Top Physics and QCD at a Linear Collider: Theory

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Outline:

1. Top Quark Physics
   - –Threshold
   - –High energy ~ rad. corrections
     ~ SM tests/new phys. searches
2. QCD
   - –α_s measurement
   - –Two-photon physics

Introduction

- Top is uniquely heavy:

$$m_t = 175\ \text{GeV}$$

⇒ largest fermion - Higgs coupling
⇒ special role in EWSB? (why $\lambda_t \simeq 1$?)

- Top decays very fast:

$$\Gamma_t = 1.4\ \text{GeV}$$

⇒ decays before hadronizing
⇒ parton level treatment justified
e.g., spin info passed to decay prod.

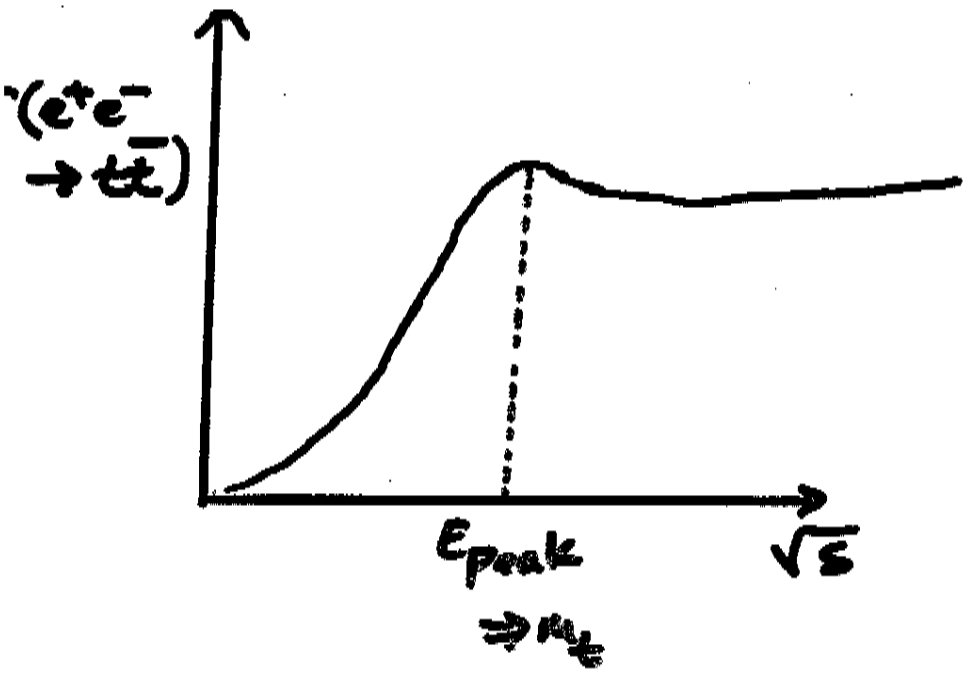
⇒ Top is prime system to study new physics
⇒ LC is excellent, clean place to do it!

- See also:
  - Higgs (Yukawa coupl.)
  - Electroweak (strong WW)
  - New phenomena (extra dim.)
  - Susy ($t \to H^+ b$ etc.)

... but you must understand SM top first!

Top at Threshold

- No toponium, but Coulomb-like QCD interaction ⇒ threshold structure:



⇒ measure

m_t

α_s

λ_t (Yukawa)

Γ_t

Thresh. scan: m_t to 50 MeV (stat)

- Sitges: NNLO corr's calculated

Problem: corr's large (normalization)

peak position keeps moving ~600-800 MeV a shift!

renorm scale dependence no better than NLO

← fig

Good news: peak position/mass problem solved

[Bad news: other two problems not solved needed for couplings]

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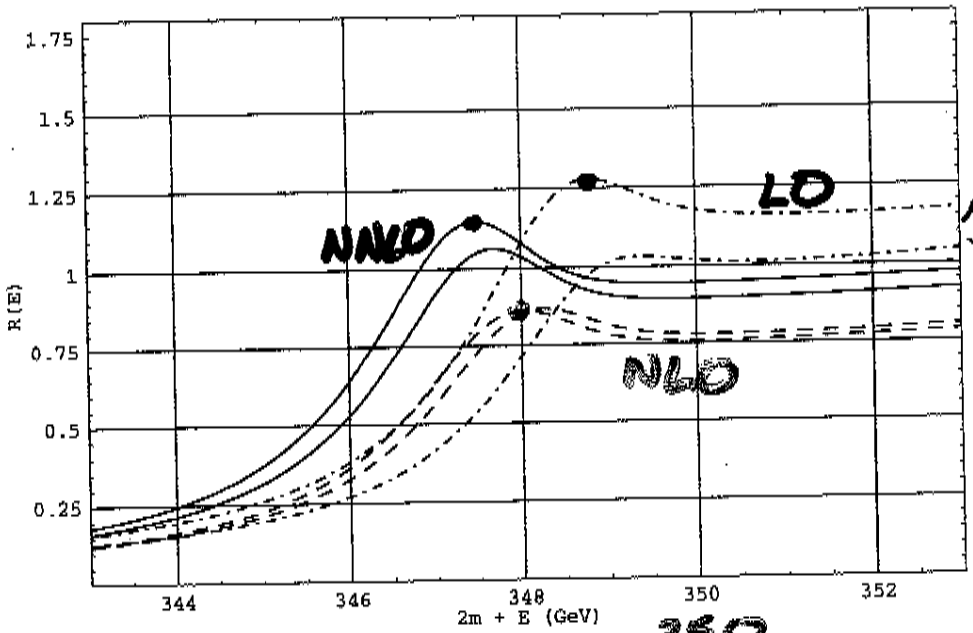
$t\bar{t}$ threshold : pole mass



- peak shift
- large corrections, even at NNLO
- large renorm. scale dependence

threshold mass + velocity resummation

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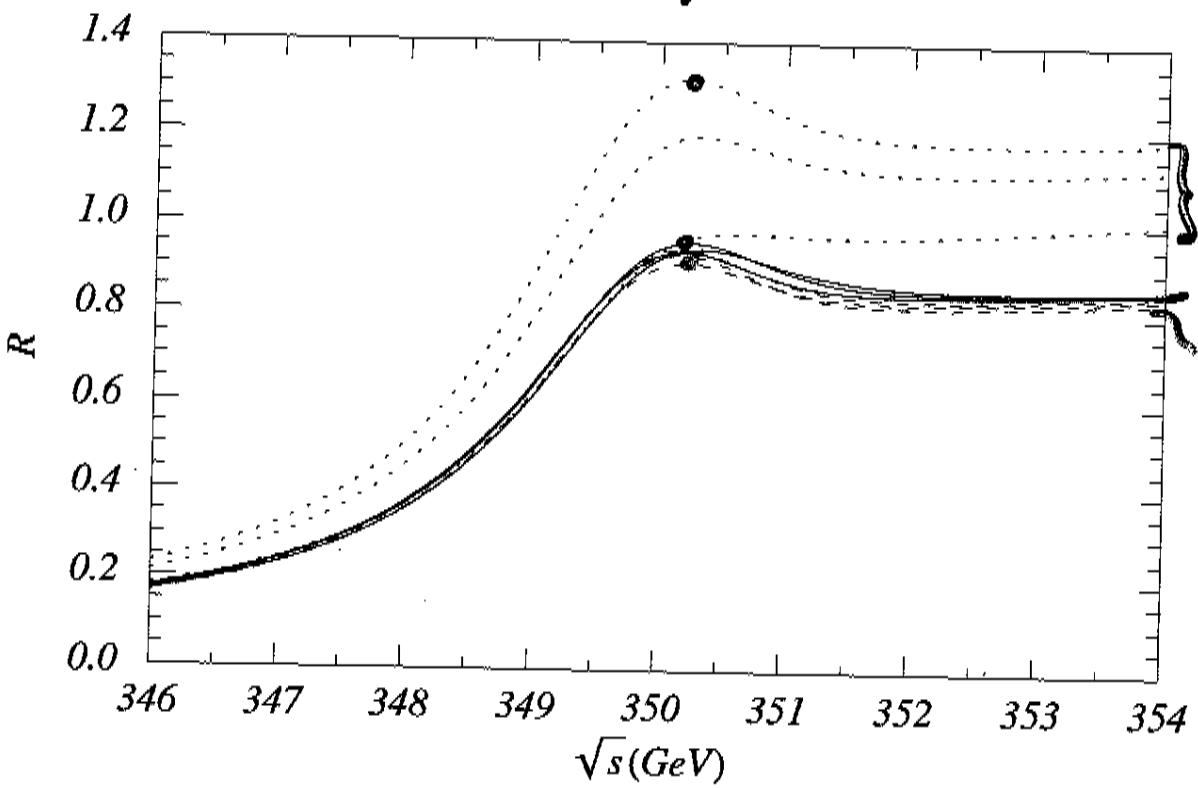


- stable peak position
- corrections under control
- renorm. scale dependence under control

Note: Different curves at given order reflect different subtraction velocities

Solutions to threshold problems:

1. Peak position: mass definition

pole mass ⇒ renormalon ambiguity ($\mathcal{O}(\Lambda_{QCD})$)

threshold mass ⇒ no problem

Hoang et al.

