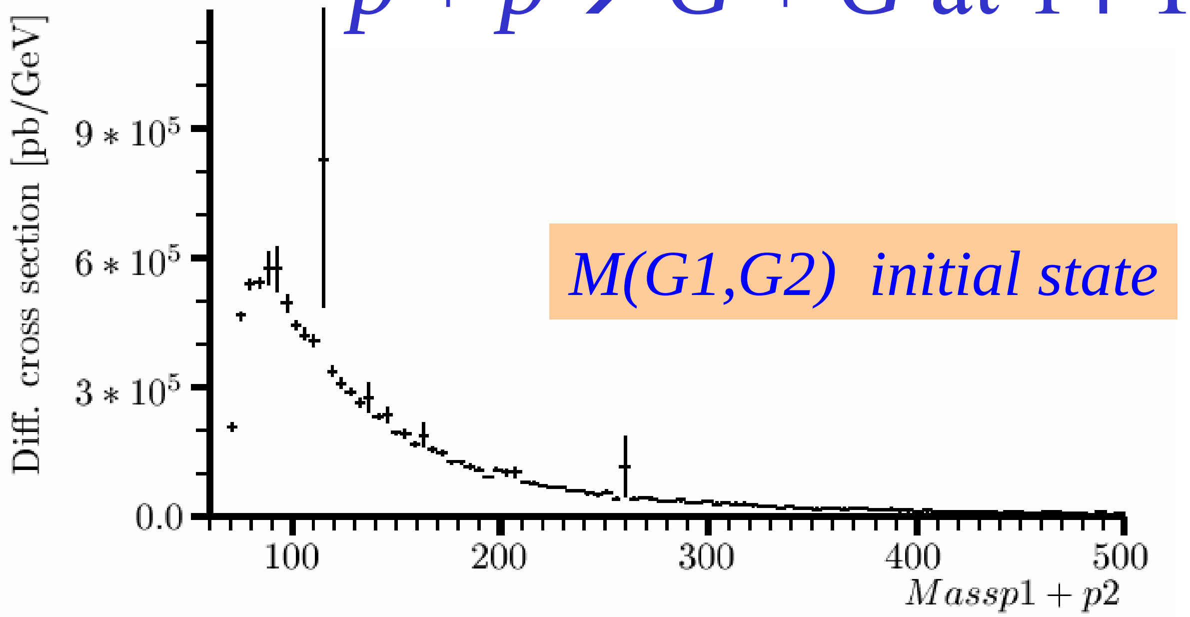
Start integration

Integration is over
Press any key

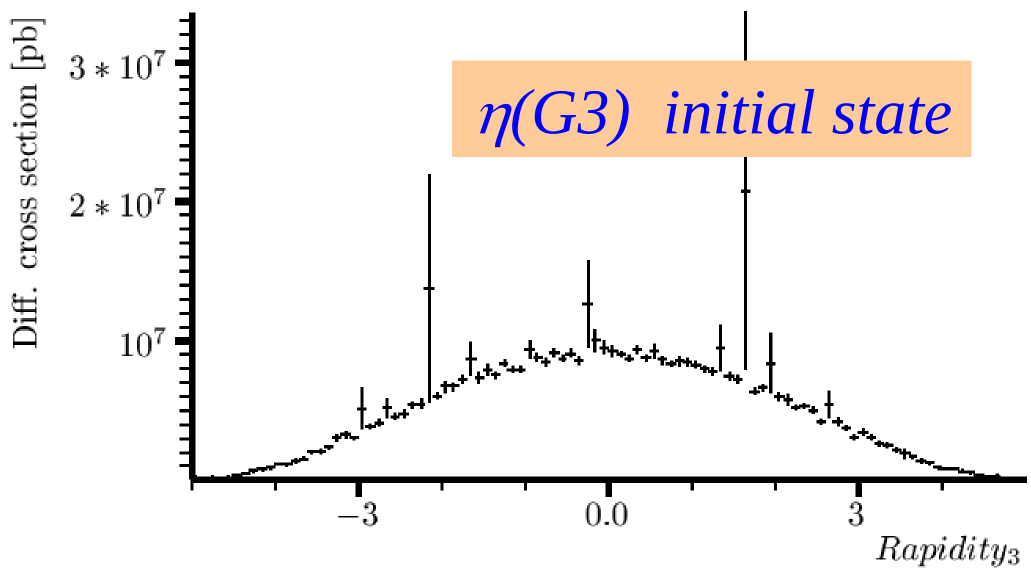
$$\sigma(pp[GG] \rightarrow GG) \simeq 5 \times 10^7 \text{ pb} \simeq 0.05 \text{ mb}$$

