Collider Physics

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July 16,17,18,19, 2018

Chapt. 1: Introduction } Lect. 1
Chapt. 2: Basic formalism }
Chapt. 3: Kinematics & phase space } Lect. 2
Chapt. 4: Particle detection @ colliders }
Chapt. 5: Lepton colliders Lect. 3
Chapt. 6: Hadron colliders Lect. 4

Four 1.5-hr lectures

Approach:

- Pedagogical
- Self-contained
- Basic concepts & methods
- Avoid technicalities & specific models

References:

arXiv:hep-ph/0508097, TASI lecturer notes, Han;
arXiv:1002.0274, TASI lecture notes, Perelstein;
arXiv:0910.4182, TASI lecture notes, Plehn.

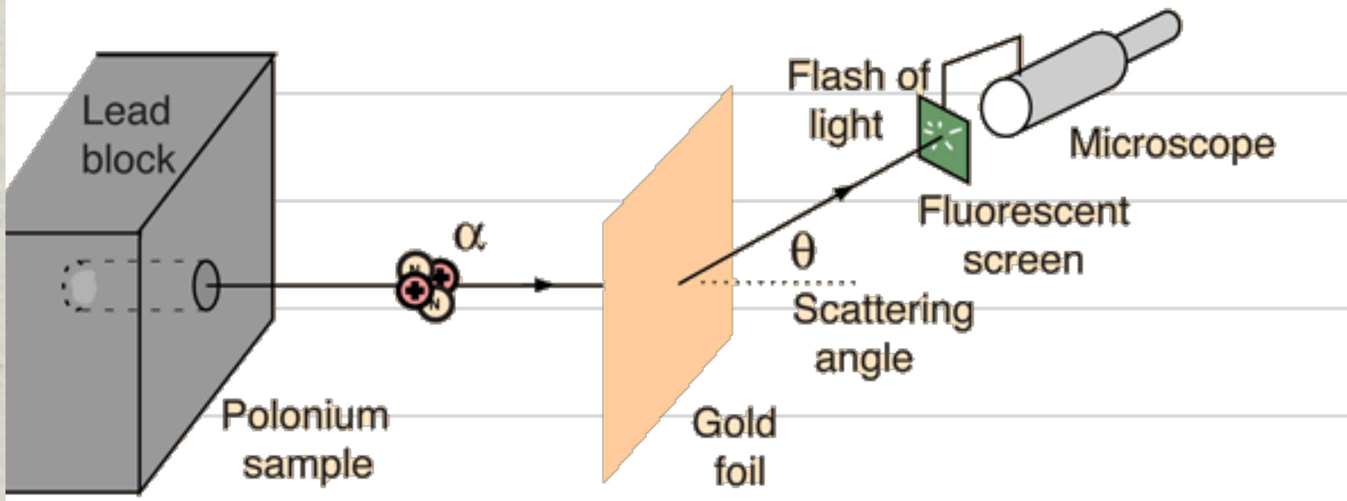
Book:

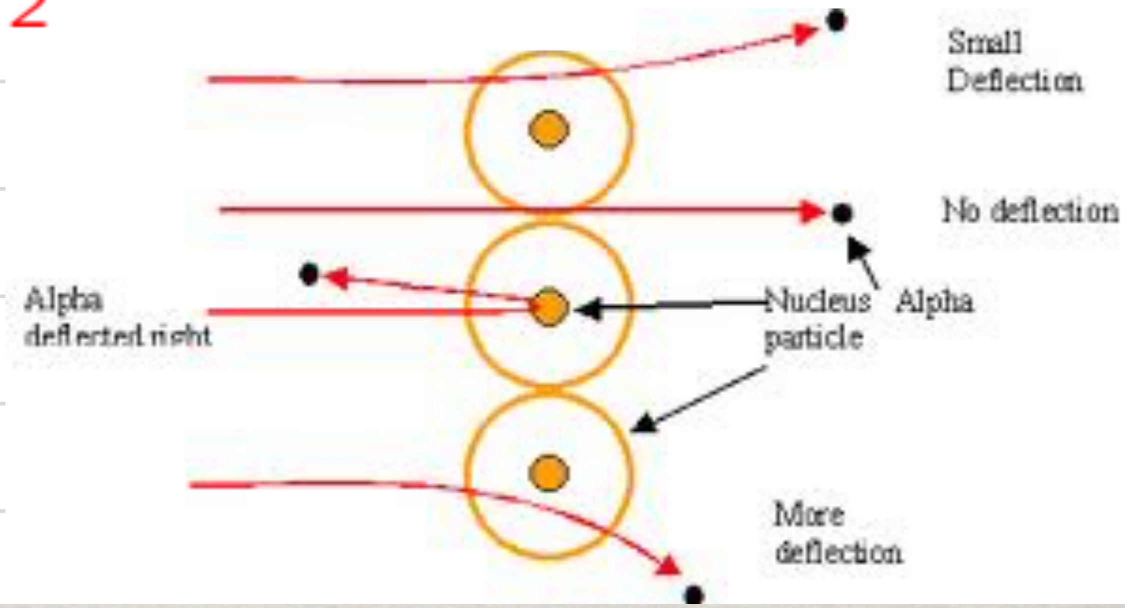
"Review of Particle Physics", PDG: Chin Phys C40 (2016);
"Collider Physics", Barger & Phillips (1987);
"The Black Book of QCD", Campbell, Huston, Krauss (2017).

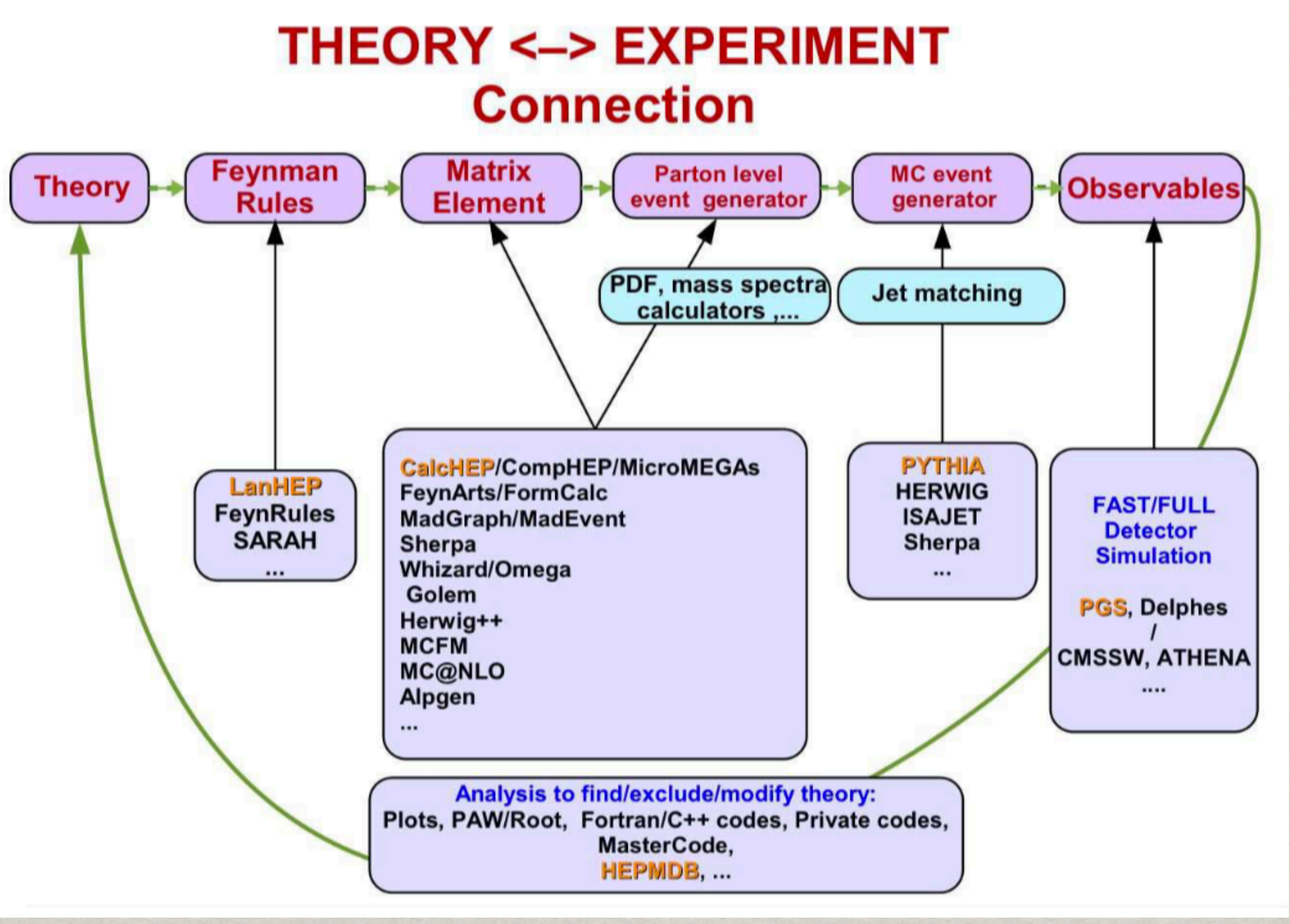
Lecture 1: Introduction

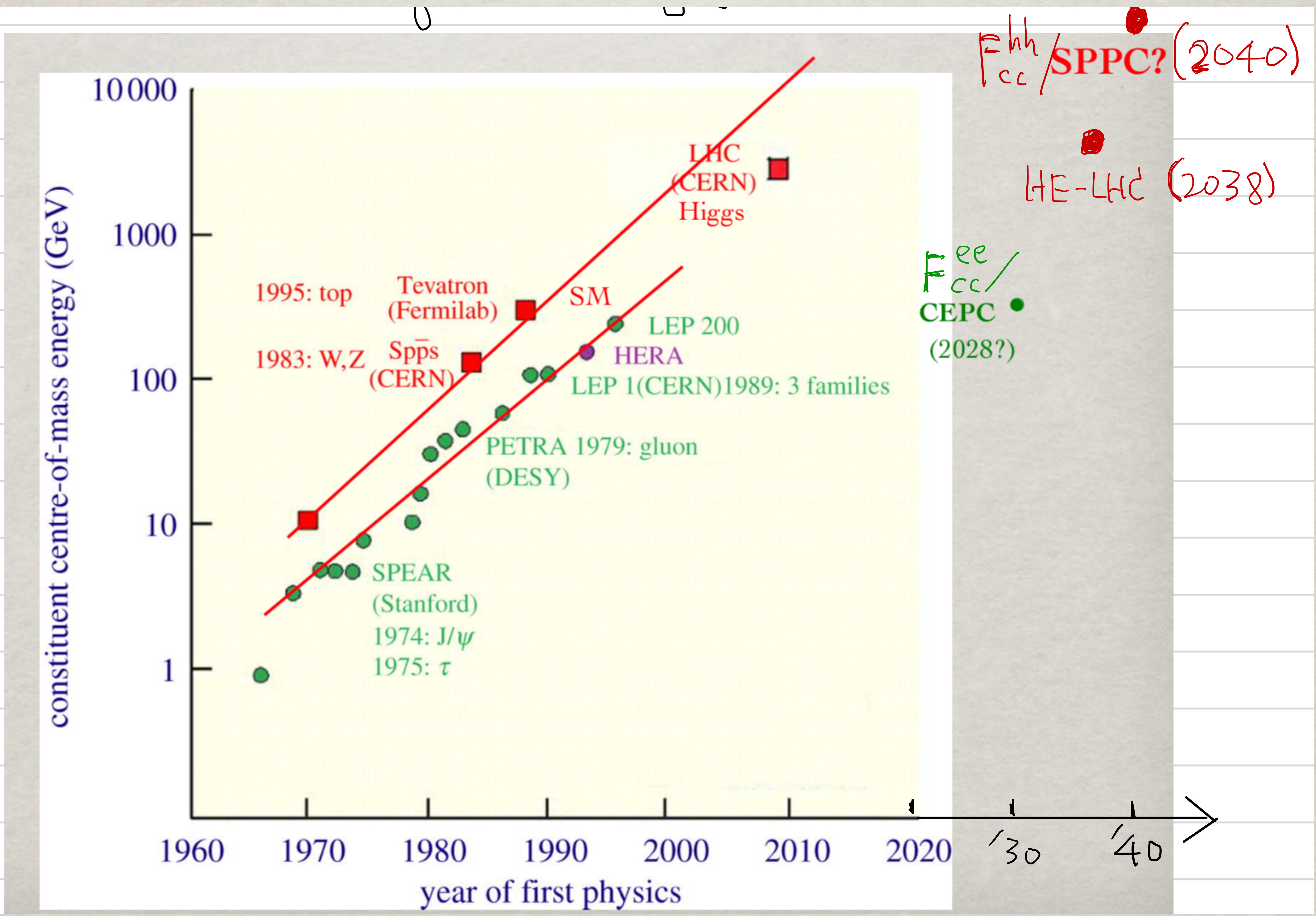
the point-like nucleus:

