QCD measurements at the future Circular Electron-Positron Collider

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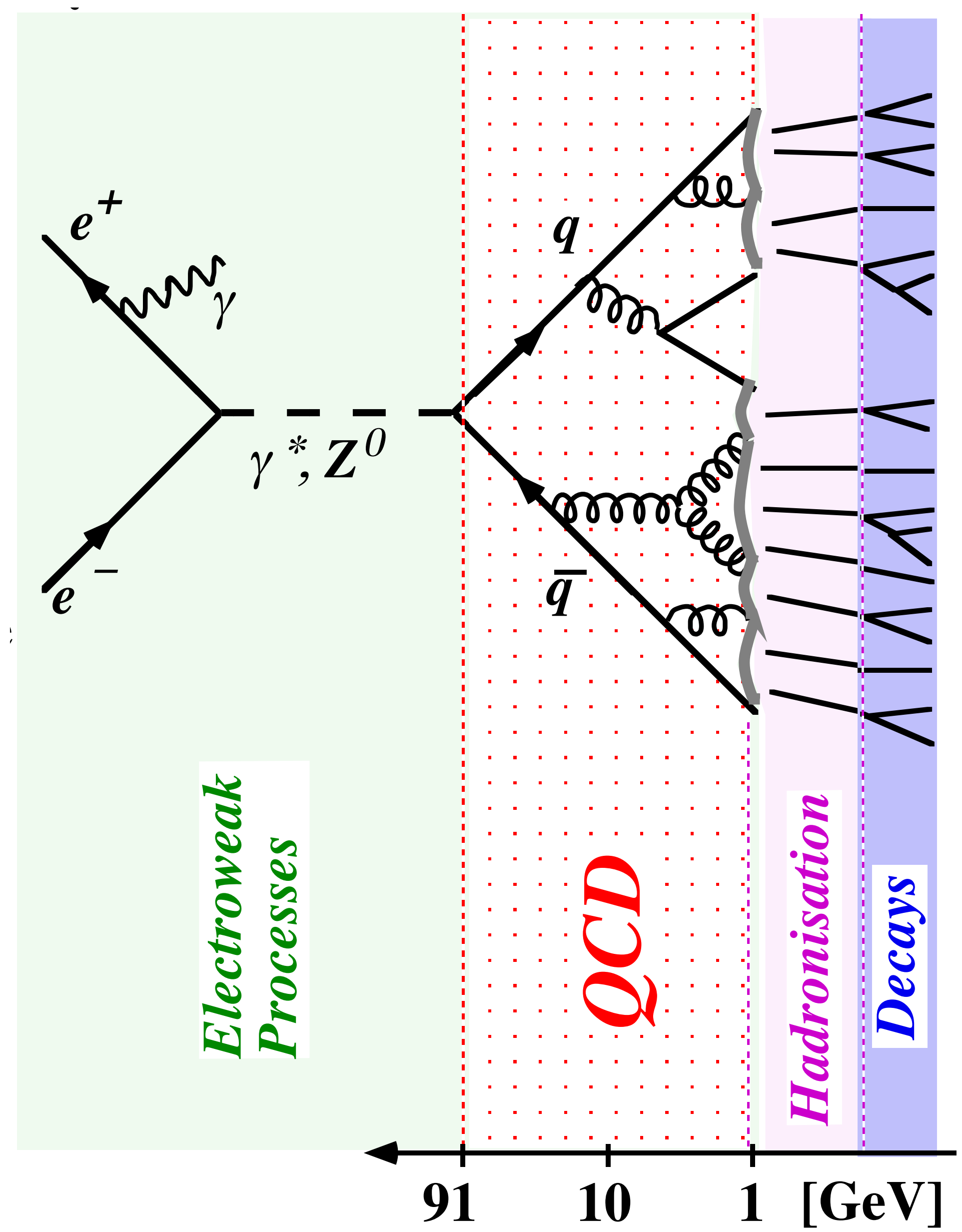
Lepton Colliders

- Ideal machine for study of precision physics; well predicted and controlled backgrounds; fixed initial state energy