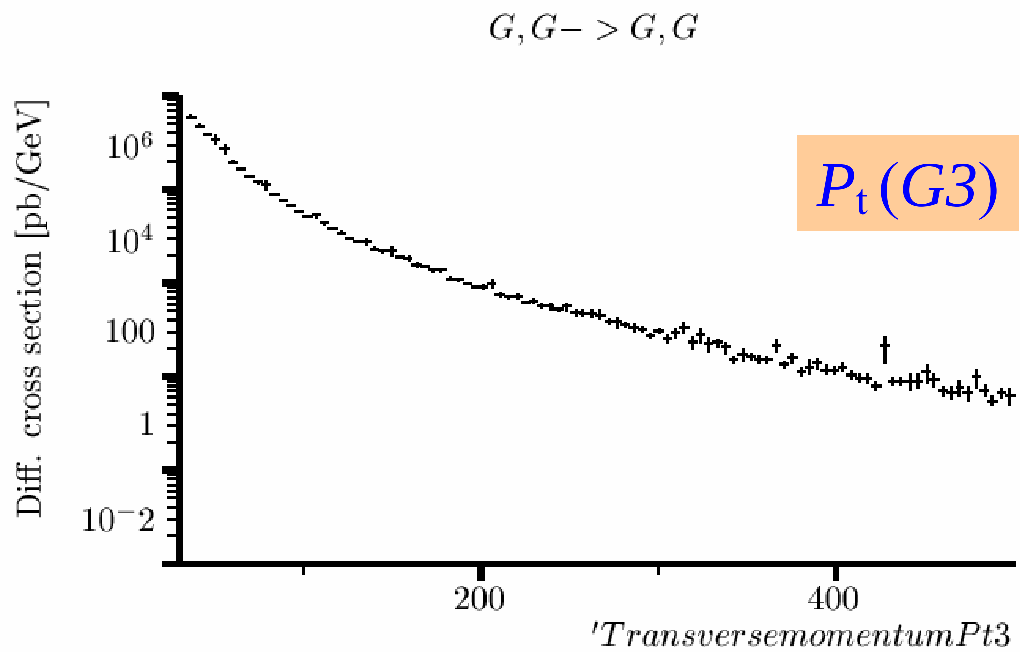
LHC

$p + p \rightarrow G + G$ at 14 TeV

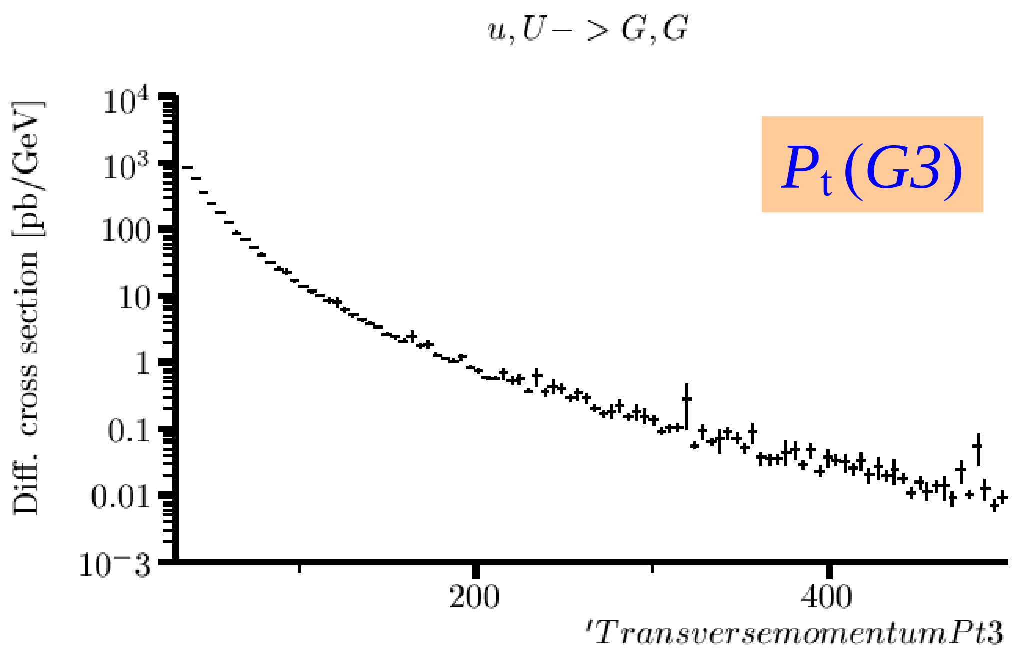


G, G− > G, G



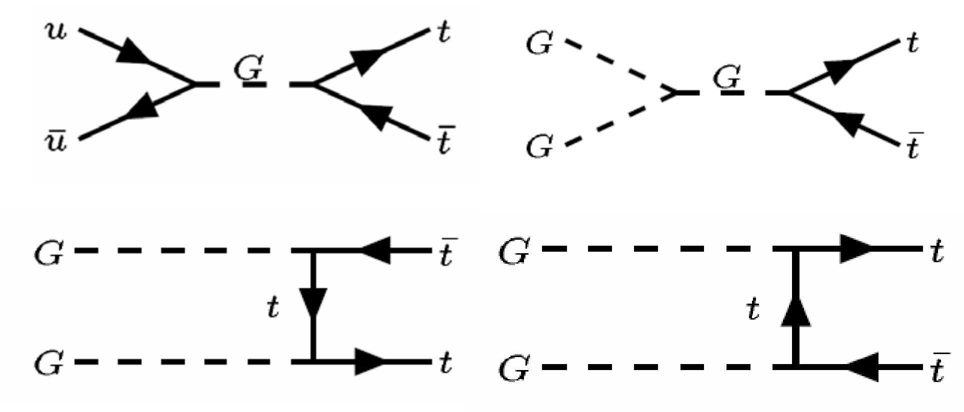


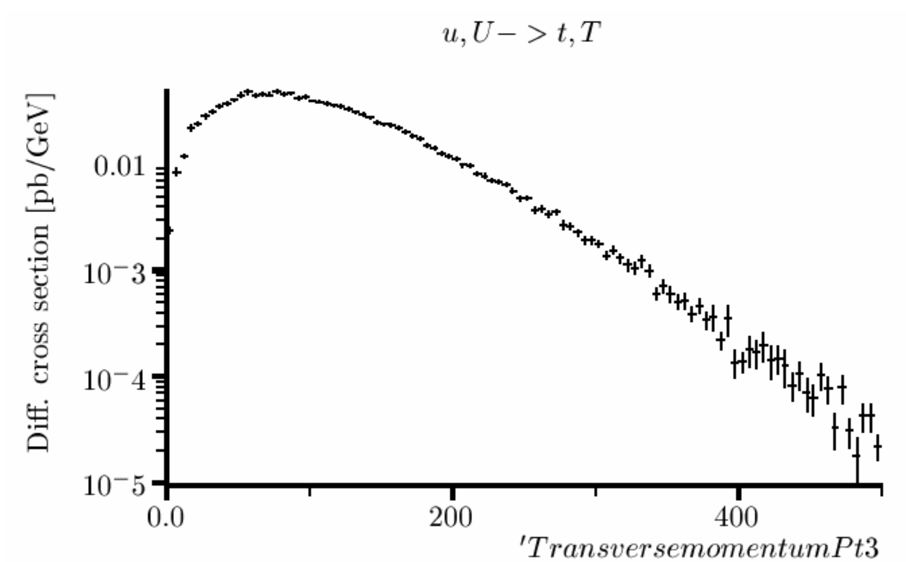
$G, G- > G, G$
Diff. cross section [pb/GeV]
10^6
10^4
100
1
10^{-2}
200
400
$'Transversemomentum Pt3$
$P_t (G3)$



$u, U- > G, G$
Diff. cross section [pb/GeV]
10^4
10^3
100
10
1
0.1
0.01
10^{-3}
200
400
$'Transversemomentum Pt3$
$P_t (G3)$