$$\frac{d\sigma}{d\Omega} = \frac{(\alpha Z_1 Z_2)^2}{4E^2 \sin^4 \theta/2}$$

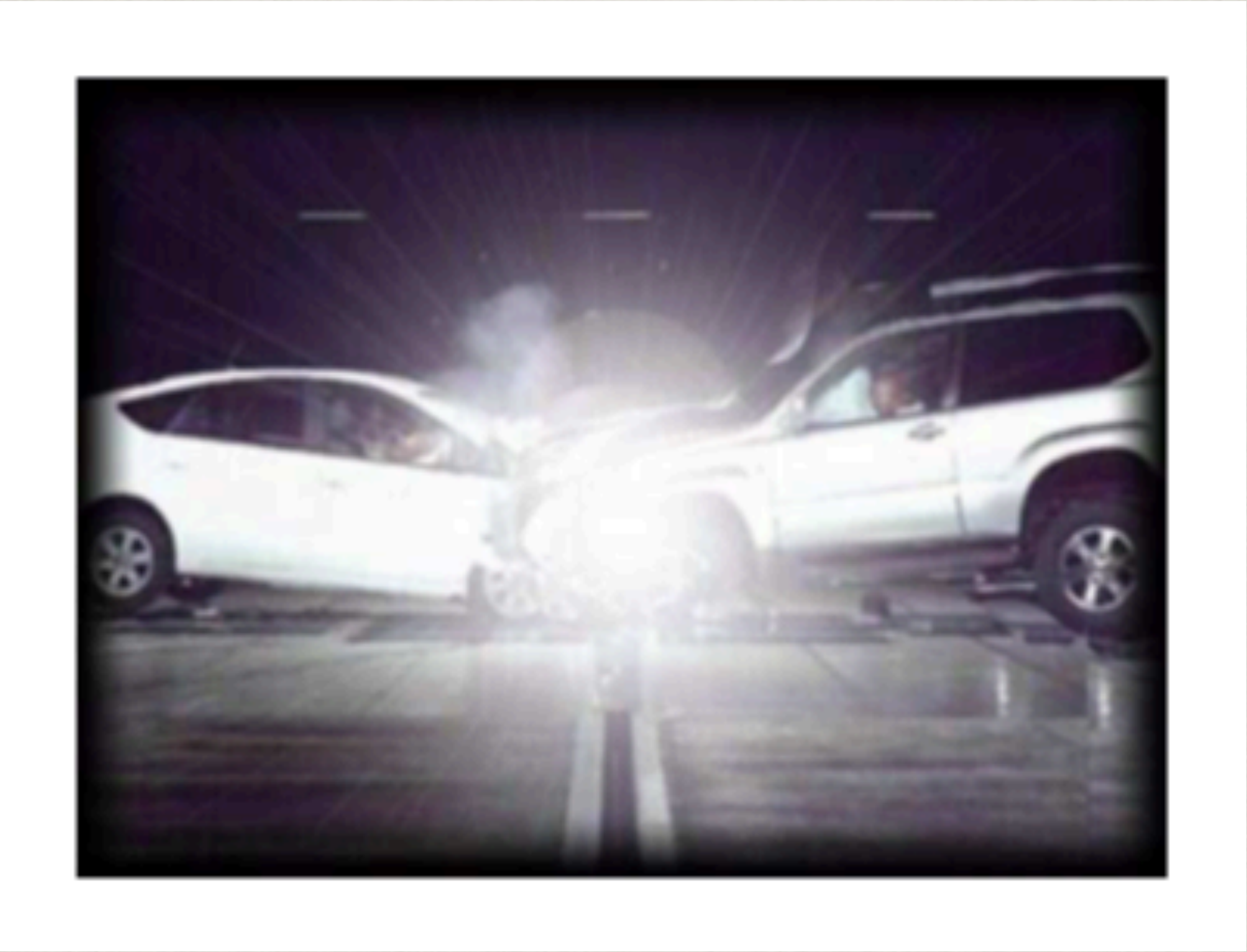


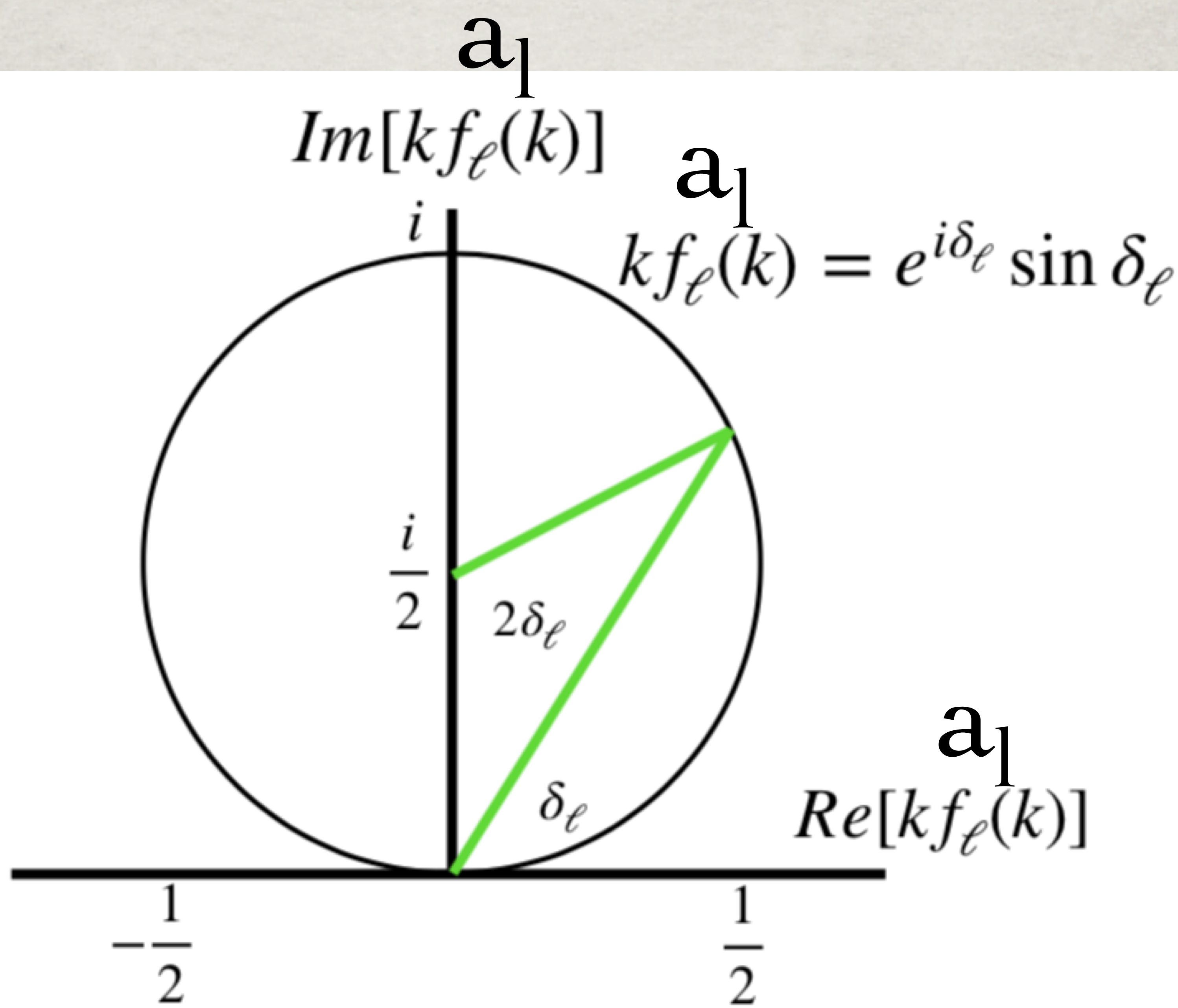



THEORY <–> EXPERIMENT
Connection
Theory
Feynman Rules
Matrix Element
Parton level event generator
MC event generator
Observables
PDF, mass spectra calculators ,...
Jet matching
LanHEP
FeynRules
SARAH
...
CalcHEP/CompHEP/MicroMEGAs
FeynArts/FormCalc
MadGraph/MadEvent
Sherpa
Whizard/Omega
Golem
Herwig++
MCFM
MC@NLO
Alpgen
...
PYTHIA
HERWIG
ISAJET
Sherpa
...
FAST/FULL Detector Simulation
PGS, Delphes
/
CMSSW, ATHENA
....
Analysis to find/exclude/modify theory:
Plots, PAW/Root, Fortran/C++ codes, Private codes,
MasterCode,
HEPMDB, ...



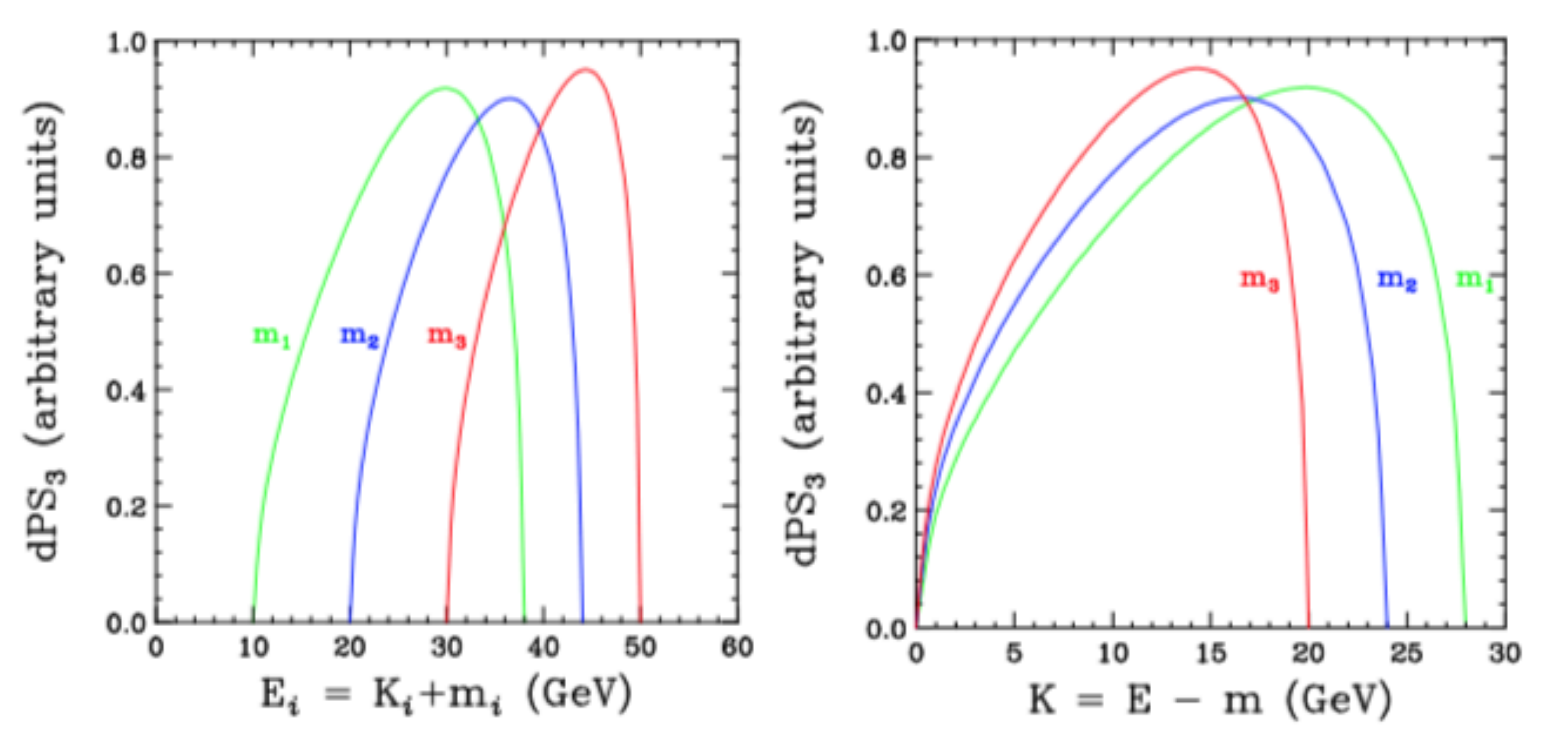
10000
1000
100
10
1
constituent centre-of-mass energy (GeV)
1960
1970
1980
1990
2000
2010
2020
'30
'40
year of first physics
LHC
(CERN)
Higgs
1995: top
Tevatron
(Fermilab)
SM
1983: W,Z
$Sp\bar{p}s$
(CERN)
LEP 200
HERA
LEP 1(CERN)1989: 3 families
PETRA 1979: gluon
(DESY)
SPEAR
(Stanford)
1974: J/ψ
1975: τ
F_{cc}^{hh}/SPPC? (2040)
HE-LHC (2038)
F_{cc}^{ee}/
CEPC
(2028?)