2. Normalization: velocity resummation

Hoang, Manohar, Stewart

⇒ 9-th measurement possibly feasible ⇒ $\Delta\sigma \sim 5\text{-}8\%$ for $m_H = 115\,\text{GeV}$

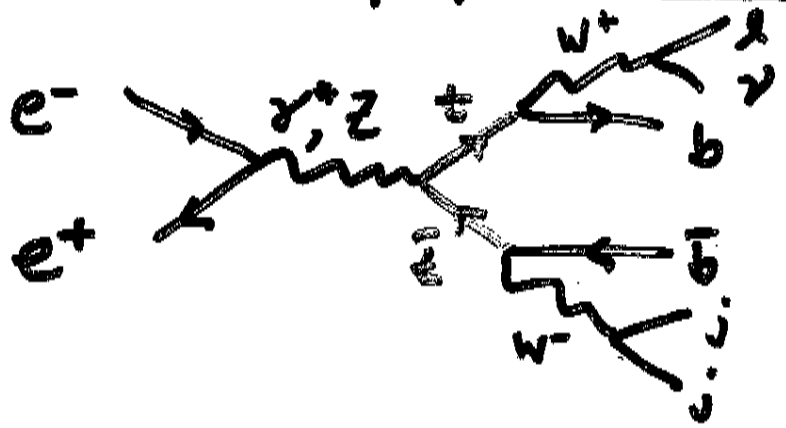
(also anom. couplings)

Needed: Differential c.s. w/ velocity resummation

Mass relation to 4 loops!

- current $\mathcal{O}(\alpha_s^3)$ ⇒ $(\Delta m_t)_{th} \sim 100\,\text{MeV}$

Continuum top production : radiative corr's



$\sqrt{s} = 500$ GeV

500 fb^{-1}

$\Rightarrow (\Delta\sigma)_{stat} < 1\%$!!

⇒ Theory has some catching up to do
⇒ Radiative corrections essential

So far :

- $\sigma(e^+e^- \to t\bar{t})$: on shell production

  QCD: 2nd order corr's — Chetyrkin, Kühn, Steinhauser, Harlander

  EW: 1-loop corr's — Beenakker, vander Mark, Hollik, Dreisen, Kraft, Denner, A Khundov, Bardin ← fig

- $\Gamma(t \to bW)$: on shell decay

  QCD: 2nd order corr's — Jezabek Kühn Czarnecki Melnikov Chetyrkin et al.

  EW: 1st order corr's — Denner Sack Eilam et al.

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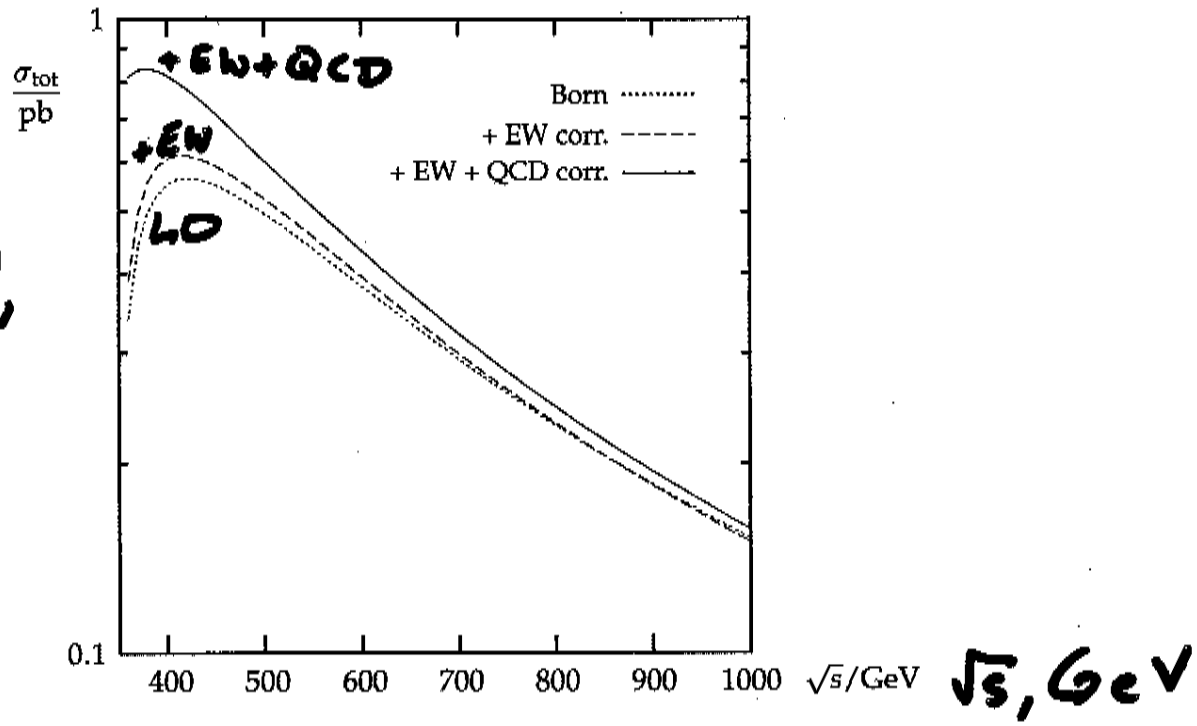


Figure 5.3.6: *The cross section for the production of top-quark pairs in the continuum as a function of the c. m. energy to lowest order, to 1-loop order in the electroweak (EW) corrections [80], and including the combined order α_s [83], α_s^2 [79] QCD and EW corrections [84]. The mass $m_t = 175$ GeV (pole mass) is used.*

the $t\bar{t}$ production vertex this amounts to real and imaginary parts, respectively. Depending on how the form factors vary with s their contribution to the cross section or to other observables can increase with the c.m. energy.

The general amplitude for the decay $t \to Wb$ contains four (complex) form factors, two chirality-conserving and two chirality-flipping ones, respectively. Here we consider only the form factor F_{1R}^W which signifies a $V+A$ admixture, and ImF_{2R}^W which, if found to be non-zero, would be evidence for non-SM CP violation [88]. (For further studies, see [90].)

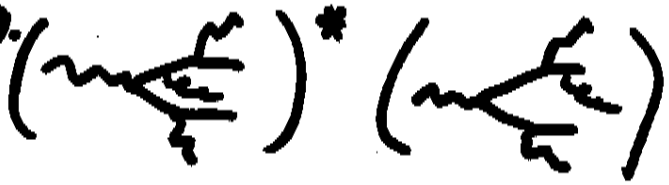
Among the "static" parameters, that is, the above form factors of the top quark which can be determined only at e^+e^- linear colliders, the following examples are of particular interest:

Z charges of the top quark. The form factors F_{1V}^Z, F_{1A}^Z can be determined from the $t\bar{t}$ production cross sections with e_L^- and e_R^- beams and the left-right asymmetry [91, 92]. Moreover, the production of top quarks near the threshold with longitudinally polarised beams leads to a sample of highly polarised quarks. The small admixture of transverse and normal polarisation induced by S-wave/P-wave interference, is extremely sensitive

Top at High Energy: NLO c.s. for $t\bar{t}$ production + decay

- For heavy unstable particles ($Z, W, t, \ldots$) corr's to production + decay should be considered together.

- Previously: Corr's to
  - production — Jersak, Laerman, Zerwas
  - decay — Jezabek, Kuhn
  - prod + decay (on-shell/narrow width) — Schmidt

- interferences:
  1) real rad. eg. 

soft g { Ji Kia, Khoze, Stirling, Dokshitzer, LHO

hard g { Siopsis, Macesanu, LHO

⇒ sensitivity to Γ_t in gluon dist

← fig

- interferences, cont.

2) virtual corr's ("nonfactorizable")

e.g.

on-shell { Melnikov, Yakovlev
Beenakker, Berends, Chapovsky

⇒ complete cancellation in inclusive quantities

Fadin, Khoze, Martin

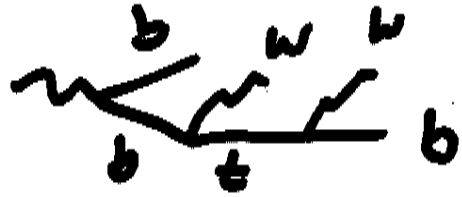
- **New**: Complete QCD NLO calc. of top prod + decay: **Macesanu**

$e^+e^- \to b\bar{b}WW(g)$

- Double pole approx (DPA)

⇒ Keep only diagrams w/ 2 resonant top propagators

+ corr

but not e.g. 

cf. WW prod. at LEP II Denner Dittmaier Roth

- Includes (among other things)
  - spin corr.
  - width in propagator
  - * off-shell top in ME (incl. residues)

- Features of note (interferences, i.e. nonfactorizable corr's)
  - In contrast to WW, not all terms can be written

    m_0 * corr.

    because top is a fermion
  - Incomplete cancellation of non-fact. corr's in off-shell DPA
    ⇒ ~O(1%) of total ← fig

- Results for total c.s.