$p + \bar{p} \rightarrow t + \bar{t}$





CompHEP at $\sqrt{s} = 2.0$ TeV

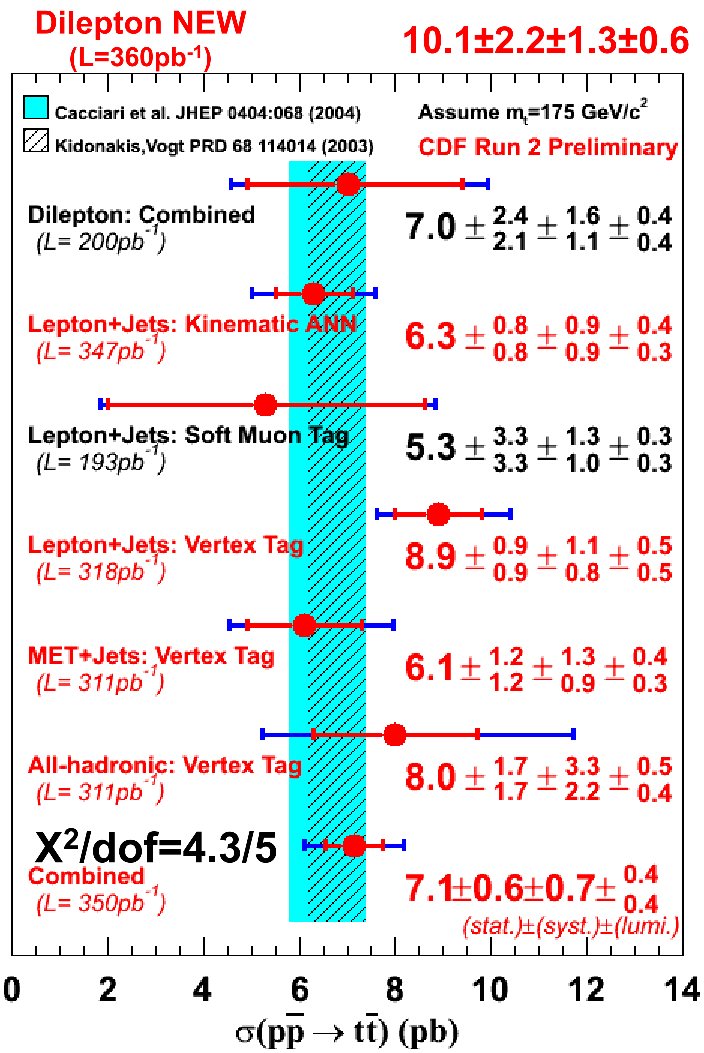
Process	σ(pb)
$u\bar{u} \rightarrow t\bar{t}$	6.88
$d\bar{d} \rightarrow t\bar{t}$	1.28
$gg \rightarrow t\bar{t}$	0.53
$\bar{u}u \rightarrow t\bar{t}$	0.014
Total	8.7