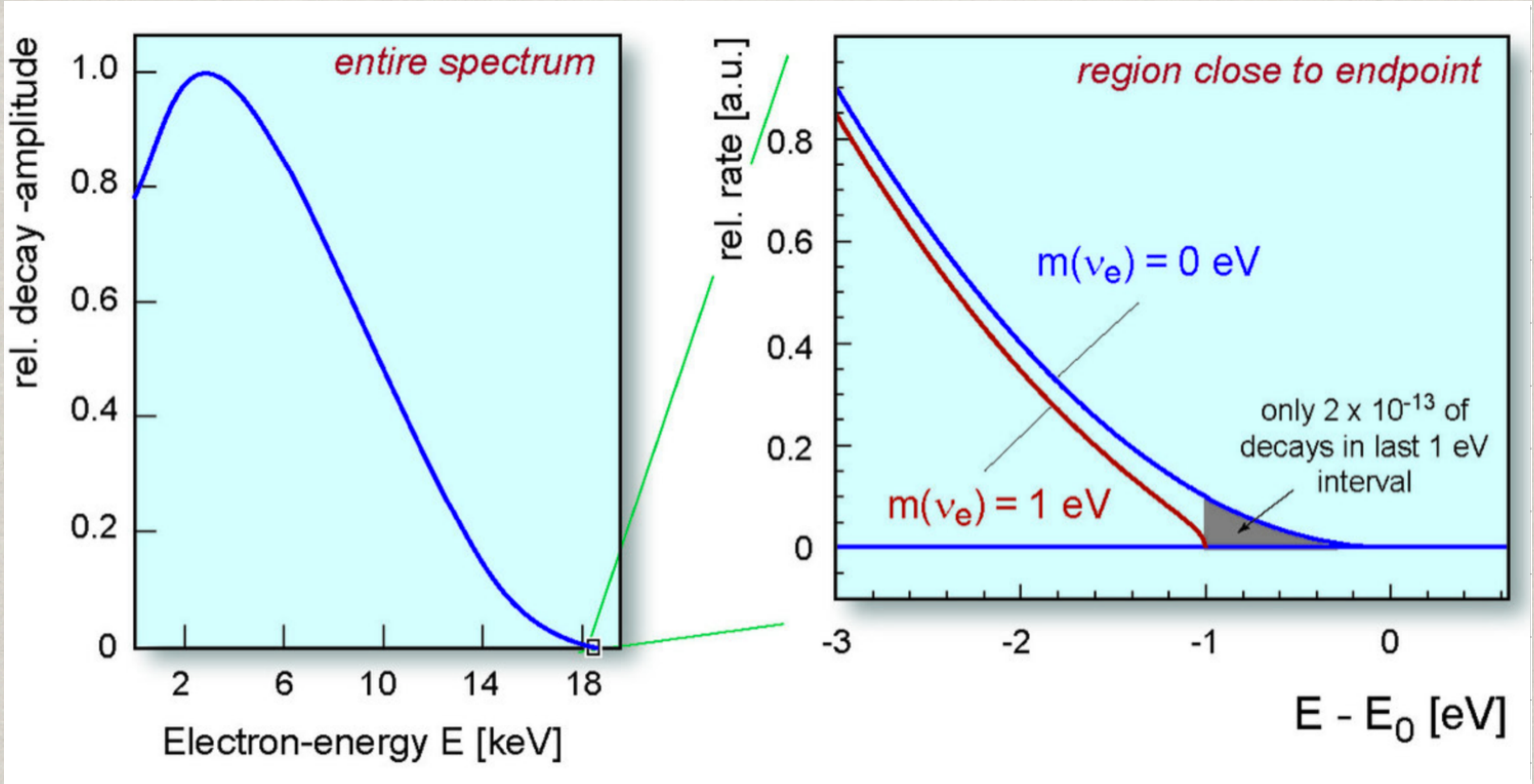


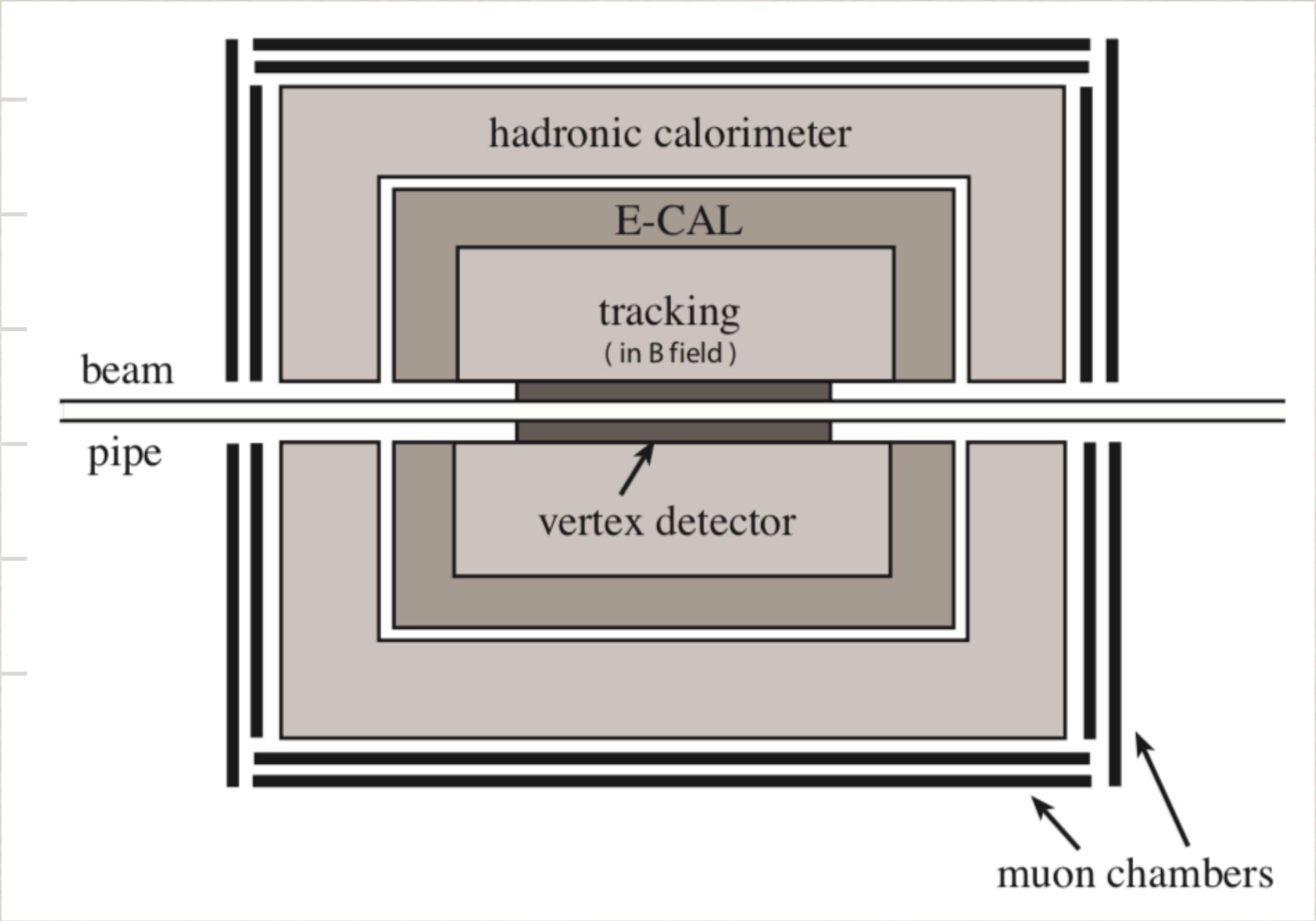


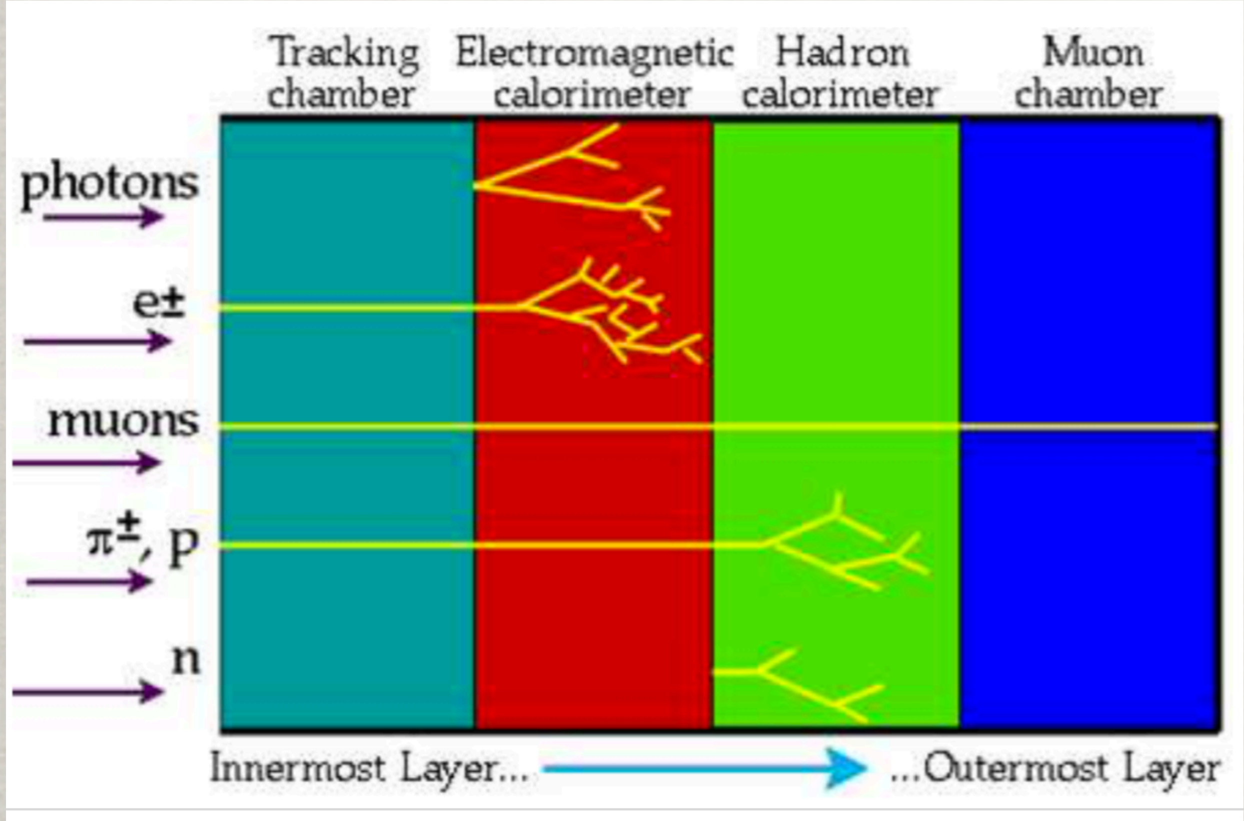
Argand diagram for partial wave unitarity

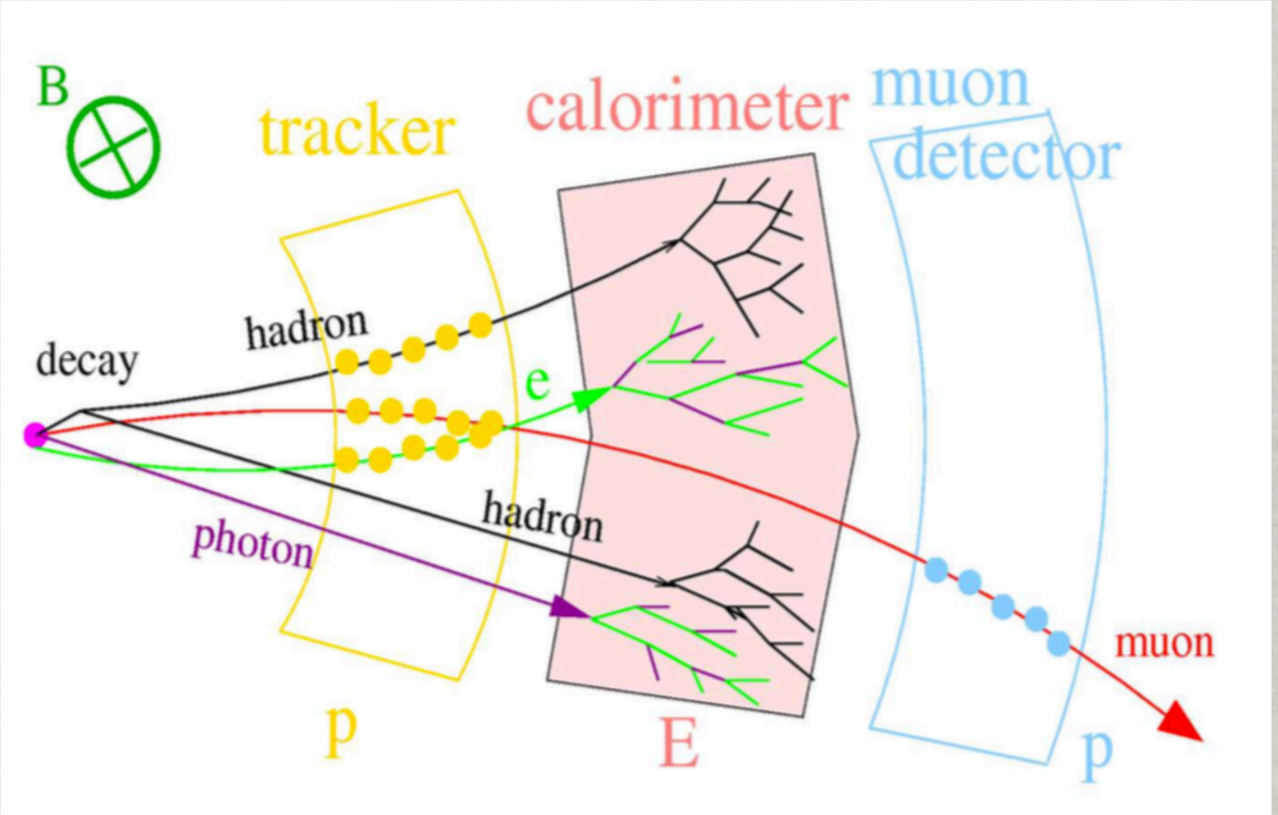
Lecture 2: Basic Formalism



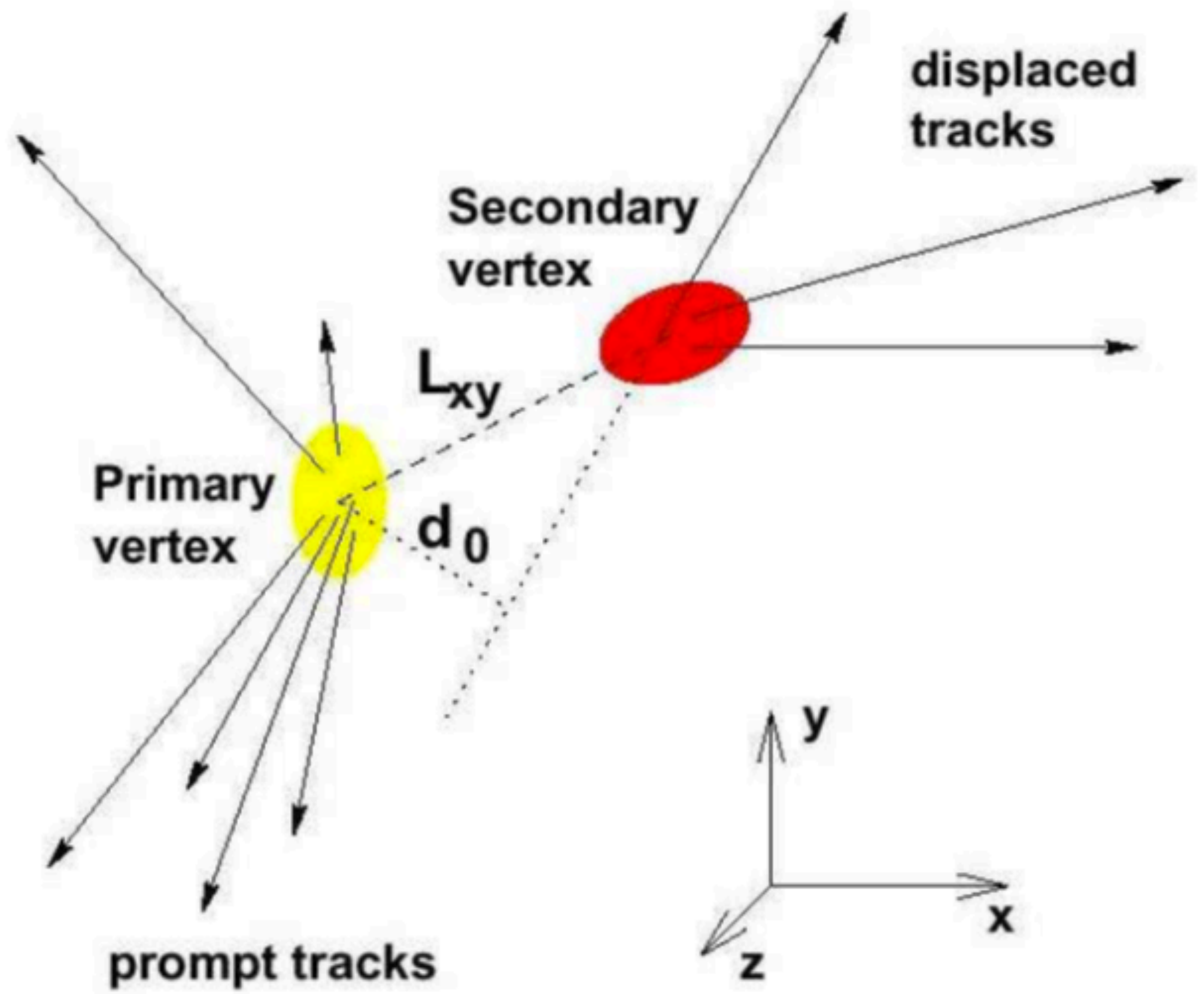

entire spectrum
rel. decay -amplitude
1.0
0.8
0.6
0.4
0.2
0
2
6
10
14
18
Electron-energy E [keV]
region close to endpoint
rel. rate [a.u.]
0.8
0.6
0.4
0.2
0
$m(\nu_e) = 0$ eV
$m(\nu_e) = 1$ eV
only 2 x 10^{-13} of decays in last 1 eV interval
-3
-2
-1
0
$E - E_0$ [eV]


hadronic calorimeter
E-CAL
tracking
(in B field)
beam
pipe
vertex detector
muon chambers


Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon chamber
photons
e±
muons
π±, p
n
Innermost Layer...
...Outermost Layer

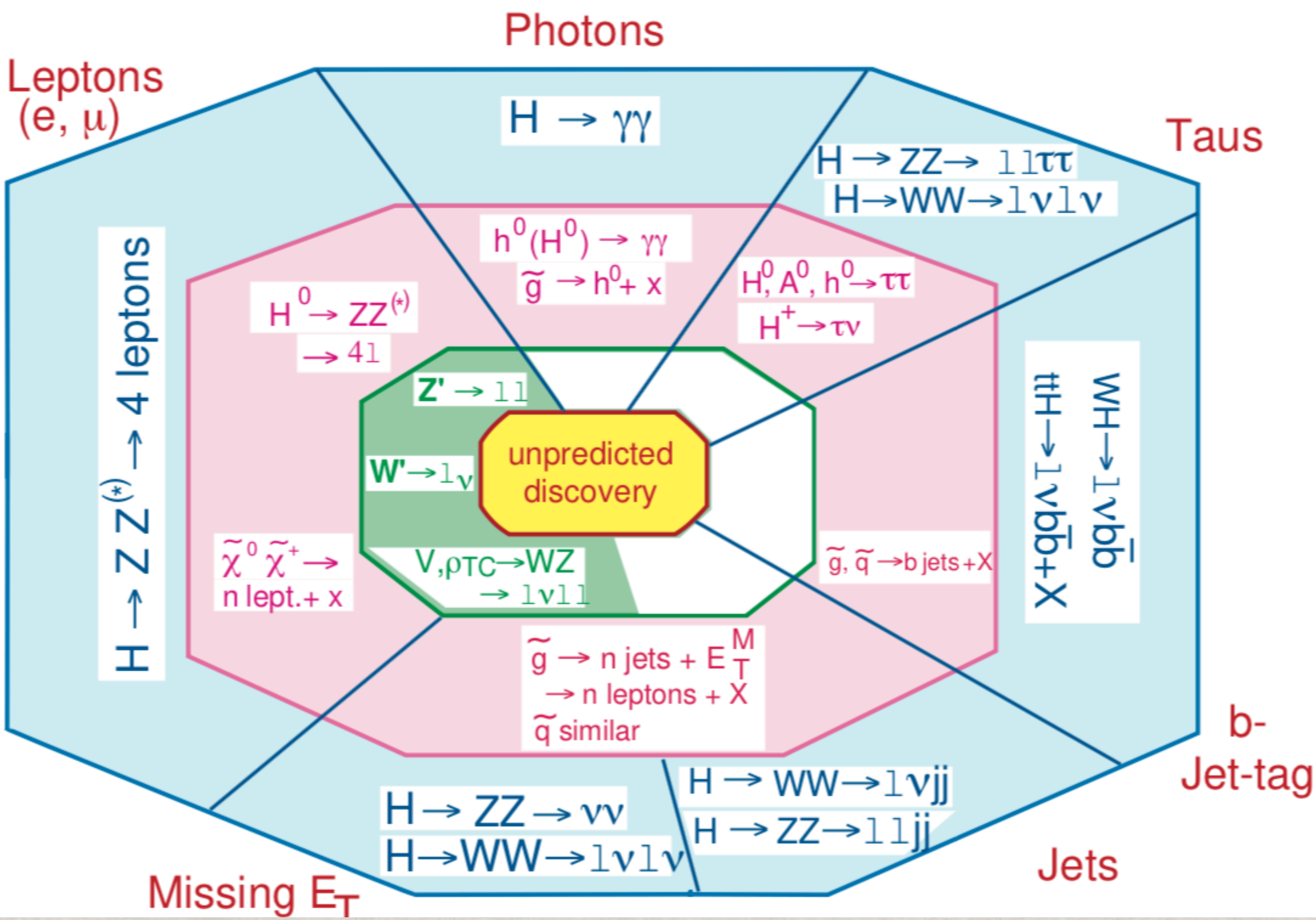

B
tracker
calorimeter
muon detector
hadron
decay
e
hadron
photon
muon
p
E
p

heavy flavor tagging: the secondary vertex:



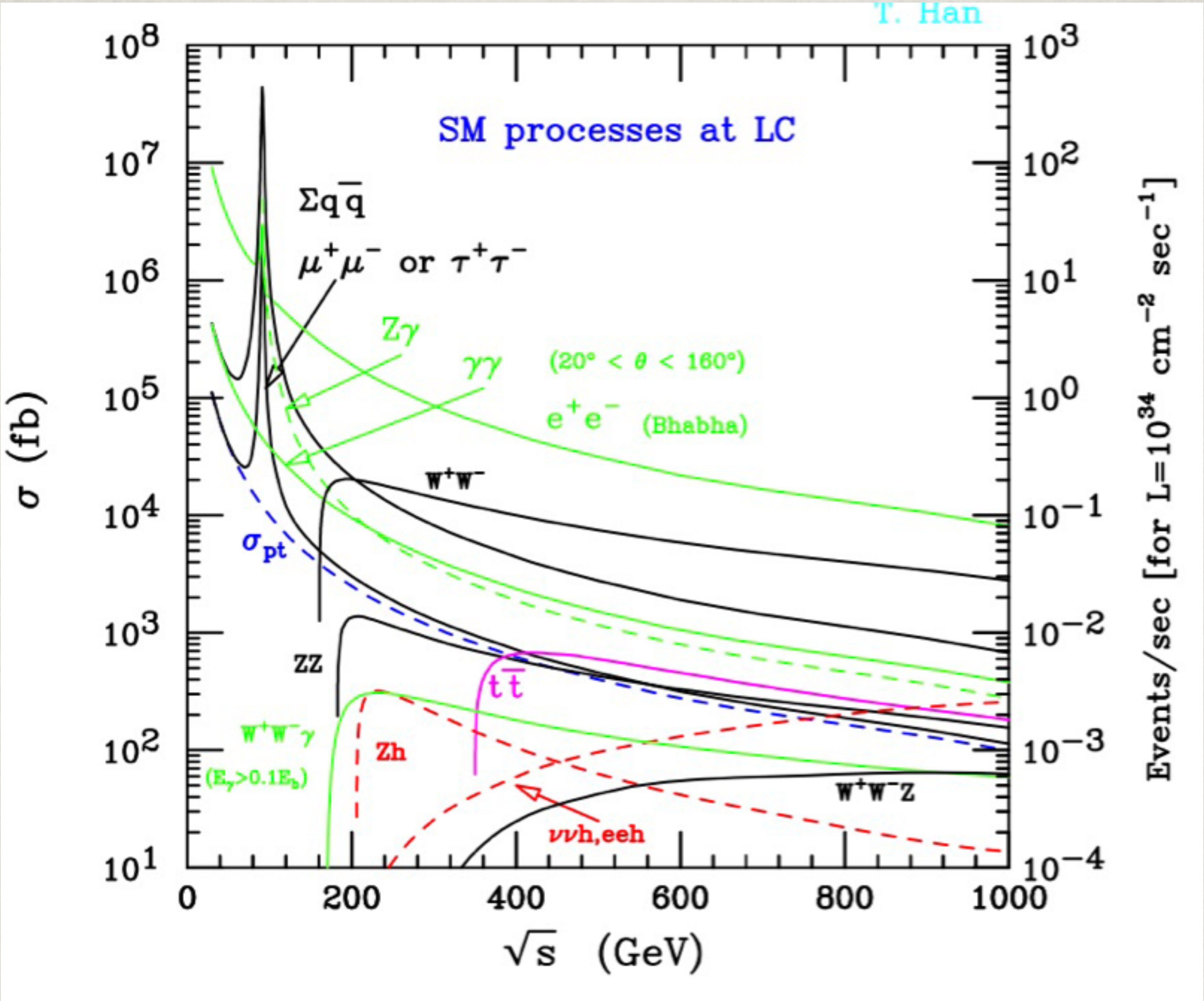
Leptons	Vetexing	Tracking	ECAL	HCAL	Muon Cham.
$e^{\pm}$	$\times$	$\vec{p}$	E	$\times$	$\times$
$\mu^{\pm}$	$\times$	$\vec{p}$	$\surd$	$\surd$	$\vec{p}$
$\tau^{\pm}$	$\surd\times$	$\surd$	$e^{\pm}$	$h^{\pm}$; $3h^{\pm}$	$\mu^{\pm}$
ν_e, ν_μ, ν_τ	$\times$	$\times$	$\times$	$\times$	$\times$
Quarks					
u, d, s	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$c \to D$	$\surd$	$\surd$	$e^{\pm}$	h's	$\mu^{\pm}$
$b \to B$	$\surd$	$\surd$	$e^{\pm}$	h's	$\mu^{\pm}$
$t \to bW^{\pm}$	b	$\surd$	$e^{\pm}$	$b+2$ jets	$\mu^{\pm}$
Gauge bosons					
γ	$\times$	$\times$	E	$\times$	$\times$
g	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$W^{\pm} \to \ell^{\pm}\nu$	$\times$	$\vec{p}$	$e^{\pm}$	$\times$	$\mu^{\pm}$
$\to q\bar{q}'$	$\times$	$\surd$	$\surd$	2 jets	$\times$
$Z^0 \to \ell^+\ell^-$	$\times$	$\vec{p}$	$e^{\pm}$	$\times$	$\mu^{\pm}$
$\to q\bar{q}$	$(b\bar{b})$	$\surd$	$\surd$	2 jets	$\times$
the Higgs boson					
$h^0 \to b\bar{b}$	$\surd$	$\surd$	$e^{\pm}$	h's	$\mu^{\pm}$
$\to ZZ^*$	$\times$	$\vec{p}$	$e^{\pm}$	$\surd$	$\mu^{\pm}$
$\to WW^*$	$\times$	$\vec{p}$	$e^{\pm}$	$\surd$	$\mu^{\pm}$

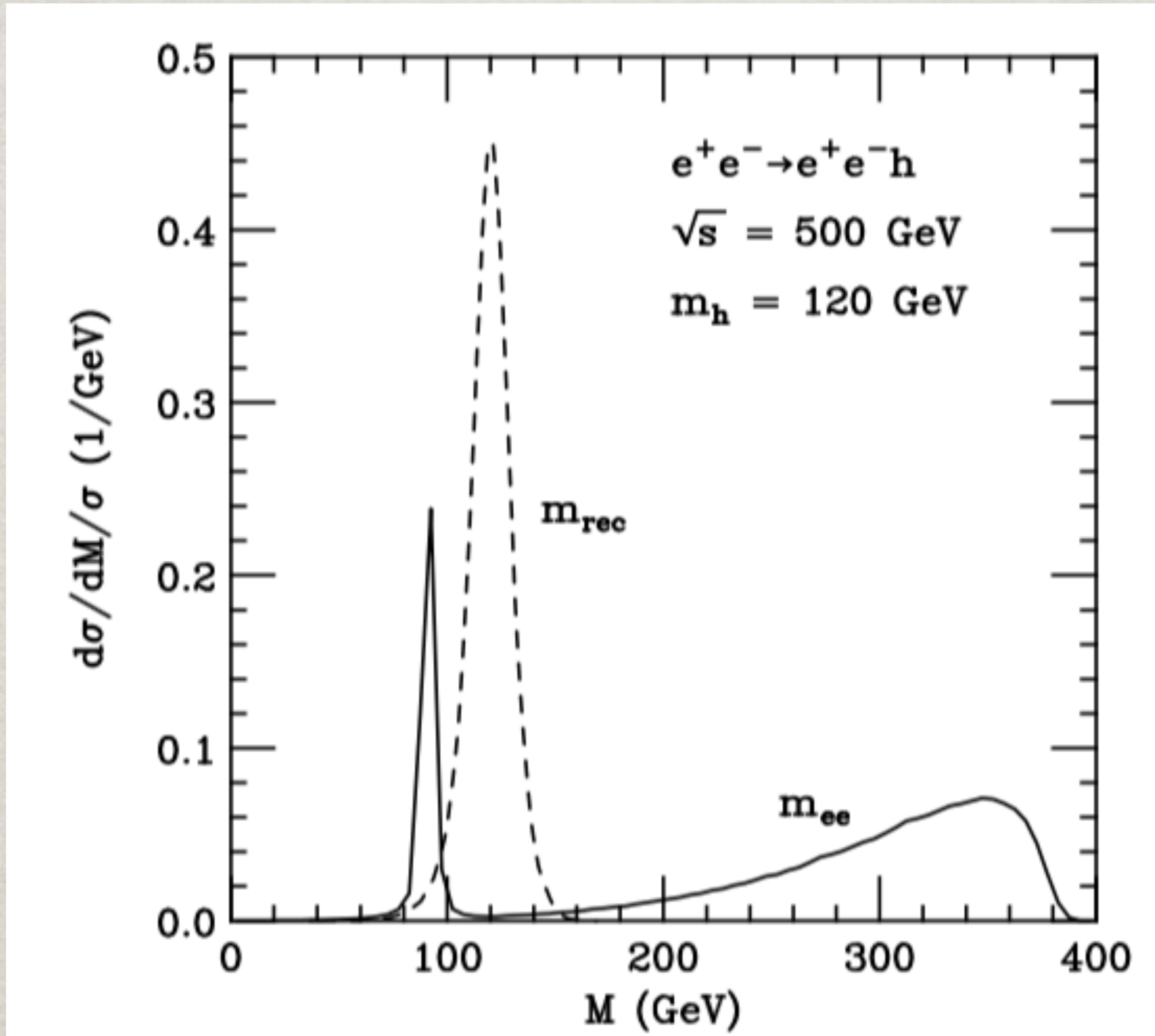
How to search for new particles?