σ(pb)

	360	500	1000 ← $\sqrt{s}$ (GeV)
$\sigma_1^{\text{on-shell}}$	0.682	0.627	0.175
σ_1^{fact}	0.670	0.629	0.178
$\sigma_1^{\text{non-fact}}$	-0.034	-0.007	-0.002

$|P_{t,\bar{t}}^2 - m_t^2| < 15\,\text{GeV}$

Needed: Non-doubly resonant contrib.'s

Miscelleneous Comments

- QCD + EW corr's combined:

  on-shell prod: Kuhn, Hahn, Harlander

  $t\bar{t}$ prod + decay in progress
  Macesanu, Wackeroth, CMO

- QCD corr's to spin correlations

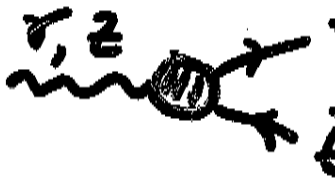
  Spin corr's essentially unchanged
  Kodaira, Nasuno, Parke

- anom. QCD couplings

  not much progress since Snowmass '96 Riego

SM tests / anomalous couplings / new physics

At LC, probe top production + decay couplings:

- prod. 

(very tough at LHC!)

$$\Gamma^{\mu}_{tt\gamma,Z} = ie\left\{\gamma^{\mu}\left[F_{1V}^{\gamma,Z} + F_{1A}^{\gamma,Z}\gamma_5\right] + \frac{(P_t - P_{\bar{t}})^{\mu}}{2m_t}\left[F_{2V}^{\gamma,Z} + F_{2A}^{\gamma,Z}\gamma_5\right]\right\}$$

form factor	SM LO	induced by SM rad. corr.?	non-SM
F_{1V}^{γ}	2/3	LO	strong EWSB ↓
F_{1V}^{Z}	0.2	LO	
F_{1A}^{γ}	0	[illegible]	?
F_{1A}^{Z}	-0.6	LO	SM dominates
$F_{2V}^{\gamma,Z}$ mag. dipole	0	$O(\alpha_s)$, light Higgs	CP-conserving
$F_{2A}^{\gamma,Z}$ elec/weak dipole	0	3 loop	cf. susy, multi-Higgs

• decay

$$\Gamma^{\mu}_{tbW} = \frac{-g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left\{ f_1^L P_L + f_1^R P_R \right\} \right.$$

$$\left. \frac{-i\sigma^{\mu\nu}}{M_W} (P_t - P_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

form factor	SM LO	non-SM
f_1^L	1	SM dominates
f_1^R	0	V+A
f_2^L	0	?
f_2^R	0	V+A, can be CP

For both prod. and decay

- angular distributions, asymmetries
- polarization buys increased sensitivity

⇒ Keep spin correlations

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to the axial Z charge a_t of the top quark [76]. Some models of strong-interaction-type electroweak symmetry breaking predict rather large anomalous contributions, δF_{1V}^Z up to 10 % [93].

Magnetic dipole moments of the top quark. These form factors are generated already in the SM at the quantum level. Gluon exchange induces a term $F_{2V}^{\gamma,Z} \sim \alpha_s/\pi$ and the interactions of a light Higgs boson would lead to a contribution of similar size. If the electrons in the annihilation process $e^+e^- \to t\bar{t}$ are left-handedly polarised, the top quarks are produced preferentially as left-handed particles in the forward direction while only a small fraction is produced as right-handed particles in the backward direction [94]. As a result of this prediction in the Standard Model, the backward direction is most sensitive to small anomalous magnetic moments of the top quarks. The anomalous magnetic moments can thus be searched for by measuring the angular dependence of the t quark cross section [94, 57].

Form factor	SM value	$\sqrt{s} = 500\,\text{GeV}$		$\sqrt{s} = 800\,\text{GeV}$	
		$p = 0$	$p = -0.8$	$p = 0$	$p = -0.8$
F_{1V}^Z	1		0.019		
F_{1A}^Z	1		0.016		
$F_{2V}^{\gamma,Z} = (g-2)^{\gamma,Z}{}_t$	0	0.015	0.011	0.011	0.008
$\text{Re}\, F_{2A}^\gamma$	0	0.035	0.007	0.015	0.004
$\text{Re}\, d_t^\gamma$ [10^{-19} e cm]	0	20	4	8	2
$\text{Re}\, F_{2A}^Z$	0	0.012	0.008	0.008	0.007
$\text{Re}\, d_t^Z$ [10^{-19} e cm]	0	7	5	5	4
$\text{Im}\, F_{2A}^\gamma$	0	0.010	0.008	0.006	0.005
$\text{Im}\, F_{2A}^Z$	0	0.055	0.010	0.037	0.007
F_{1R}^W	0	0.030	0.012		
$\text{Im} F_{2R}^W$	0	0.025	0.010		

Table 5.3.1: *1 s.d. statistical sensitivities to some (non) SM form factors in $t\bar{t}$ production [57, 95, 96] and in t decay to Wb [57, 88]. The second column contains the respective SM value to lowest order, p denotes the polarisation of the electron beam. For the c.m. energy $\sqrt{s} = 500\,GeV(800\,GeV)$ an integrated luminosity of 300 fb^{-1} (500 fb^{-1}) was used. F_{1R}^W measures $(V+A)/(V-A)$.*

Examples

- model-indep : Kiyo. Analyze spin corr. à la Parke-Shadmi off-diag. basis

  ⇒ lepton asym.

  ← fig

- model-indep : Grzadkowski & Hioki : CP

  ⇒ lepton, b asym.

  ← fig

- large extradim : Lee, Song, Park, Song, Yu

  ⇒ FB asym.

  ← fig

- top-color assisted TC : Huang, Xiong, Lu

  ⇒ effect on total C.S.

  ← fig

- non-SM decays

  $t \to b H^+$, $t \to \tilde{t}\,\tilde{\chi}^0$

  ← fig

  FCNC $t \to c\gamma, cZ$

Kiyo, FNAL LCWS

$$A = \frac{\int_{\varphi_e=0}^{\pi} d\varphi \frac{d\sigma}{d\cos\Theta\, d\varphi_e} - \int_{\varphi_e=\pi}^{2\pi} (\quad)}{+}$$

$e_R^+ e_L^-$ $\qquad$ $e_L^+ e_R^-$

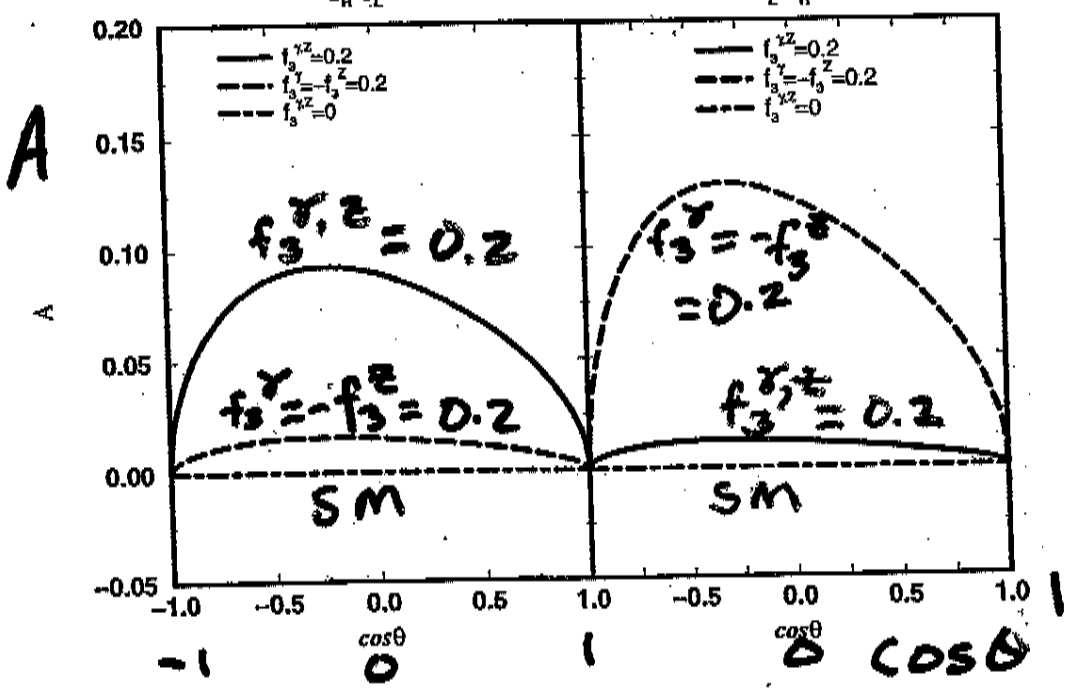


Figure 5: Azimuthal asymmetry as a function of $\cos\theta$ in the off-diagonal basis.