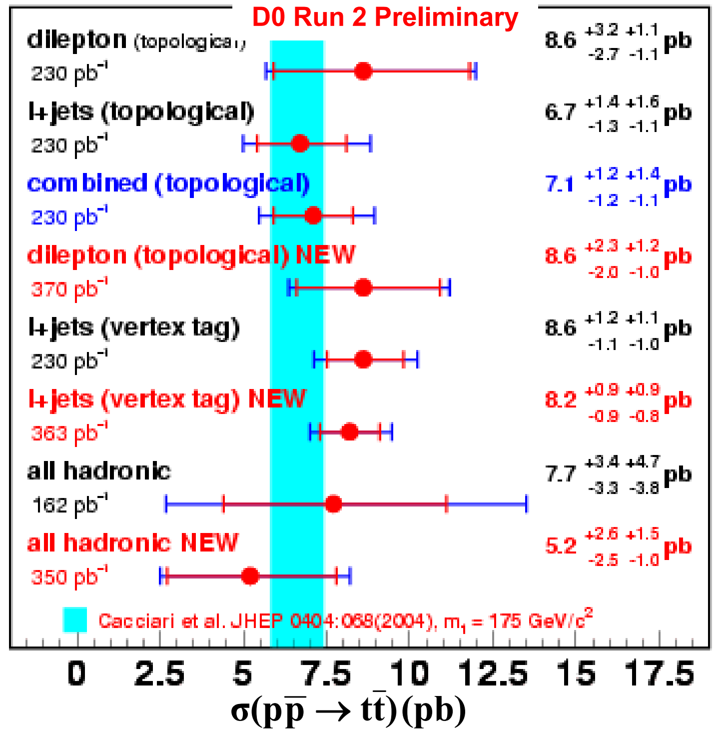
$m_t = 174.3$ GeV

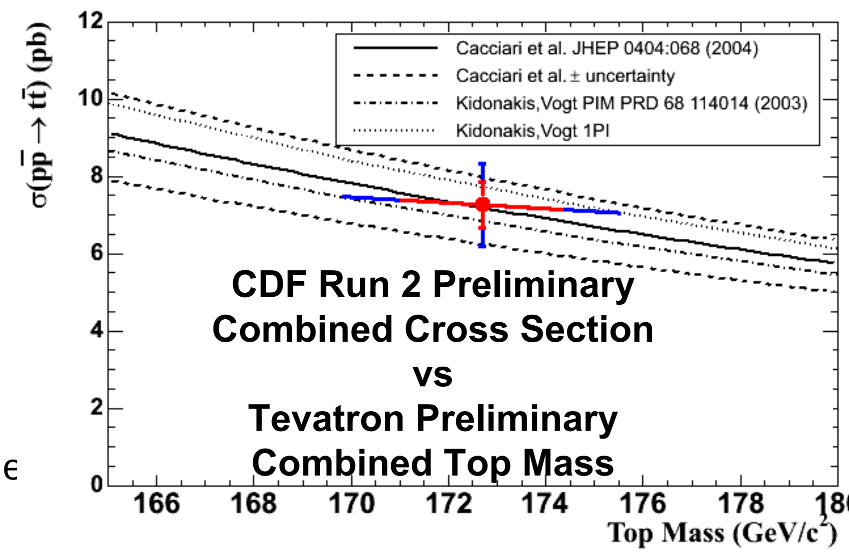
Top Pair Production Rate

Evelyn Thomson talk at PANIC 2005

- Are measurements in different final states consistent with each other and with theory?