Lecture 3: Lepton colliders

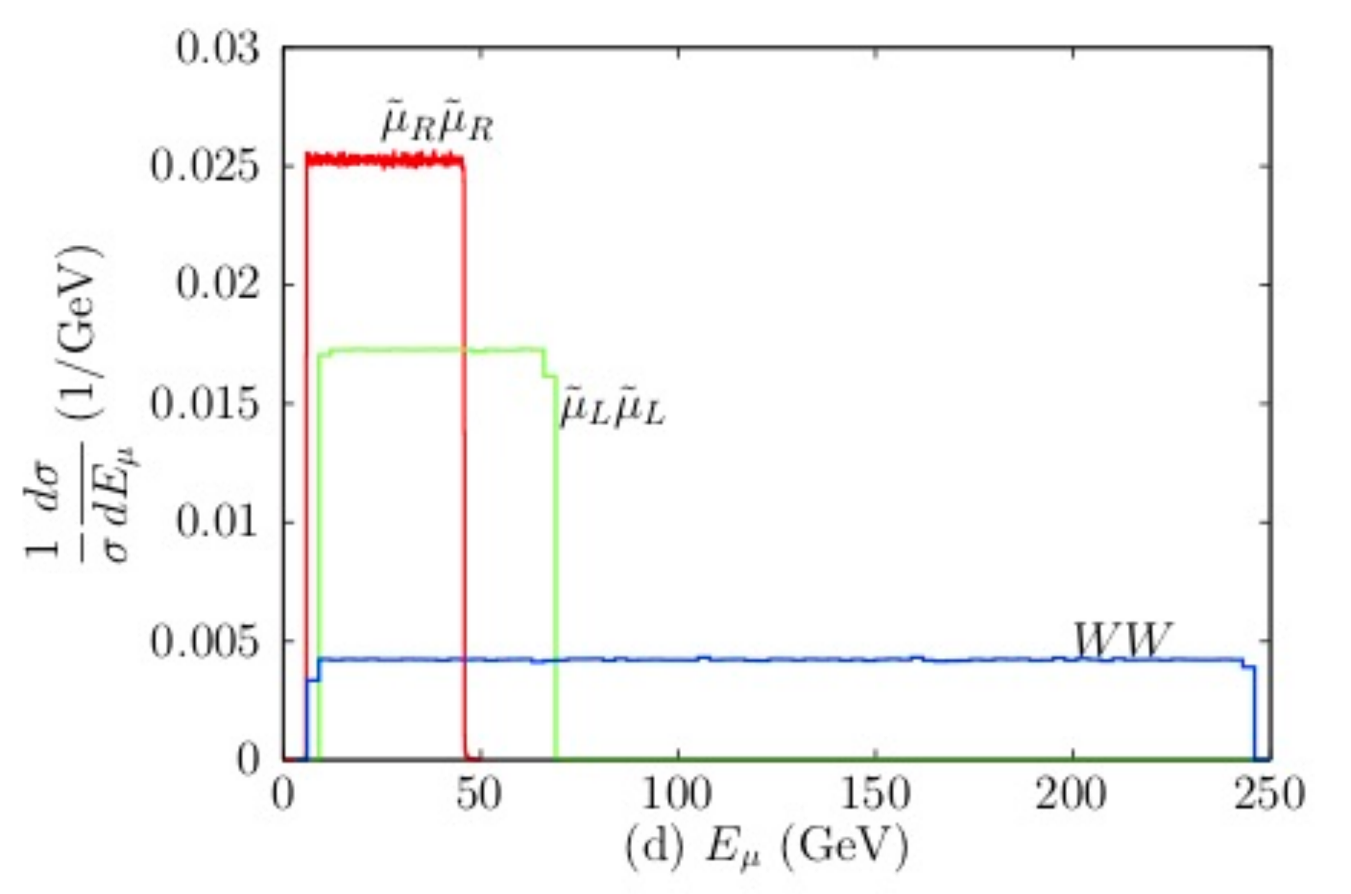
Colliders	$\sqrt{s}$ (GeV) (GeV)	$\mathcal{L}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$\delta E/E$	f (kHz)	polar.	L (km)
LEP I	M_Z	2.4×10^{31}	$\sim 0.1\%$	45	55%	26.7
SLC	~ 100	2.5×10^{30}	0.12%	0.12	80%	2.9
LEP II	~ 210	10^{32}	$\sim 0.1\%$	45		26.7
ILC	0.5–1	2.5×10^{34}	0.1%	3	80, 60%	14 – 33
CEPC	0.25–0.35	2×10^{34}	0.13%			50-100
CLIC	3–5	$\sim 10^{35}$	0.35%	1500	80, 60%	33 – 53


T. Han
SM processes at LC
σ (fb)
Events/sec [for L=10^34 cm^-2 sec^-1]
√s (GeV)
Σqq̄
μ+μ- or τ+τ-
Zγ
γγ
(20° < θ < 160°)
e+e- (Bhabha)
W+W-
σpt
ZZ
tt̄
W+W-γ
(Eγ>0.1Eb)
Zh
νν̄h,eeh
W+W-Z