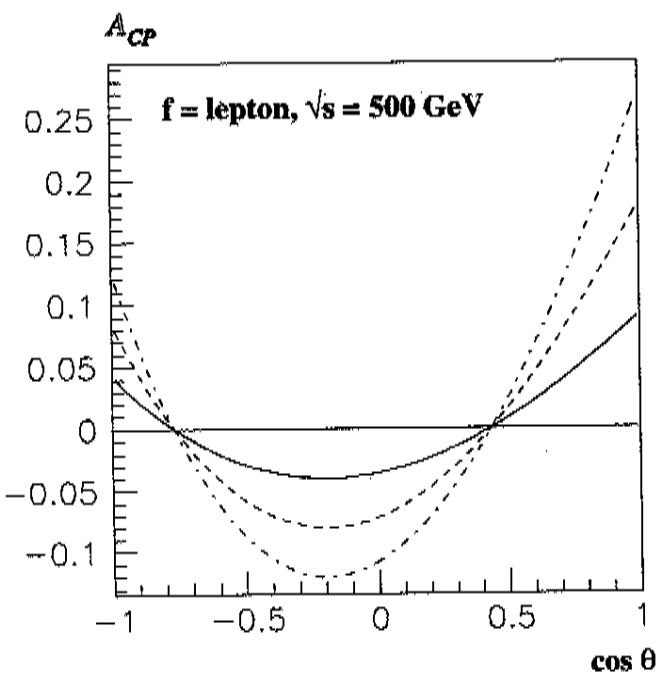
$|f_3| = 1 \leftrightarrow 10^{-16}$ e cm in EDM

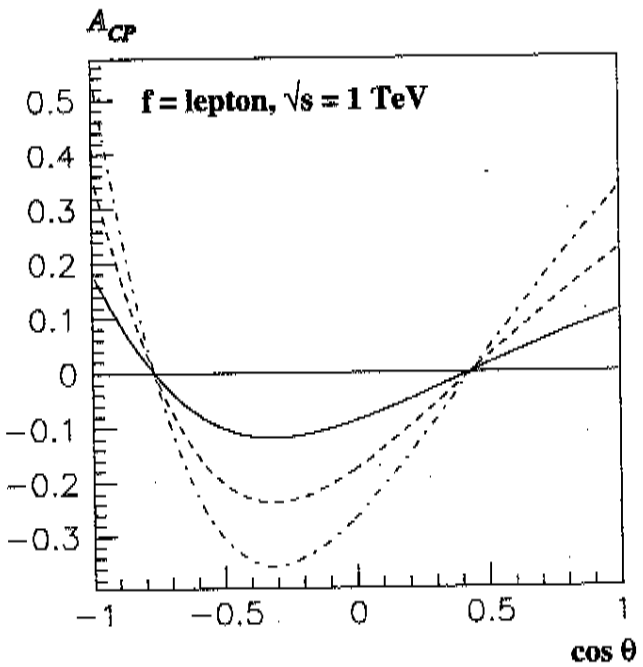
$$\Gamma^{\gamma,Z}_{t\bar{t}} = g_V \left\{ Q_L^{\gamma,Z} \gamma_\mu L + Q_R^{\gamma,Z} \gamma_\mu R + \frac{(t-\bar{t})_\mu}{2m_t} \left[G_L^{\gamma,Z} L + G_R^{\gamma,Z} R \right] \right\}$$