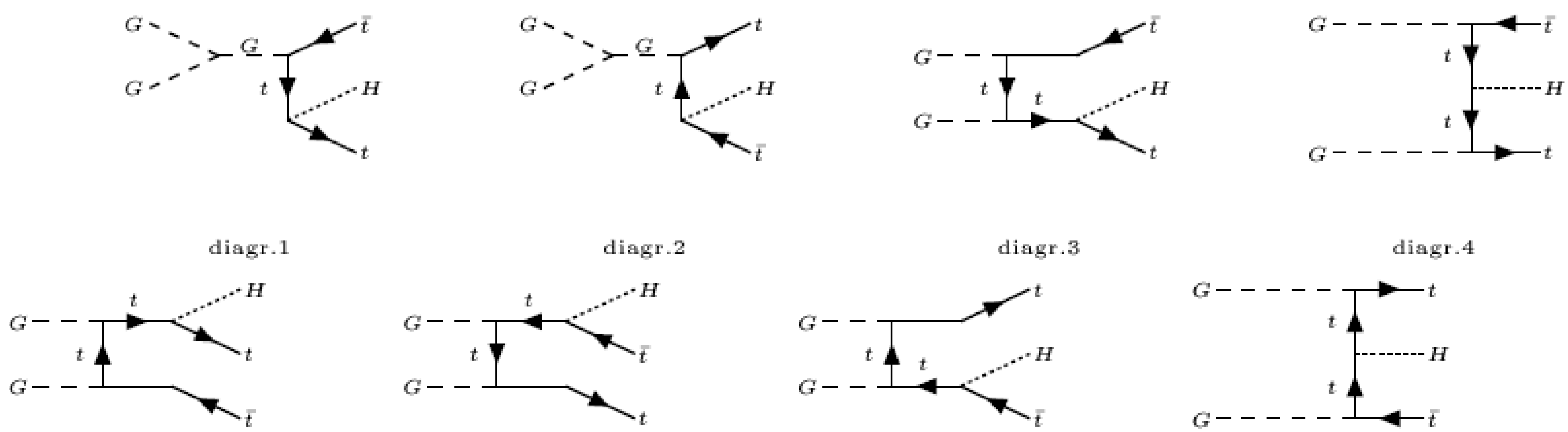






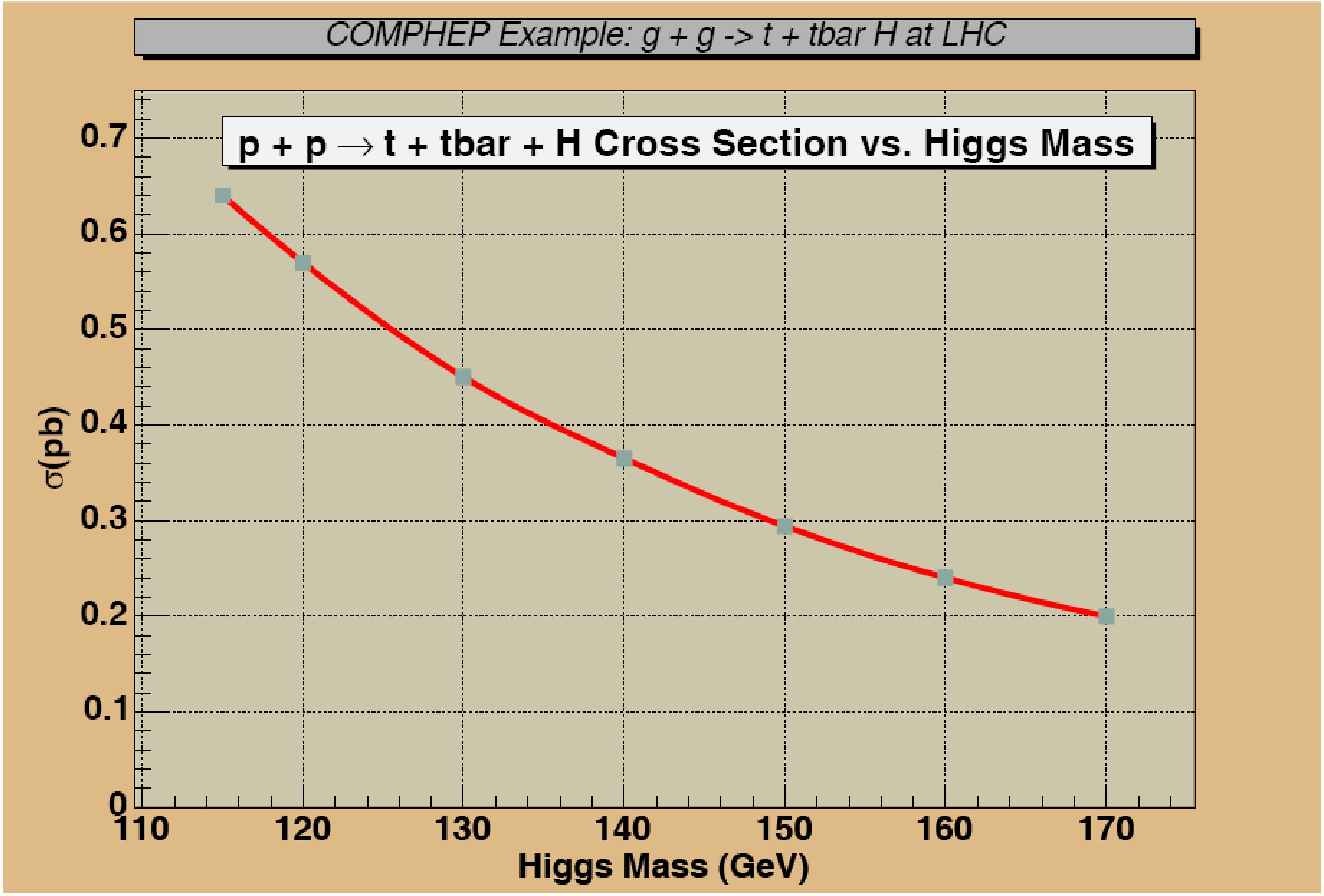
$p + p \rightarrow t + \bar{t} + H$

- At the LHC, the mode with best sensitivity for a low-mass Higgs particle appears to be $H \rightarrow \gamma\gamma$.