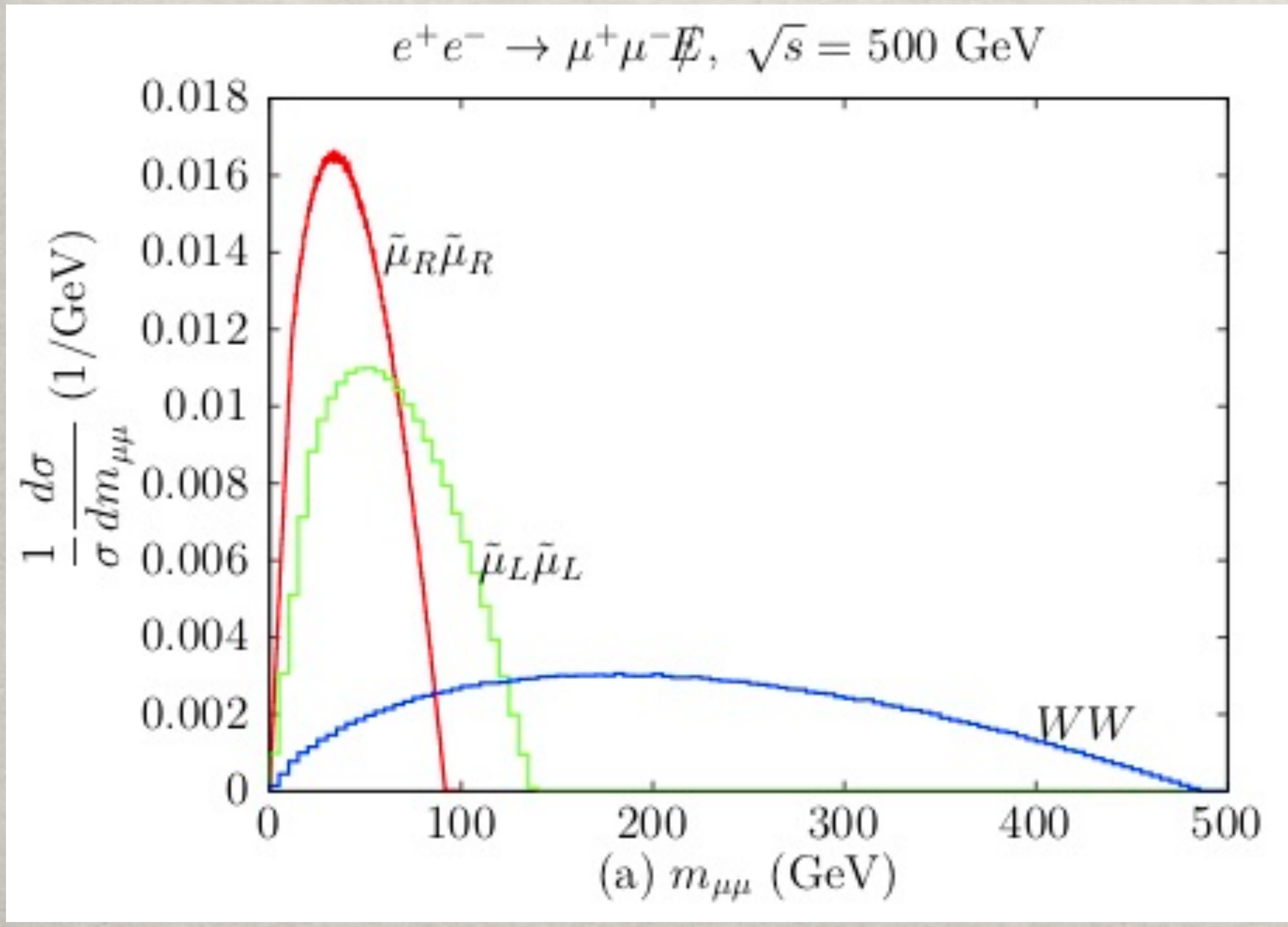


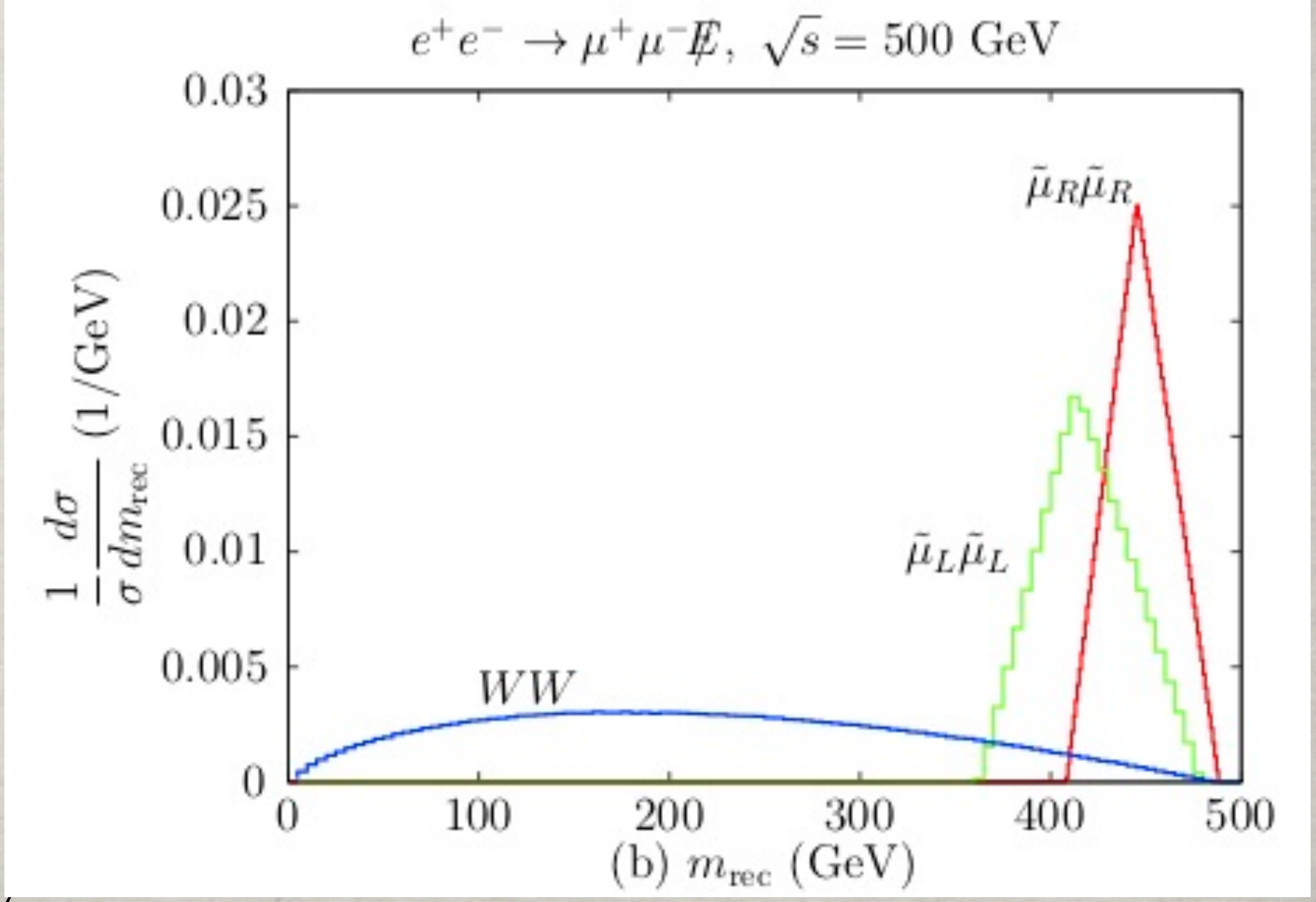
Model-independent recoil mass

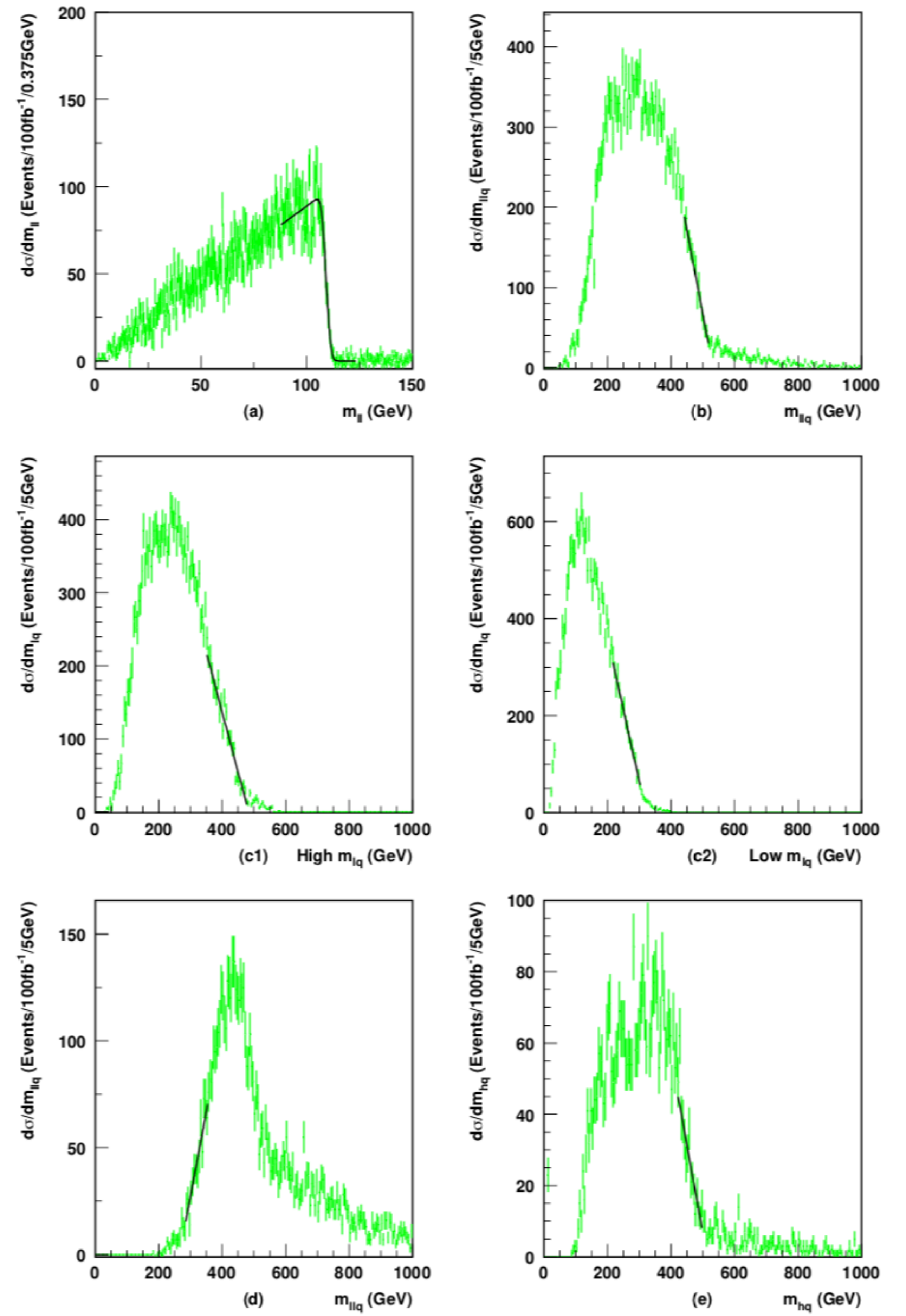
Mono-chromatic,
But boosted muon:

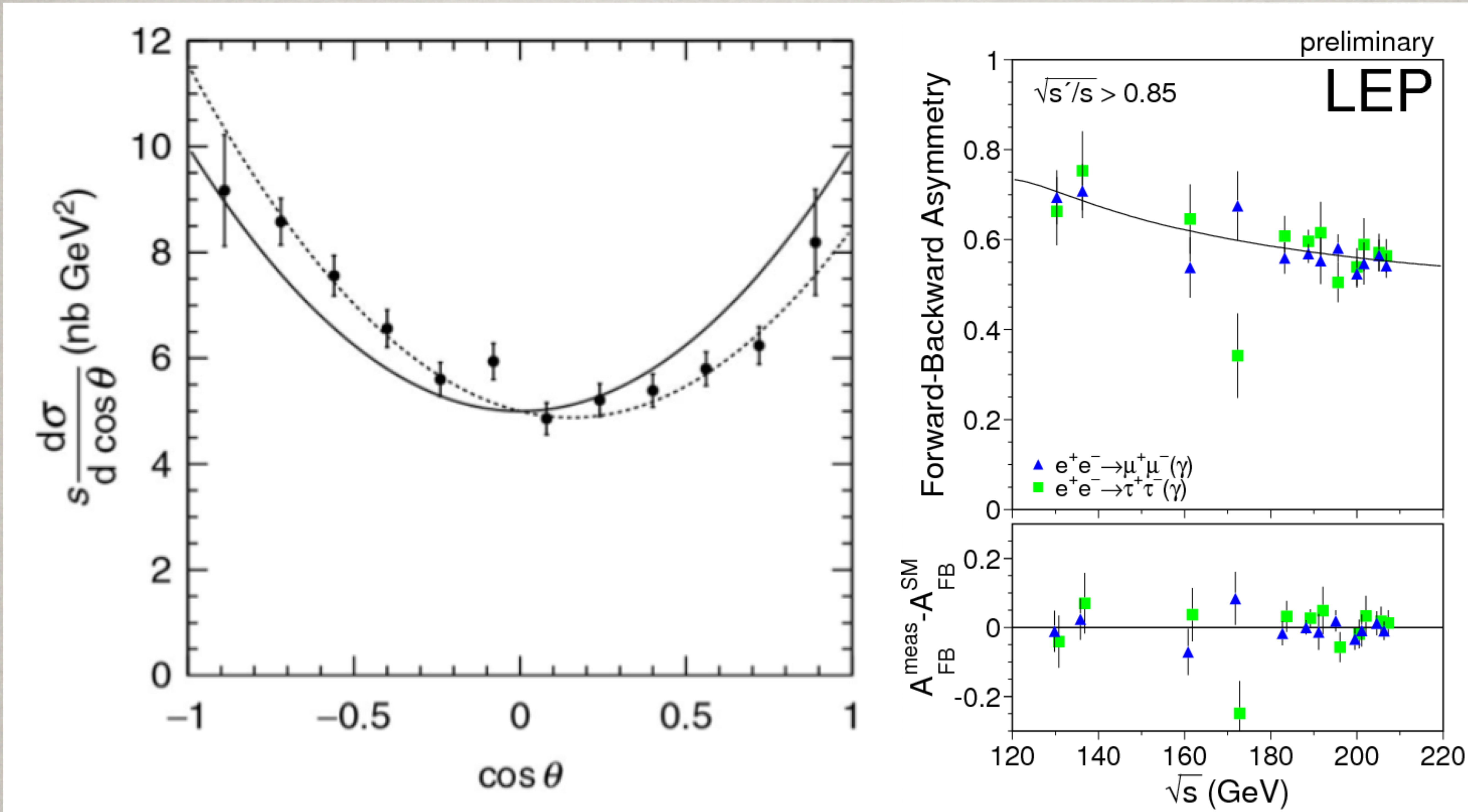


Kinematic cusps in M(mumu) & M(recoil)

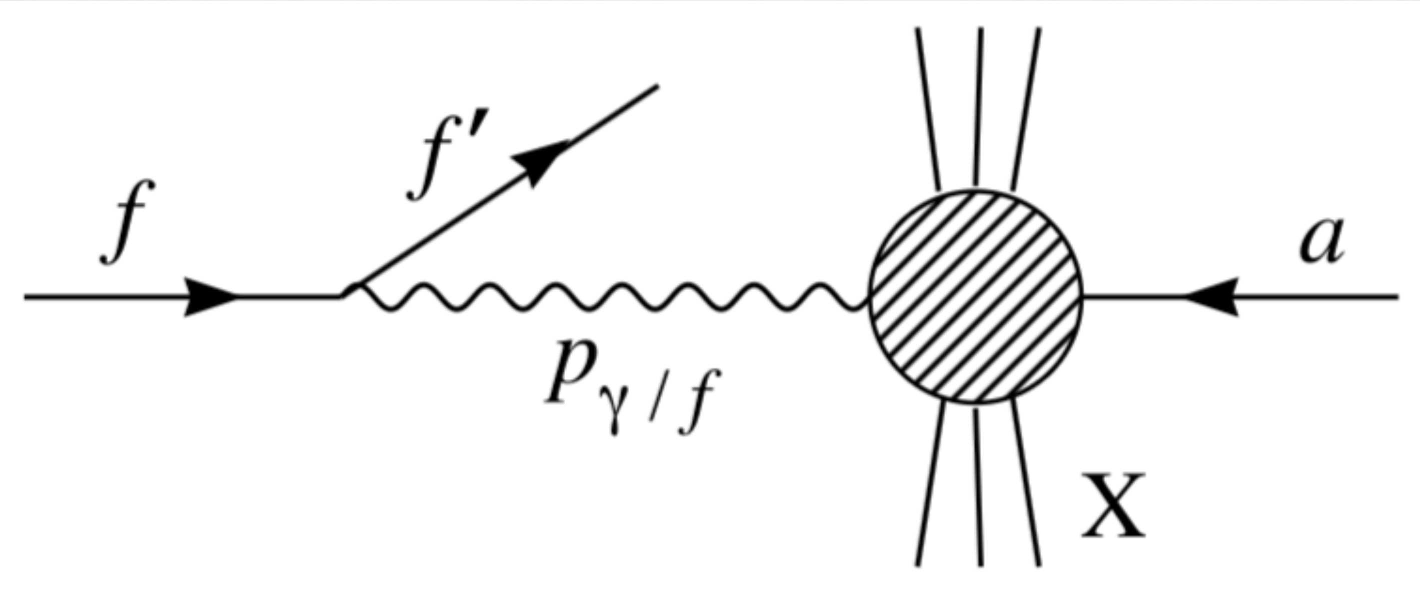





dσ/dm_ll (Events/100fb^-1/0.375GeV)
(a)
m_ll (GeV)
dσ/dm_llq (Events/100fb^-1/5GeV)
(b)
m_llq (GeV)
dσ/dm_lq (Events/100fb^-1/5GeV)
(c1)
High m_lq (GeV)
dσ/dm_lq (Events/100fb^-1/5GeV)
(c2)
Low m_lq (GeV)
dσ/dm_llq (Events/100fb^-1/5GeV)
(d)
m_llq (GeV)
dσ/dm_hq (Events/100fb^-1/5GeV)
(e)
m_hq (GeV)