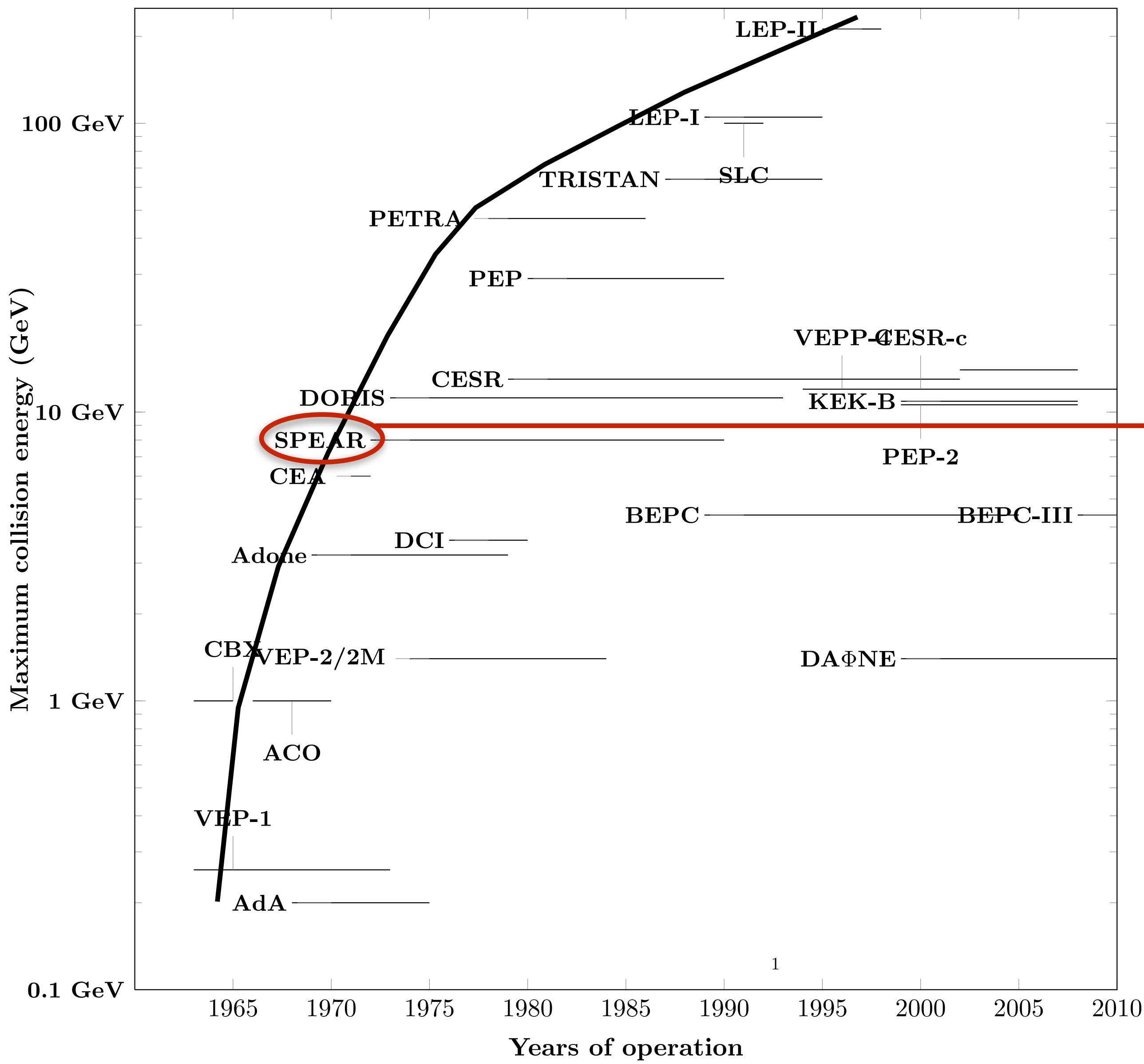


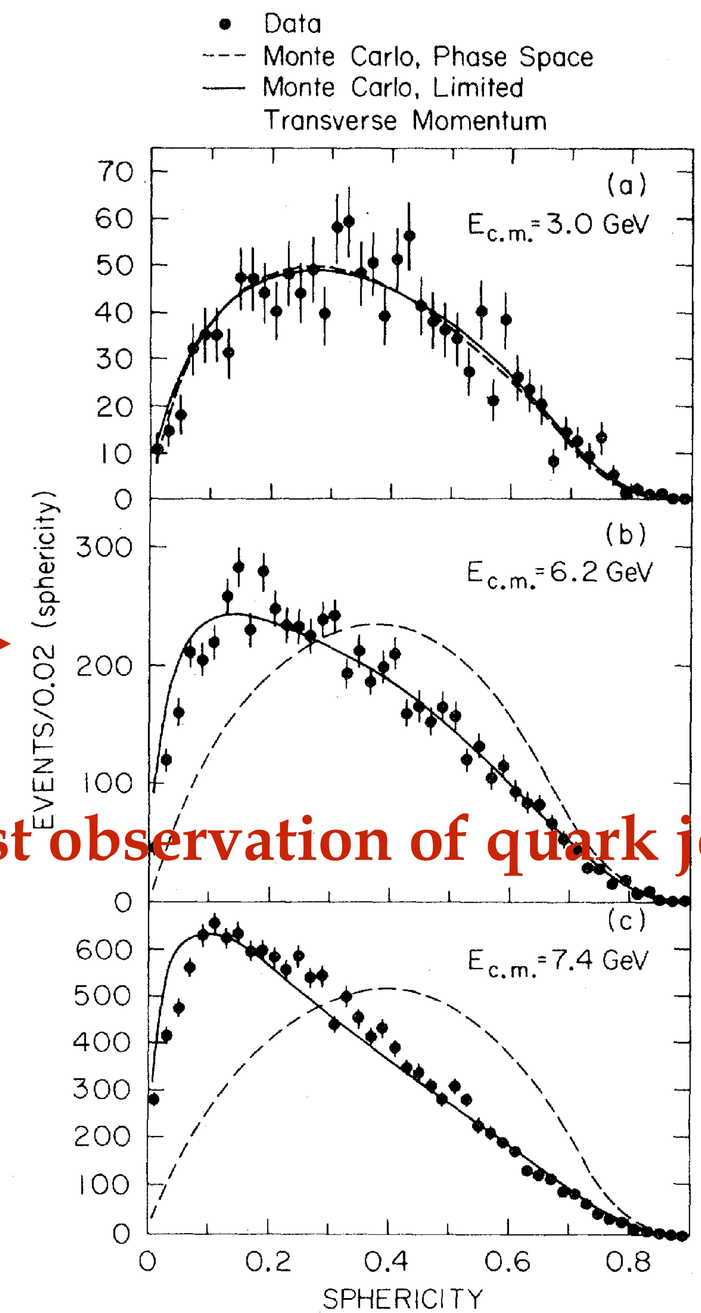
anatomy of hadronic events at lepton colliders

- EW, Higgs physics
- Flavor, hadronic physics
- Top-quark physics
- Dark matter and new physics
- QCD and Jet physics

QCD and Jets

- Seminal contributions to the establishment of QCD from experimental study at lepton colliders