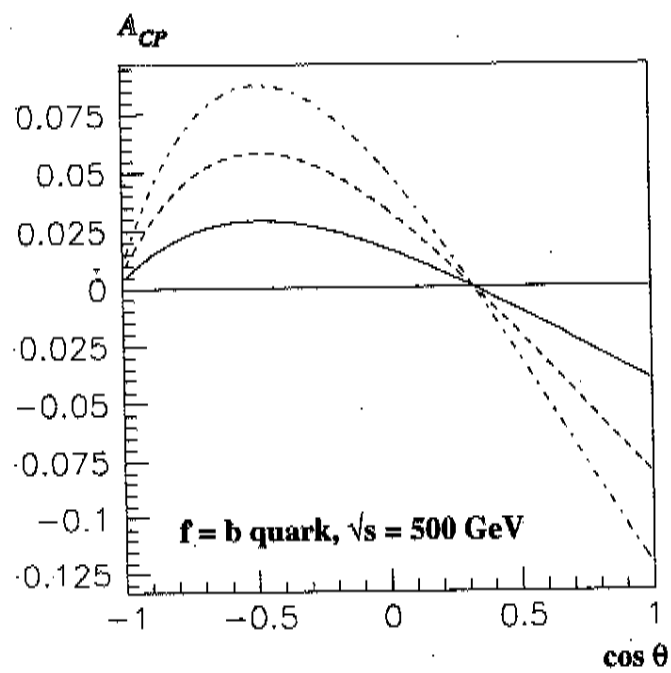
$if_2 = G_0 - G_-$

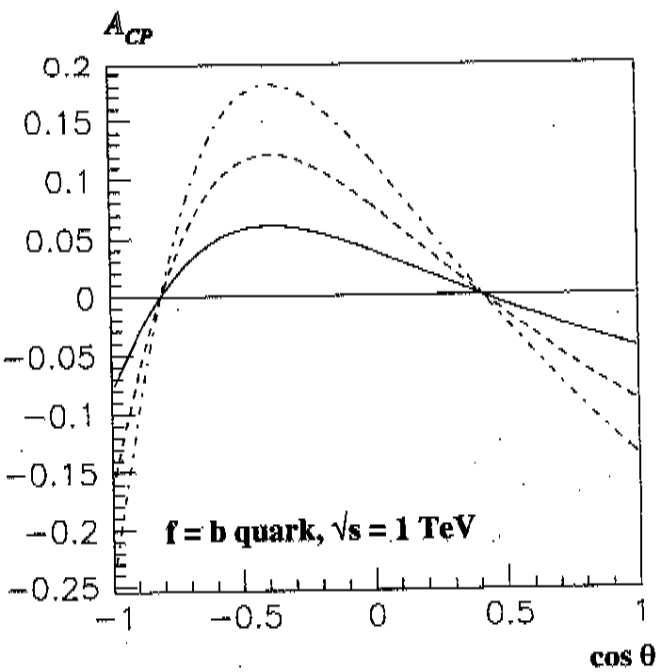
Grzadkowski
Hioki

CP asymmetries







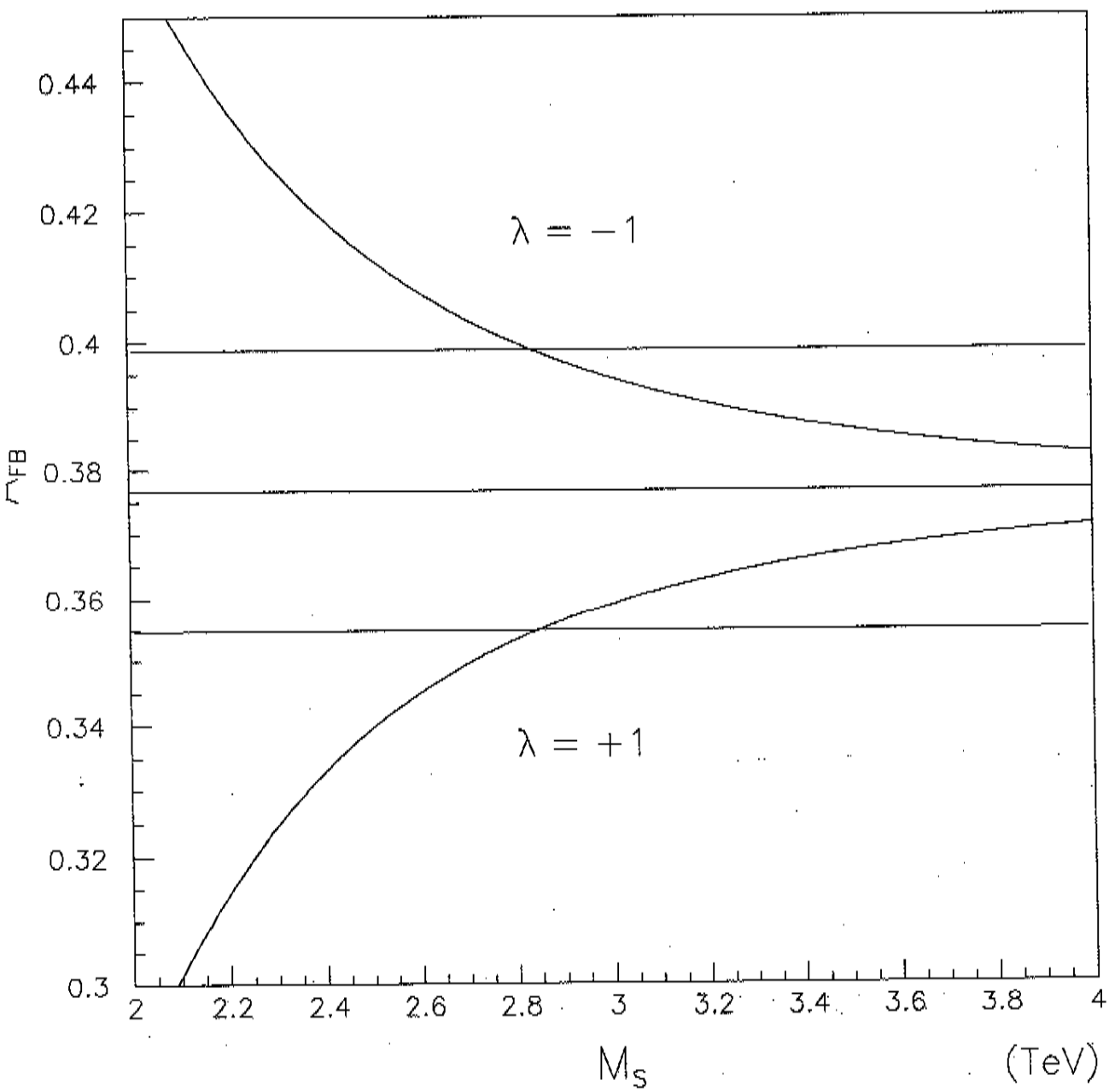


$e^+e^- \to t\bar{t}$ via graviton exch.

Lee, Song, Park, Song, Yu

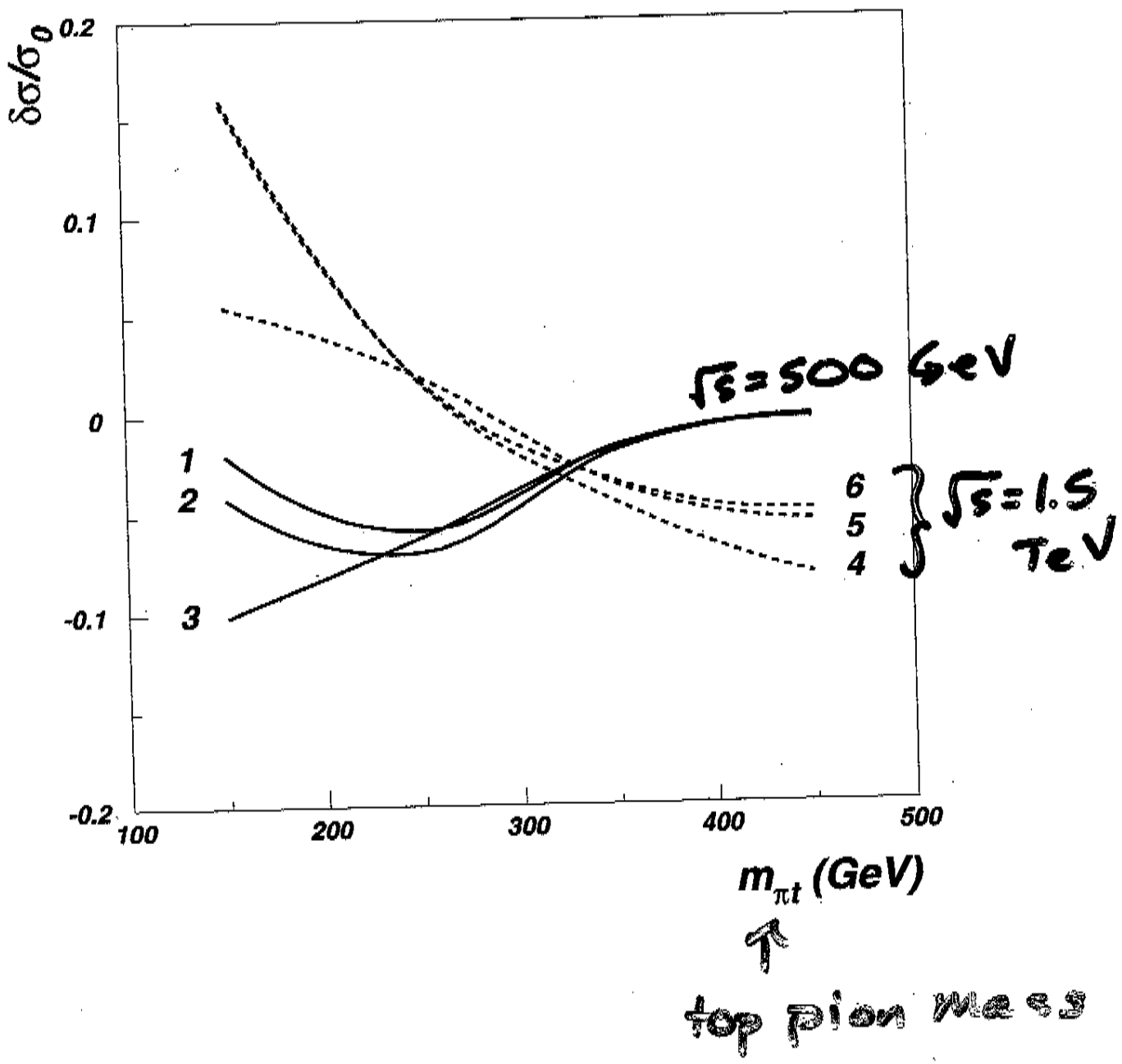
$$\mathcal{M} = \frac{\lambda}{M_S^4}\{\text{Lorentz} + \text{dirac structure}\}$$

M_S = D-dim fundamental scale



Huang, Xiong, Lu

Topcolor assisted technicolor



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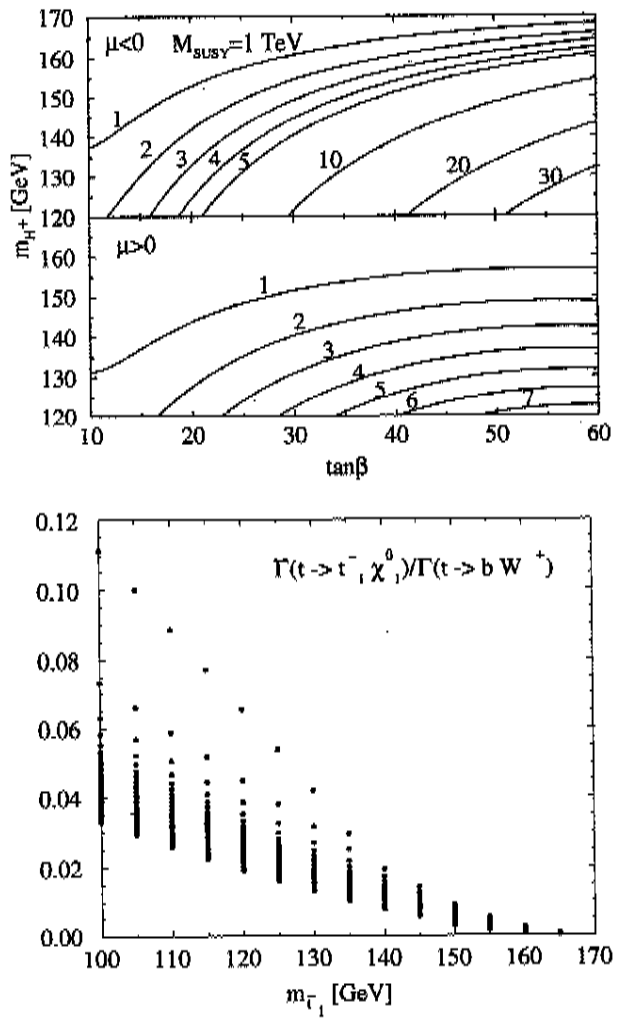

Figure 5.3.1: *a) Contour of fixed branching ratios (in percent) of top quark decays to charged Higgs bosons in supersymmetric theories, for two characteristic sets of parameters [68]. Also shown is the range of charged Higgs boson masses as a function of the coupling* $\tan\beta$ *that can be detected experimentally for a given luminosity. b) Range of the branching ratio of top quark decay to a stop particle and the lightest neutralino in supersymmetric theories [58].*

invariant mass of colour singlet final states recorded in the detector necessarily has a larger uncertainty.

Why should it be desirable to measure the top mass with high precision? Two immediate reasons can be given:
(*i*) The top mass is an important ingredient for the electroweak precision analyses at

Combining Matrix Elements w/ Parton Showers

- Multipurpose MC's typically take

  LO ME * PS

  to get gluon radiation. Okay for leading QCD effects but more needed

⇒ Recent efforts to incorporate higher order ME's (careful: double counting)

Sjostrand Catani Krauss Webber Kuhn Pötter Schorner Seymour Corcella . . .

ex: ME corrections to gluon radiation in PYTHIA, HERWIG for heavy particles

2 – QCD

It's everywhere!

signals, background,

loops...