- By looking for the Higgs in association with t quarks, we might be able to see $H \rightarrow b\bar{b}$, which would be the dominant decay mode.



(Also have production from initial-state quarks.)

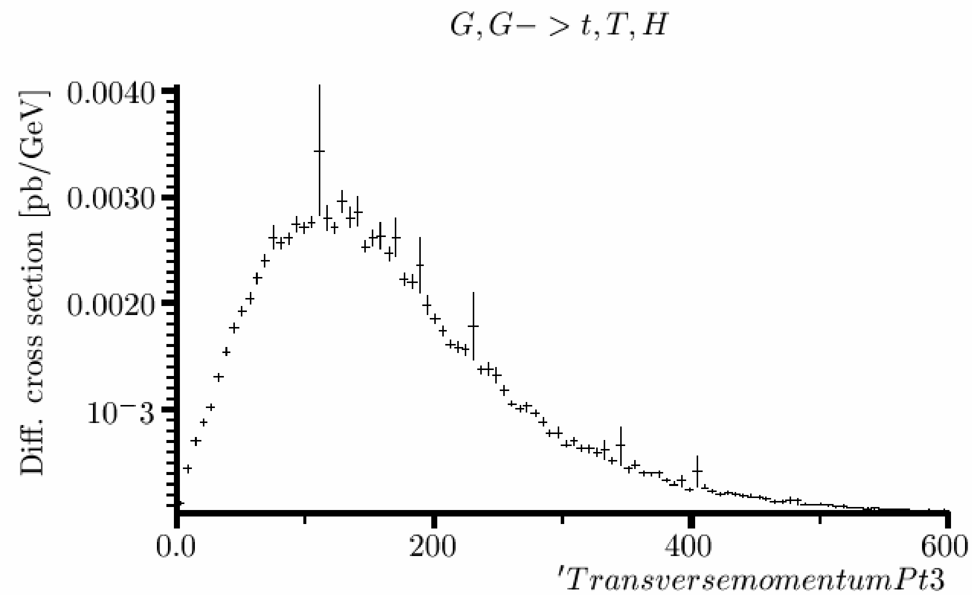
Signal cross section vs. *m*(*H*)