first observation of quark jets

evolution of lepton colliders

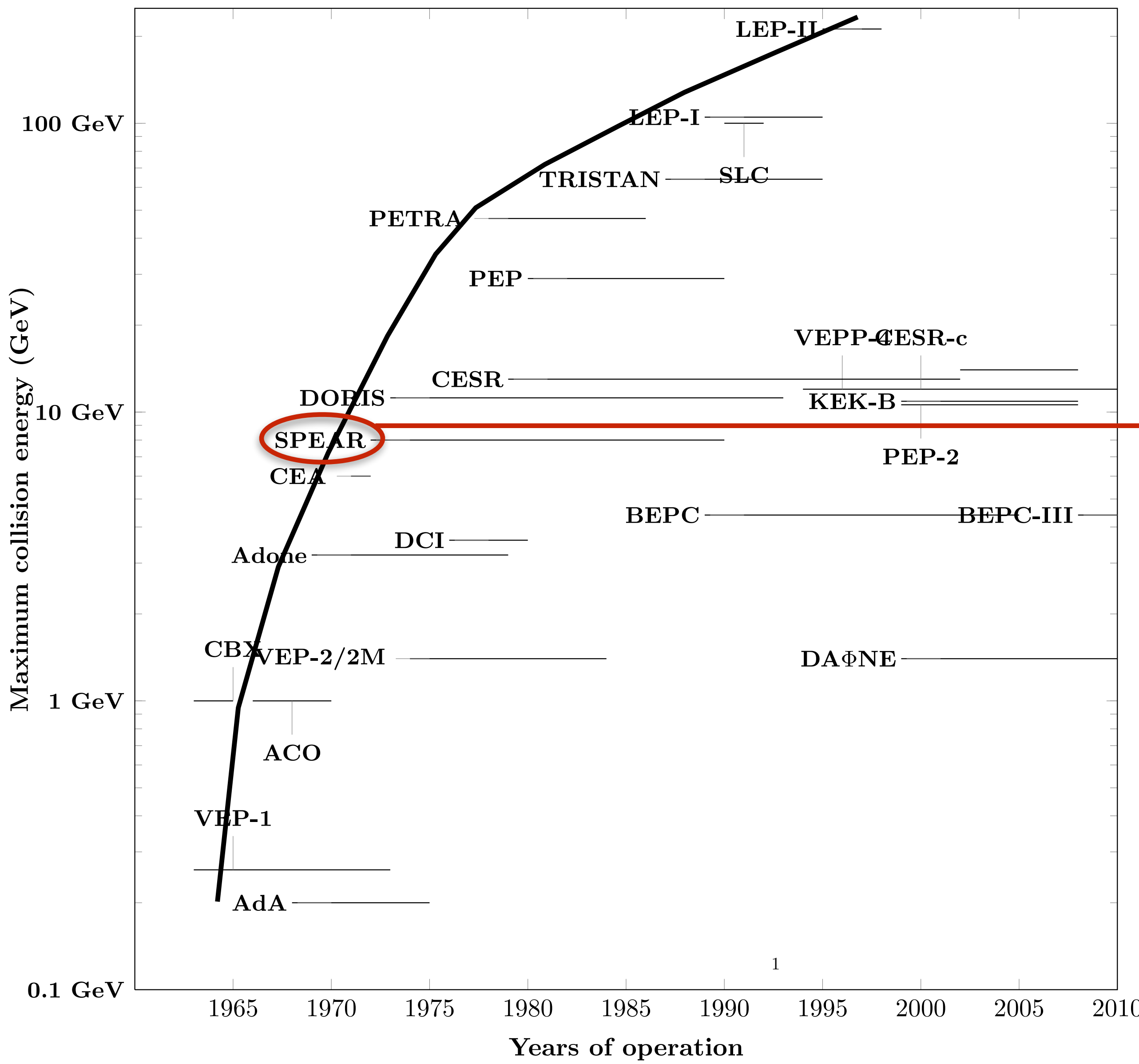
RPL 35, 1609 (1975), SLAC-LBL

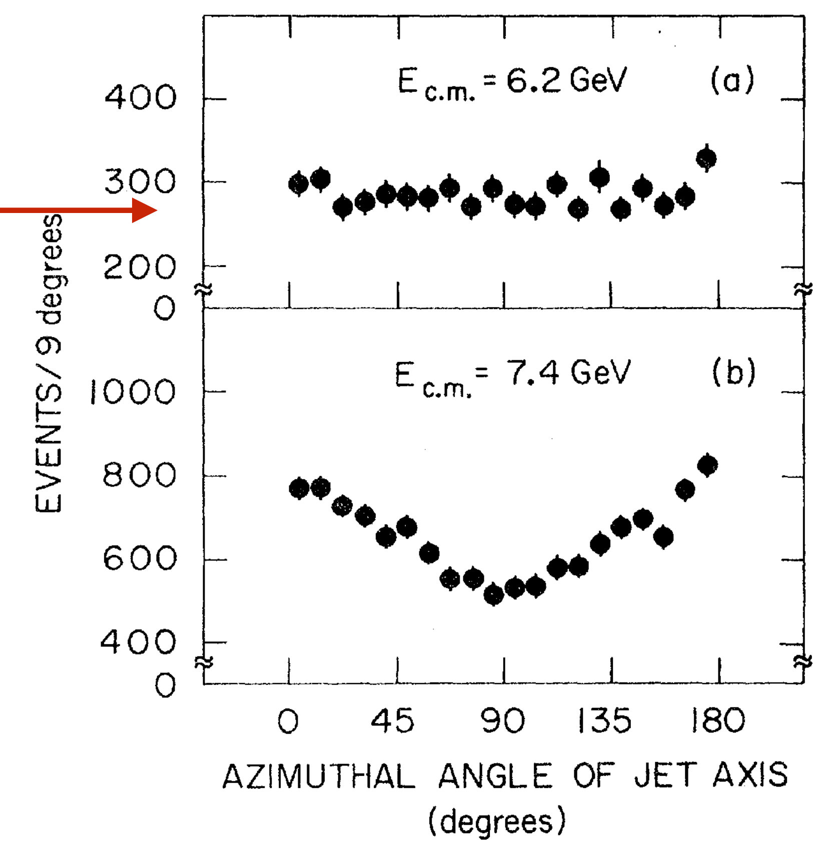
QCD and Jets

- Seminal contributions to the establishment of QCD from experimental study at lepton colliders

angular distributions support spin 1/2 nature of the quarks

$$\frac{d\sigma}{d\Omega} \sim 1 + \alpha \cos^2\theta + \alpha P_+ P_- \sin^2\theta \;\; \cos 2\phi$$