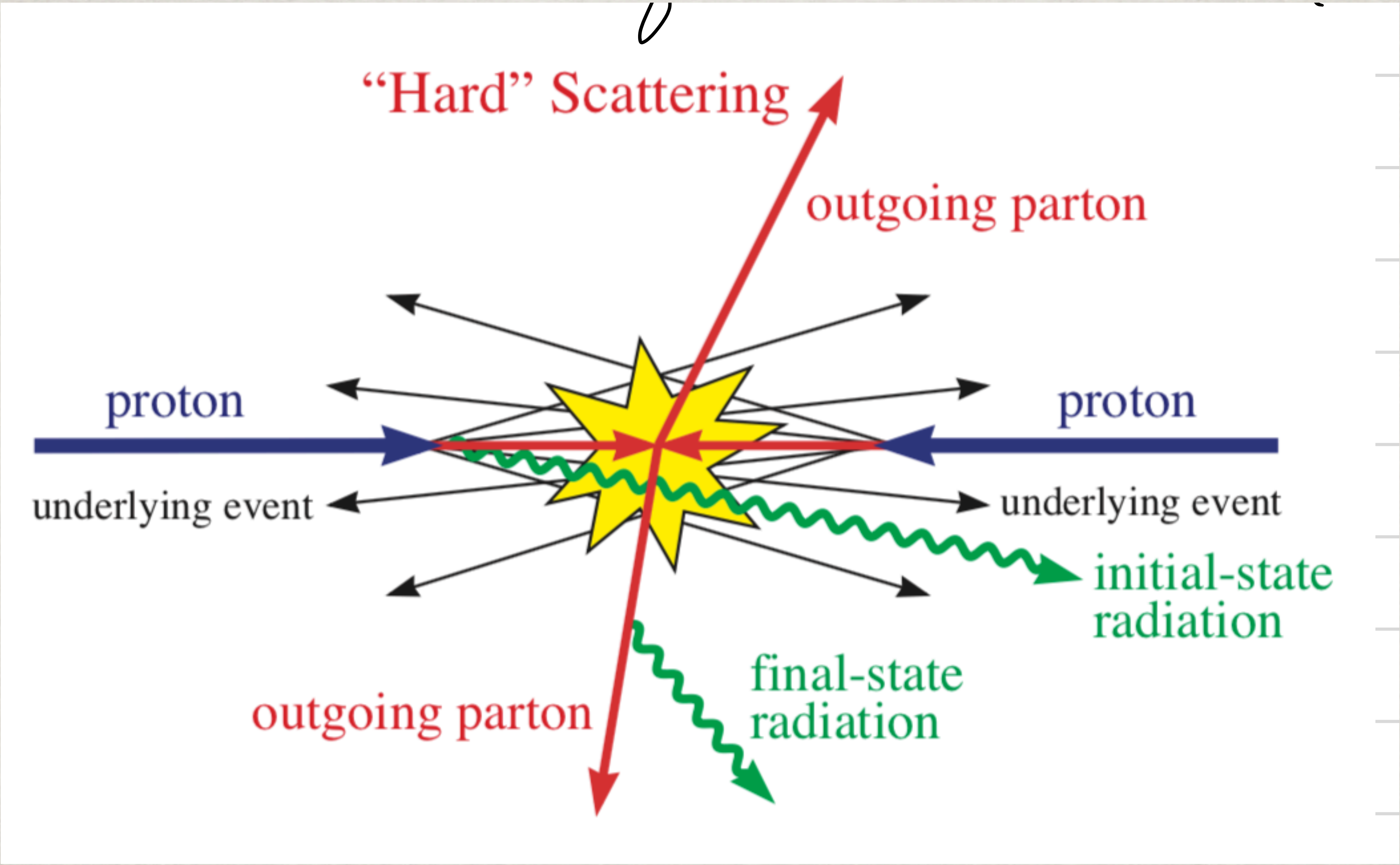


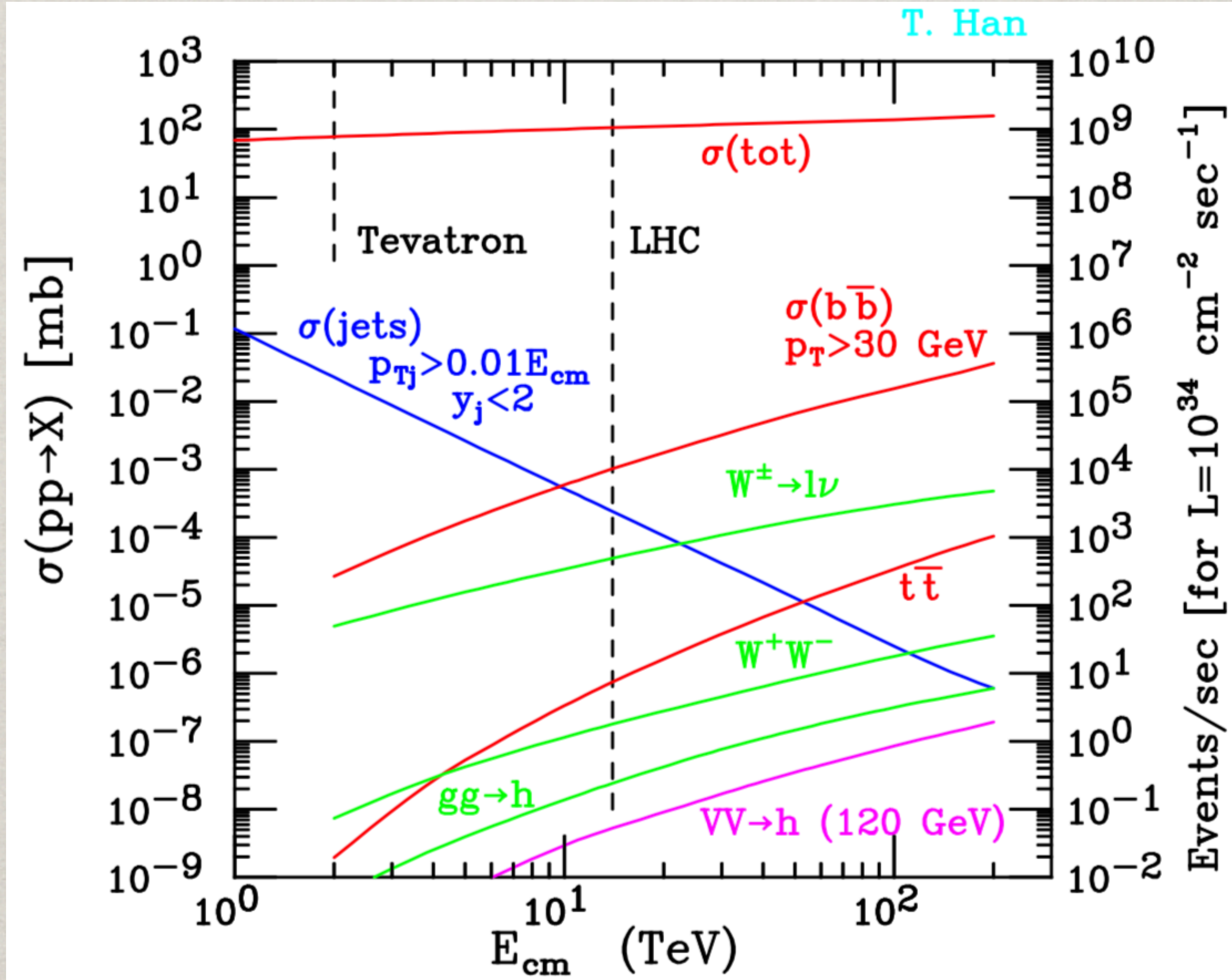
Forward-backward Asymmetry @ LEP:
Parity violation, sensitive to the chiral interactions @ given E


f
f′
a
$p_{\gamma/f}$
X

Lecture 4: Hadron colliders

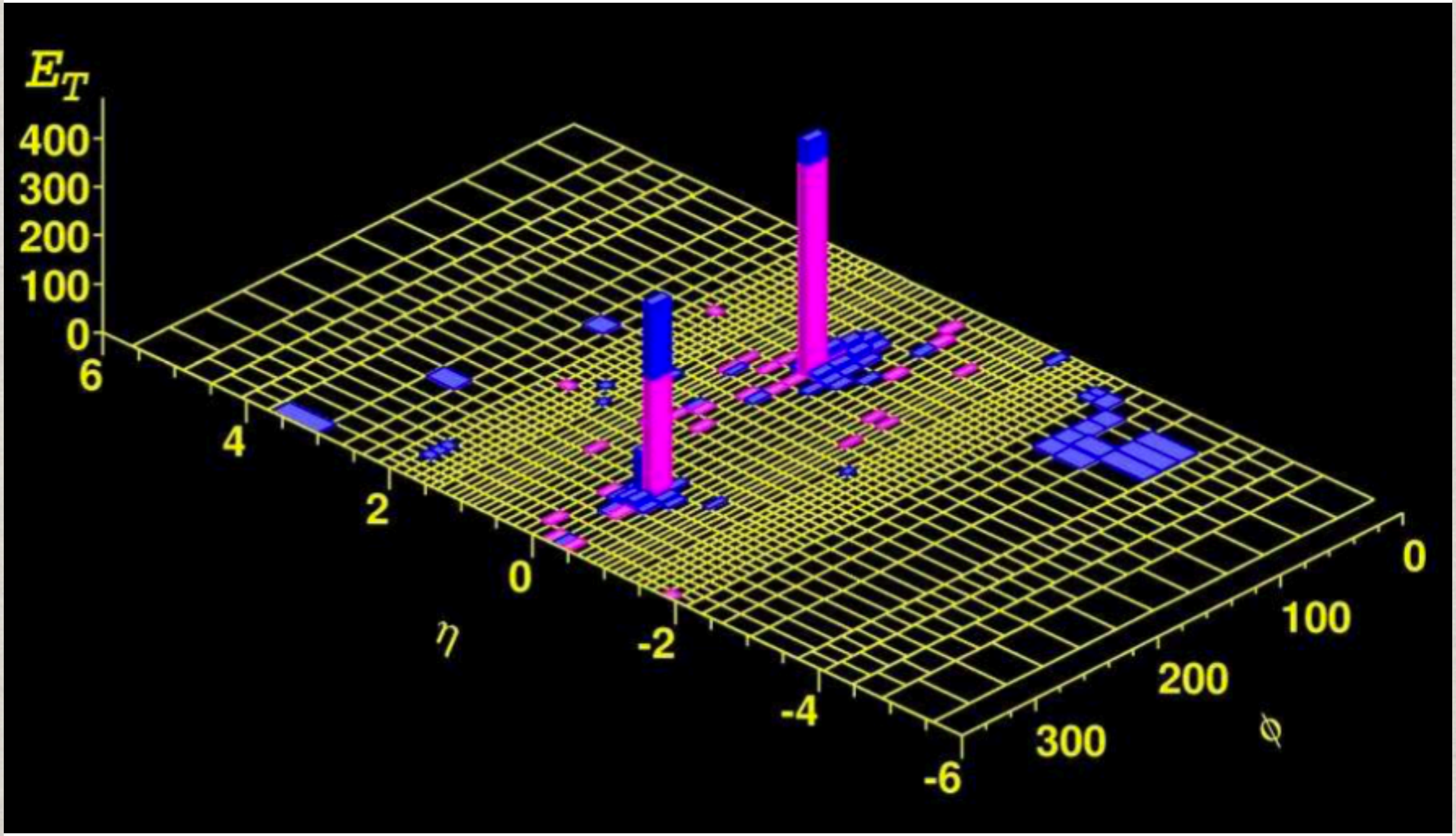
Colliders	$\sqrt{s}$ (TeV)	$\mathcal{L}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$\delta E/E$	f (MHz)	#/bunch (10^{10})	L (km)
Tevatron	1.96	2.1×10^{32}	9×10^{-5}	2.5	p: 27, $\bar{p}$: 7.5	6.28
HERA	314	1.4×10^{31}	0.1, 0.02%	10	e: 3, p: 7	6.34
LHC	14	10^{34}	0.01%	40	10.5	26.66
LHC Run (I) II	(7,8) 13	(10^{32}) 10^{33}	0.01%	40	10.5	26.66
HL-LHC	14	7×10^{34}	0.013%	40	22	26.66
FCC_{hh} (SppC)	100	1.2×10^{35}	0.01%	40	10	100


"Hard" Scattering
outgoing parton
proton
proton
underlying event
underlying event
initial-state radiation
final-state radiation
outgoing parton

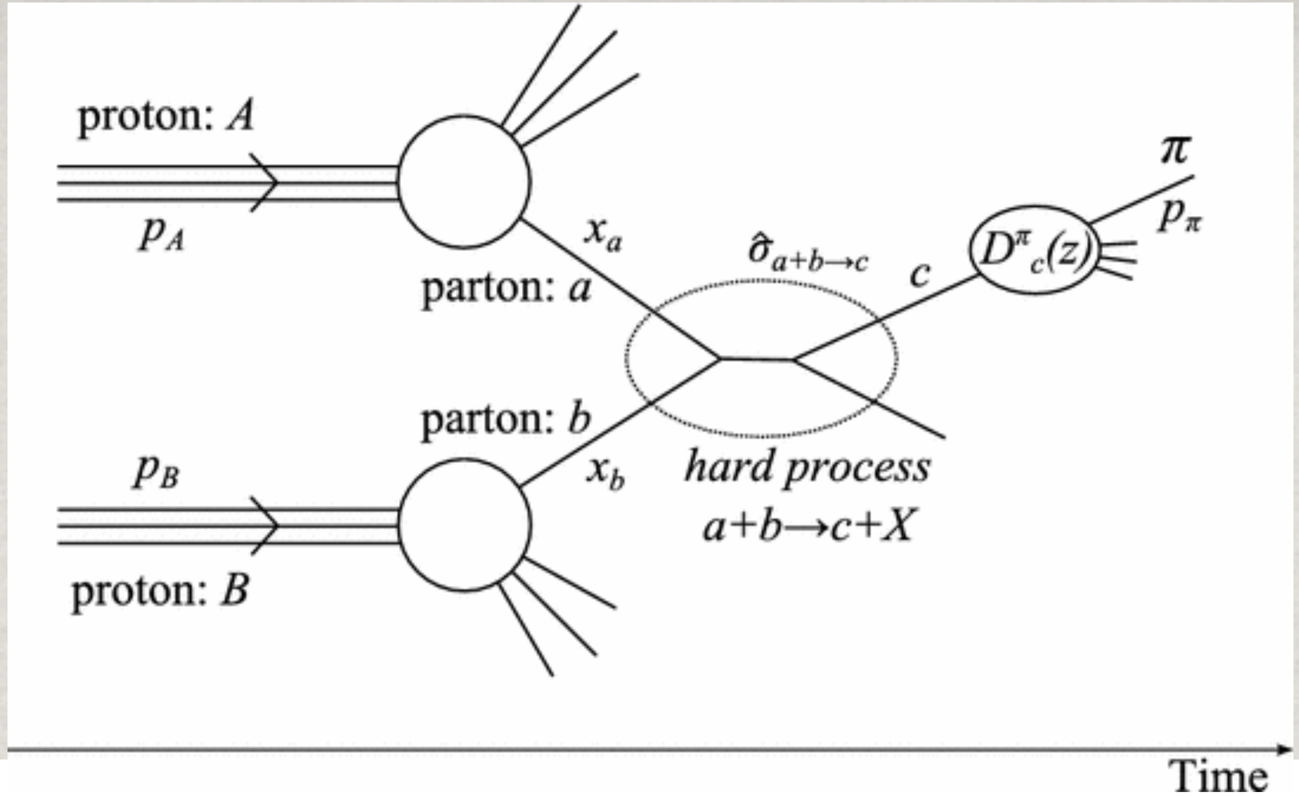

T. Han
Tevatron
LHC
σ(tot)
σ(jets)
p_Tj>0.01E_cm
y_j<2
σ(b b̄)
p_T>30 GeV
W^±→lν
t t̄
W^+W^-
gg→h
VV→h (120 GeV)
σ(pp→X) [mb]
Events/sec [for L=10^34 cm^-2 sec^-1]
E_cm (TeV)

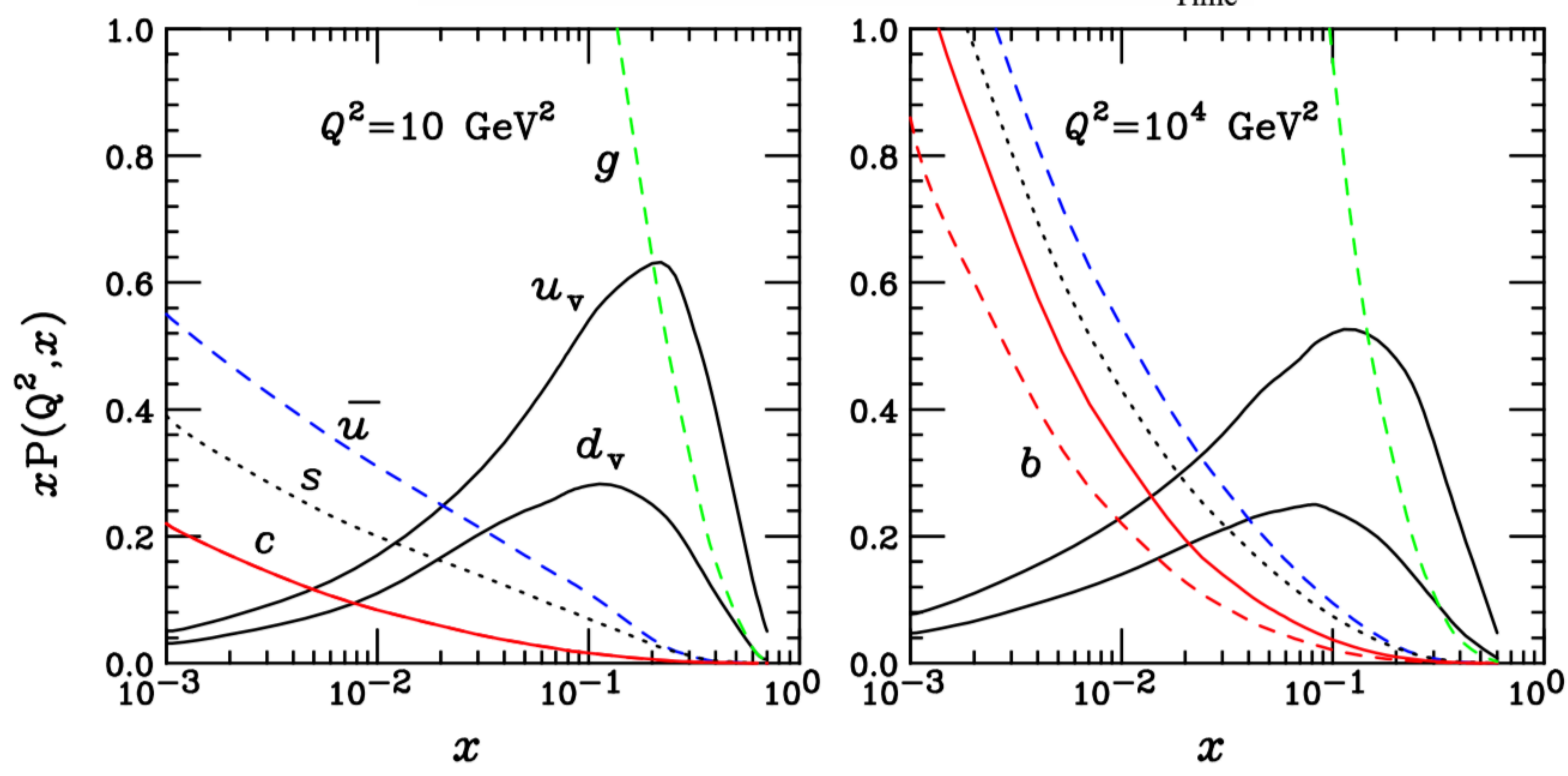
	ATLAS	
Objects	η	p_T (GeV)
μ inclusive	2.4	6 (20)
e/photon inclusive	2.5	17 (26)
Two e's or two photons	2.5	12 (15)
1-jet inclusive	3.2	180 (290)
3 jets	3.2	75 (130)
4 jets	3.2	55 (90)
τ/hadrons	2.5	43 (65)
$\not{E}_T$	4.9	100
Jets+$\not{E}_T$	3.2, 4.9	50,50 (100,100)