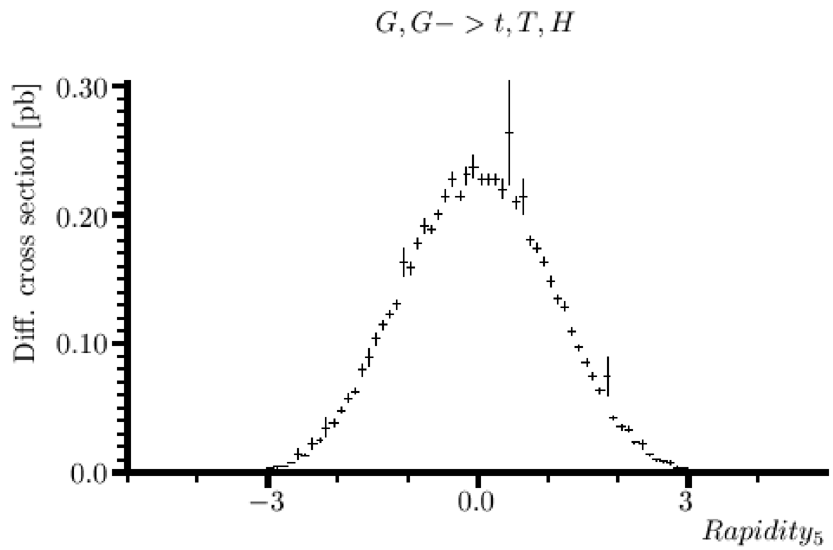


$p + p \rightarrow t + \bar{t} + H$

$\sqrt{s} = 14$ TeV $\quad m_H = 115$ GeV

Process	σ (pb)
$gg \rightarrow t\bar{t}H$	0.647
$u\bar{u} \rightarrow t\bar{t}H$	0.074
$d\bar{d} \rightarrow t\bar{t}H$	0.045
Total (gg+2uu+2dd)	0.885





Challenge: Backgrounds from pp→$t\bar{t}$gg and pp→$t\bar{t}b\bar{b}$

$$\sigma(gg \rightarrow t\bar{t}gg) \approx 400 \text{ pb}$$

$p_t(g \text{ jets}) > 20$ GeV), $|\eta_{\text{jets}}| < 3$, $\cos\theta_{jj} < 0.7$

$$\sigma(gg \rightarrow t\bar{t}b\bar{b}) \approx 6 \text{ pb}$$

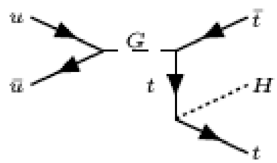
$p_t(b \text{ jets}) > 20$ GeV)

Background cross sections should not be taken too literally…

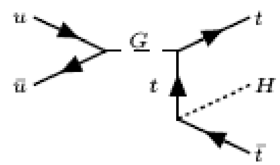
Conclusions

- CompHEP is very fast and easy. It can provide a quick look at the overall situation for a physics analysis at the LHC.
- It seems to be fairly reliable for electroweak processes.
- Strong interaction processes and corrections are complicated, especially the identification of jets with partons. Predictions based on CompHEP alone—without jet fragmentation– must be treated with a lot of caution!
- Next step: understand how CompHEP events can be given to Pythia to treat the jet fragmentation.