α_s measurement

- fundamental parameter of SM
- uncertainty in α_s ⇒ unc. on all pQCD
  → esp. multijets
- running $\alpha_s(Q^2)$
  - tests QCD
  - constrains GUT scale
- LC perfect ⇒ extend lever arm in Q^2
  sensitivity → 0.5% stat

  evt. shapes, $Z \to had$ ← fig
- theory status
  - $O(\alpha_s^2)$ ⇒ 5%
  - need $O(\alpha_s^3)$

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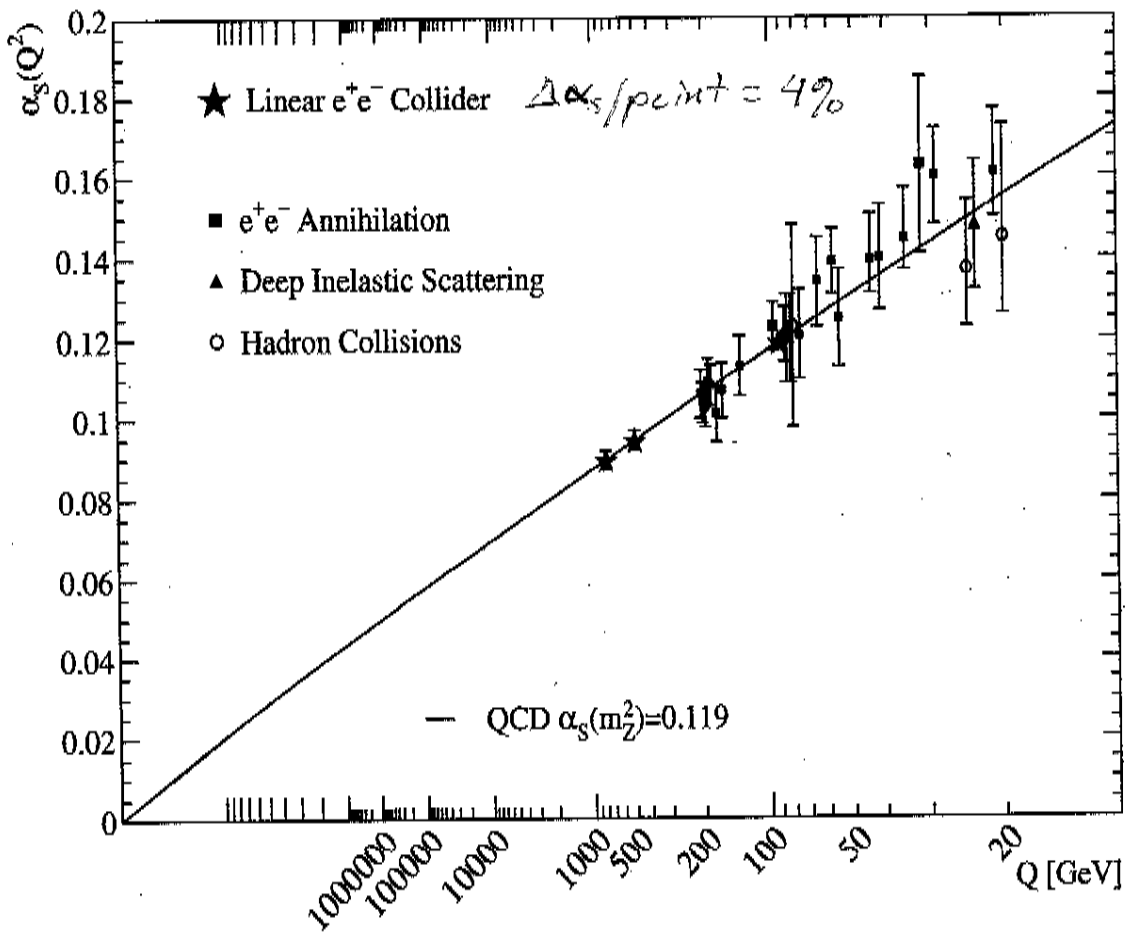
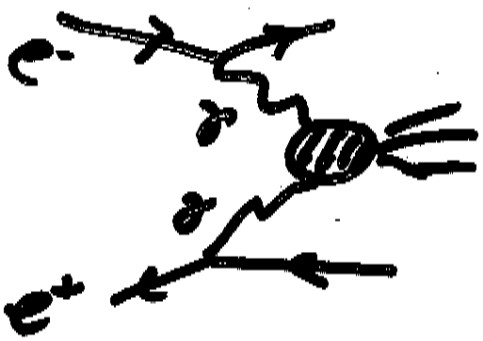
Measurement of α_s



PDG 2000: $\alpha_s(m_{e^+e^-}) = 0.118 \pm 0.002$

Two-photon Physics

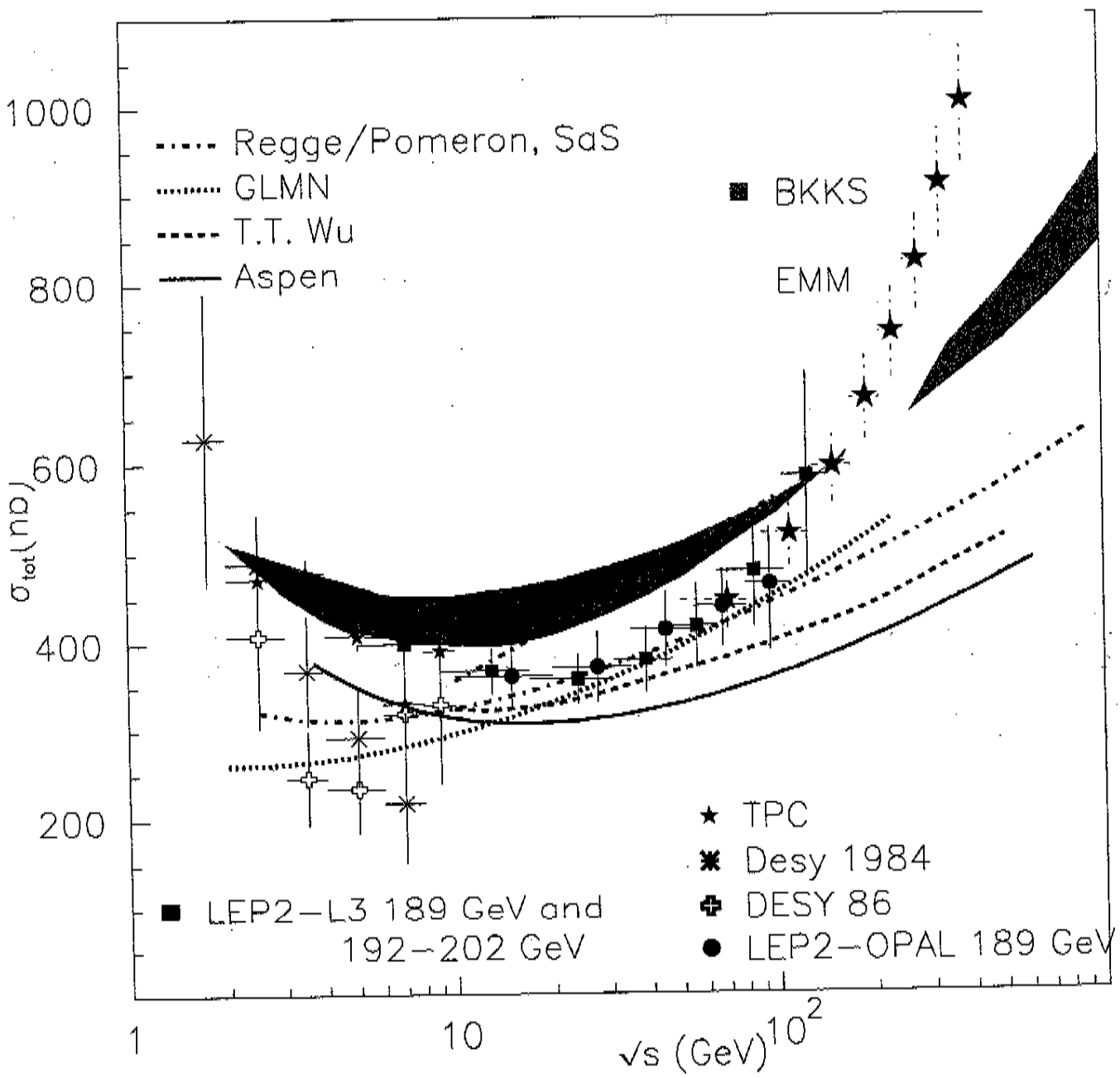
e^+e^- gives $\gamma^{(*)}\gamma^{(*)}$ for free:



- Total c.s. $\sigma_{tot}(\gamma\gamma)$
  - rises w/ $\sqrt{s_{\gamma\gamma}}$
  - models but no 1st princ. theory
    - fig
- Photon structure (eγ DIS)
  - F_2^γ
    - fig
  - QCD evolution