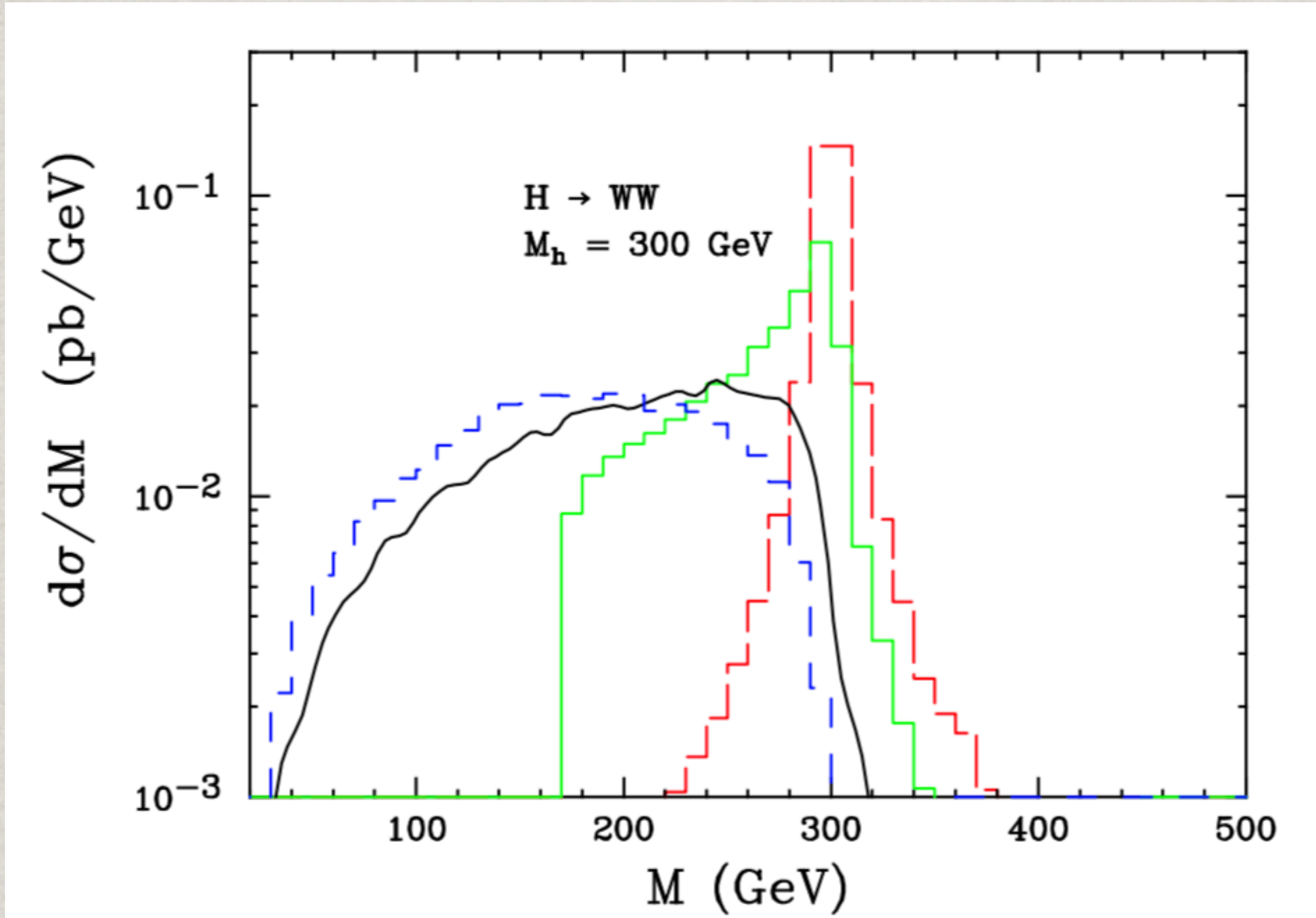
($\eta = 2.5 \Rightarrow 10°$; $\eta = 5 \Rightarrow 0.8°$.)



E_T
400
300
200
100
0
6
4
2
0
η
-2
-4
-6
0
100
200
300
φ


proton: A
p_A
x_a
parton: a
σ̂_{a+b→c}
c
D^π_c(z)
π
p_π
parton: b
x_b
p_B
hard process
a+b→c+X
proton: B
Time


Q²=10 GeV²
g
u_v
d_v
ū
s
c
Q²=10⁴ GeV²
b
xP(Q²,x)
x
1.0
0.8
0.6
0.4
0.2
0.0
10⁻³
10⁻²
10⁻¹
10⁰

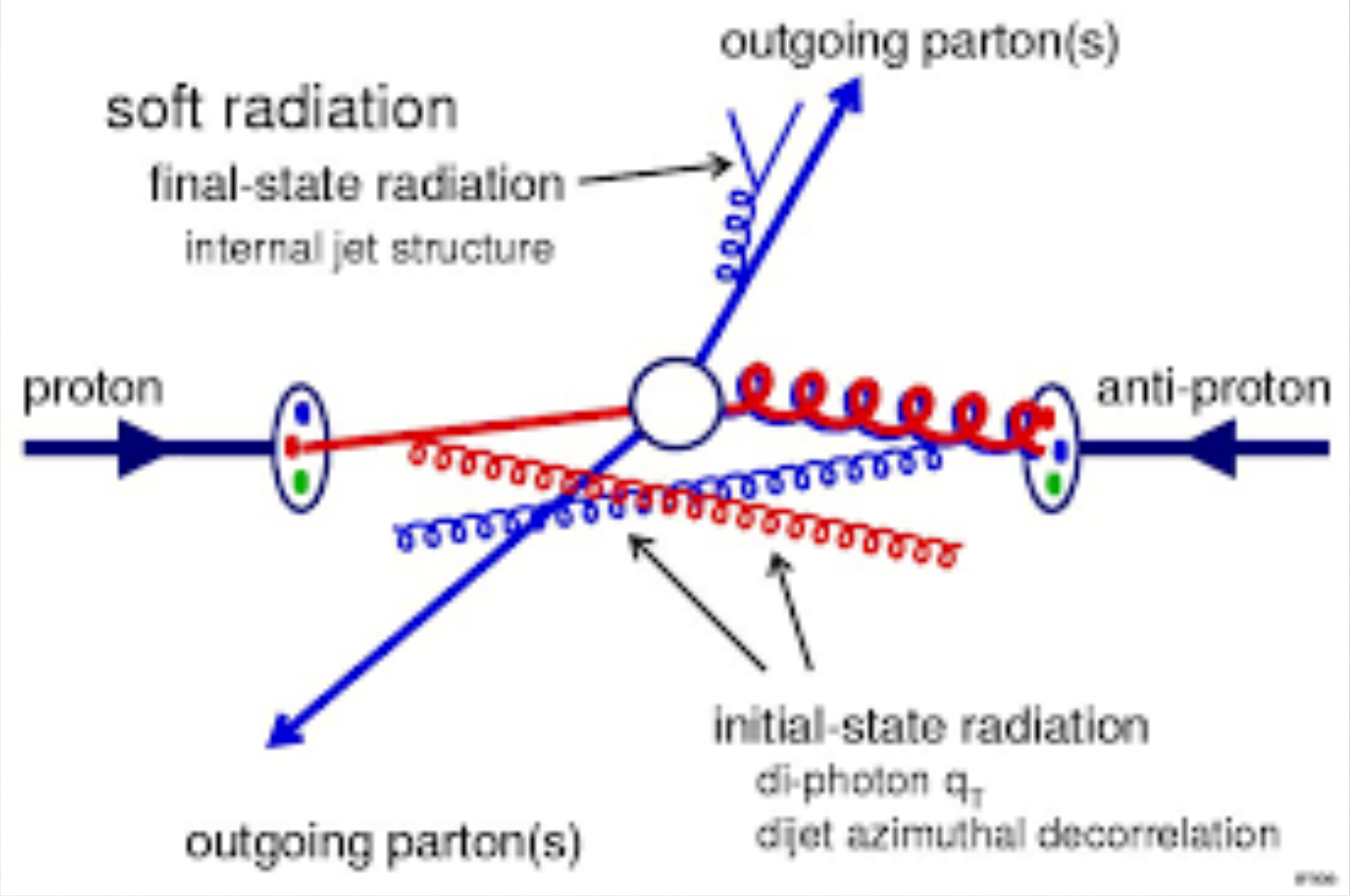


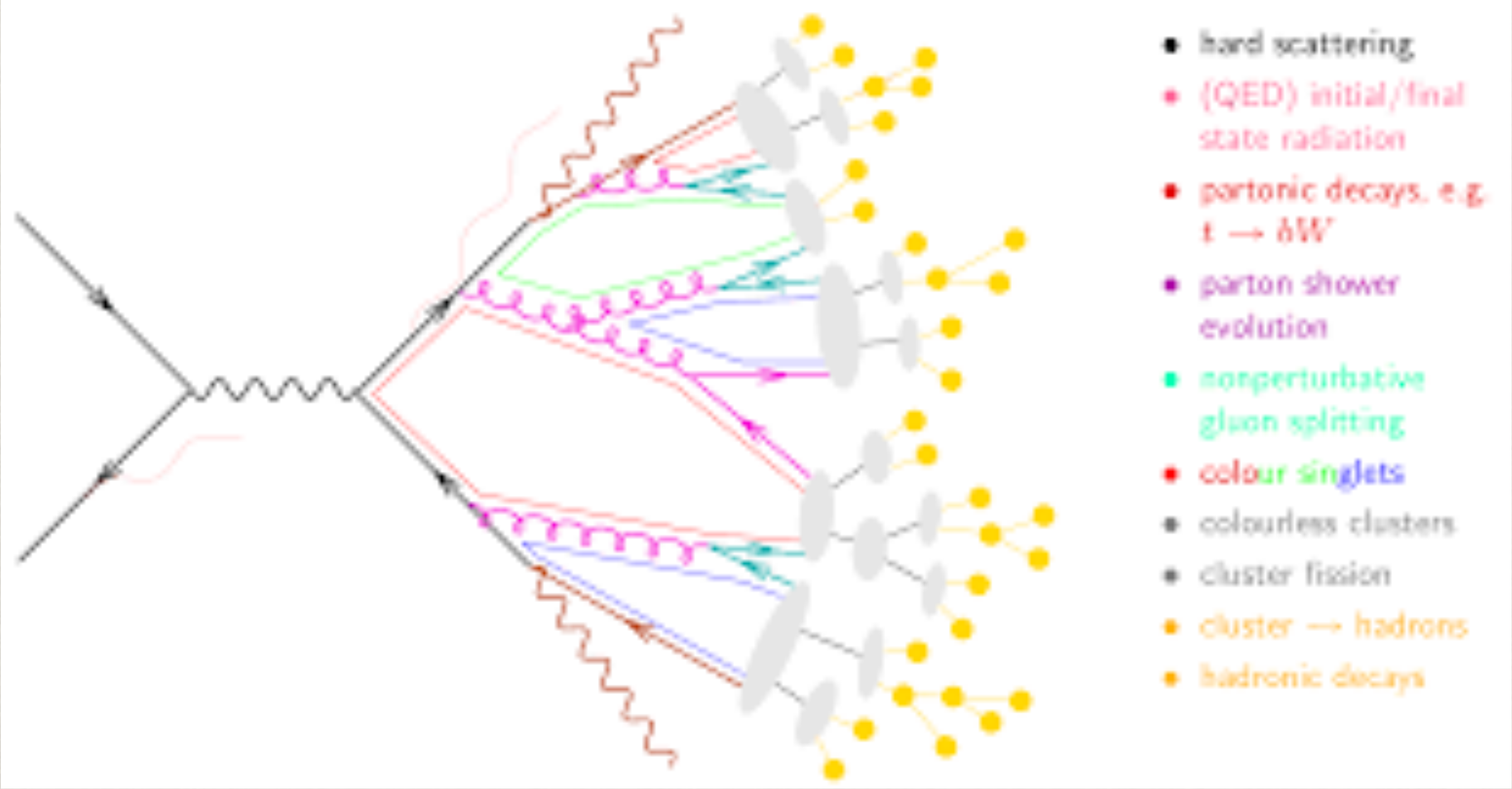
M_{WW} invariant mass (WW fully reconstructable): - - - - - - - -

$M_{WW,\ T}$ transverse mass (one missing particle ν): ———————

$M_{eff,\ T}$ effetive trans. mass (two missing particles): - - - - - - -

$M_{WW,\ C}$ cluster trans. mass (two missing particles): ———————


outgoing parton(s)
soft radiation
final-state radiation
internal jet structure
proton
anti-proton
initial-state radiation
di-photon q_T
dijet azimuthal decorrelation
outgoing parton(s)


hard scattering
(QED) initial/final state radiation
partonic decays, e.g. $t \to bW$
parton shower evolution
nonperturbative gluon splitting
colour singlets
colourless clusters
cluster fission
cluster → hadrons
hadronic decays

FB Asymmetry @ the LHC