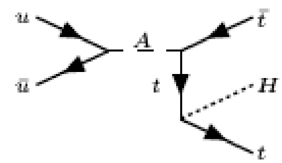
Extra Slides



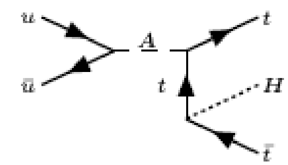
diagr.1



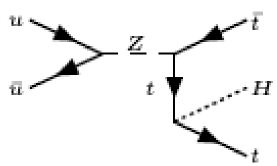
diagr.2

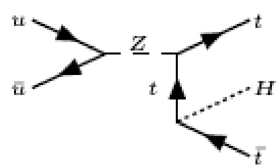


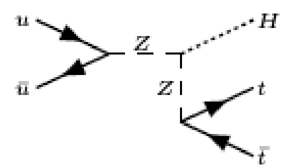
diagr.3



diagr.4



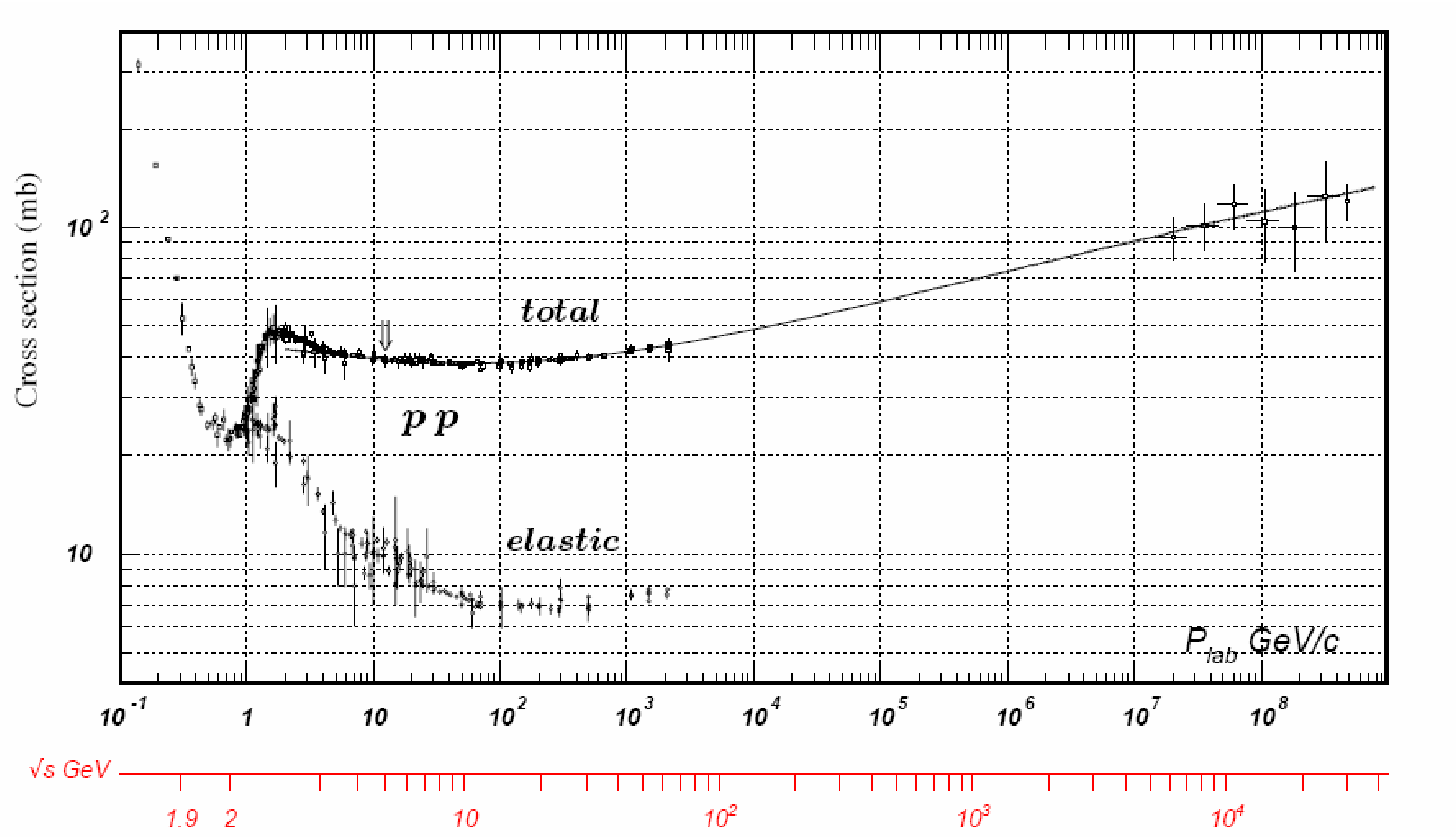




Energy Scales

- Band gap of silicon: 1.12 eV
- Binding energy of H-atom (n=1): 13.6 eV
- Binding energy per nucleon in typical nucleus: 8 MeV
- Mass of proton (940 MeV) and neutron (940 MeV)
- Mass of b quark: 4.6 GeV
- Masses of W (80 GeV) and Z (91 GeV)
- Mass of t quark: 174 GeV
- Vacuum expectation value of Higgs field
- Planck mass:

$p+p$ scattering cross section from PDG



Higgs Branching Fractions