$\sigma_{tot}(\gamma\gamma)$

LC Orange Book



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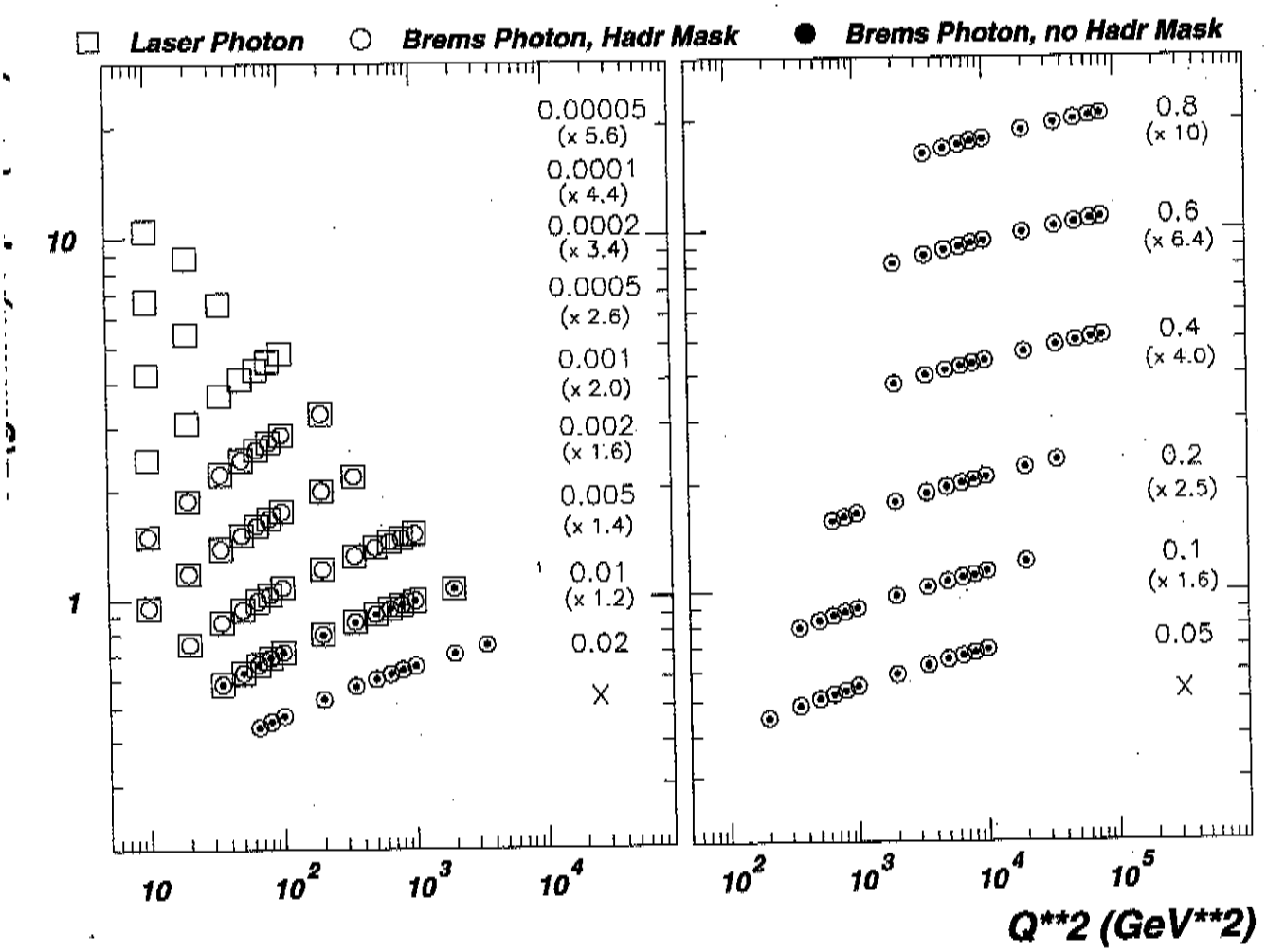
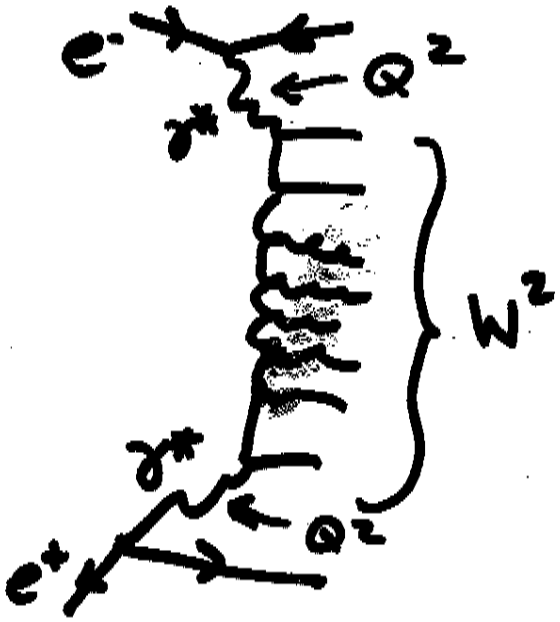


BFKL in $\gamma^*\gamma^*$ scattering

- BFKL resums large logs: $(\alpha_s \ln)^n$



BFKL: $W^2/Q^2 \gg 1$

$s \gg Q^2$

- L3: excess over asymptotic QCD

⇒ not in asymptotic regime!

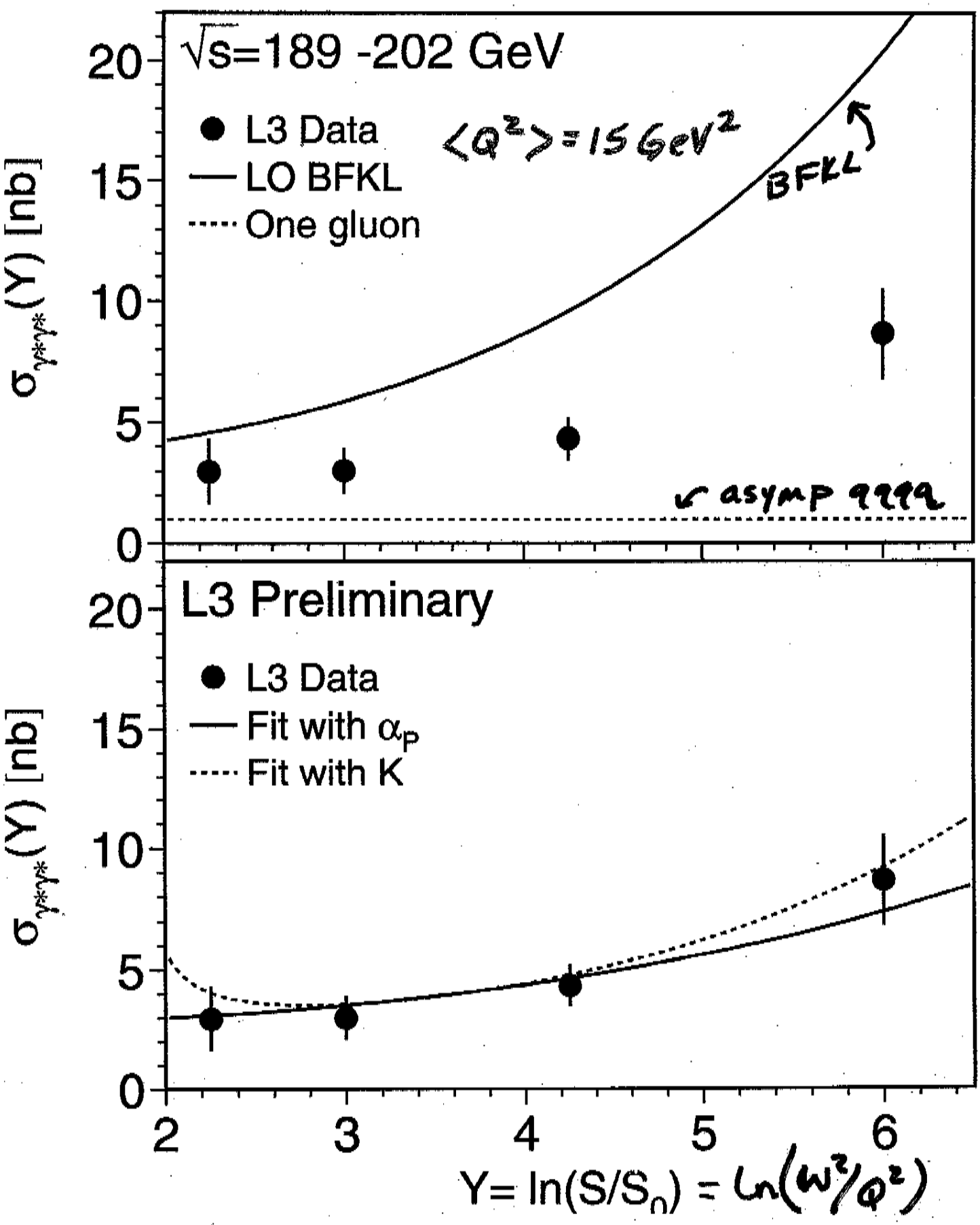
Del Duca, Maltoni, Trócsányi; LHO, Stirling

⇒ need for BFKL still open question

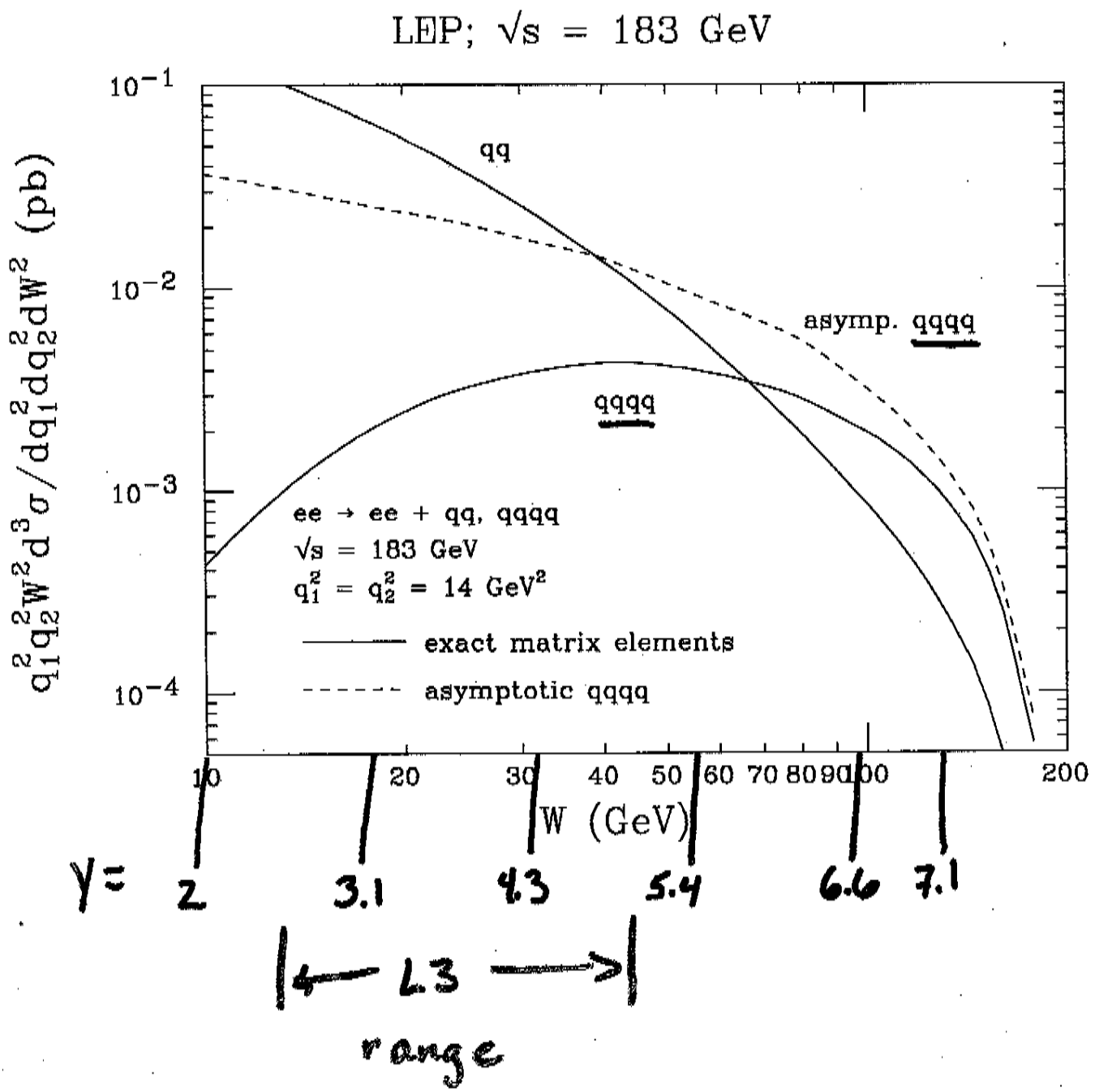
LC can help!

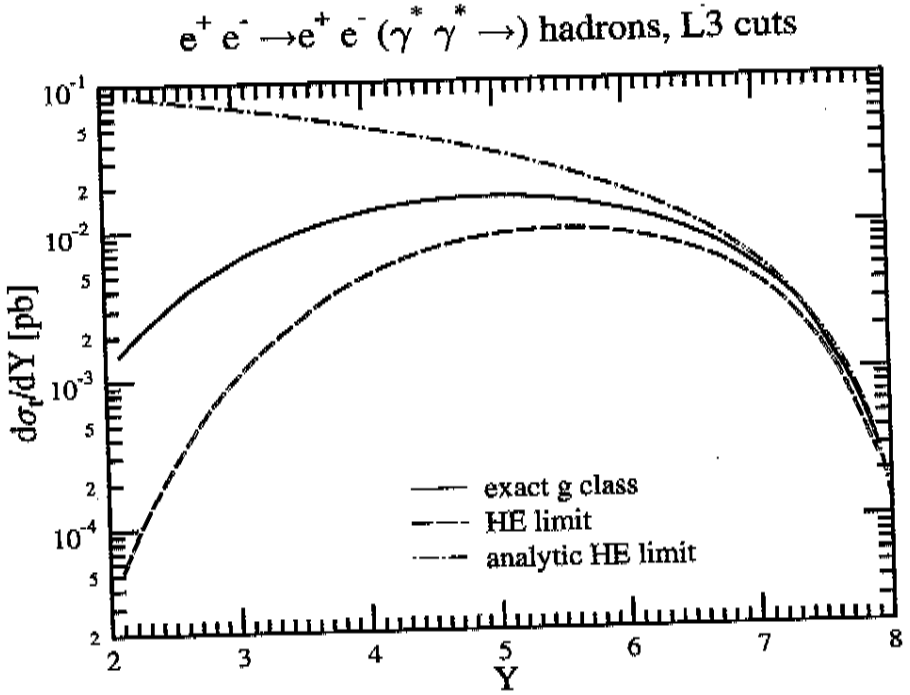
- still needed
  - NLO QCD for $\gamma^*\gamma^* \to 4g$
  - Proper BFKL MC

L3

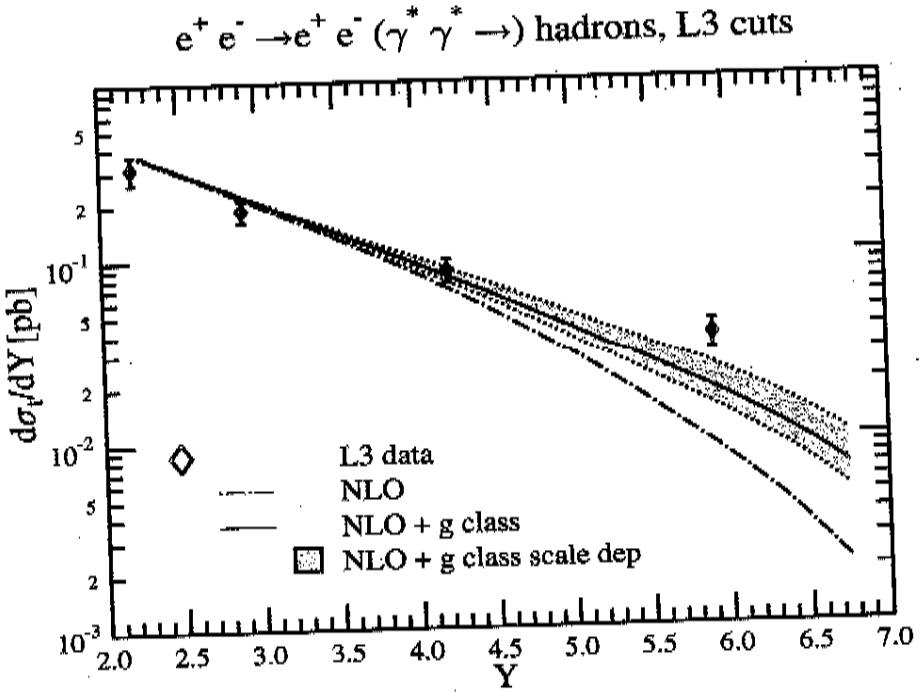

√s=189 -202 GeV
L3 Data
LO BFKL
One gluon
⟨Q²⟩=15 GeV²
BFKL
asymp
L3 Preliminary
L3 Data
Fit with αP
Fit with K
σγ*γ*(Y) [nb]
Y= ln(S/S0) = ln(W²/Q²)

Stirling LHC





Del Duca
Maltoni
Trócsányi



Concluding Remarks

- See LC Orange Book, TESLA TDR
- Get to work!