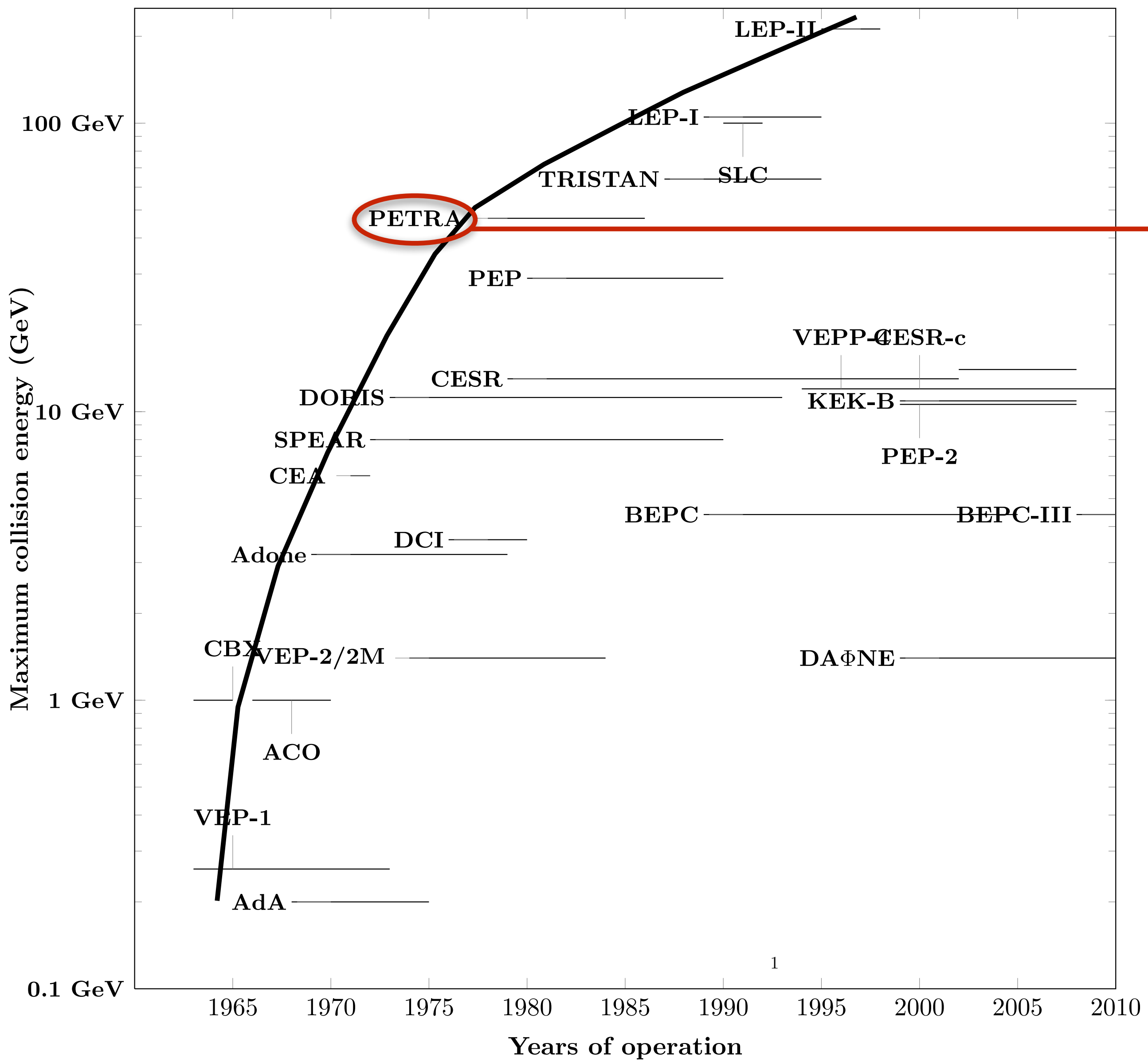
evolution of lepton colliders

RPL 35, 1609 (1975), SLAC-LBL

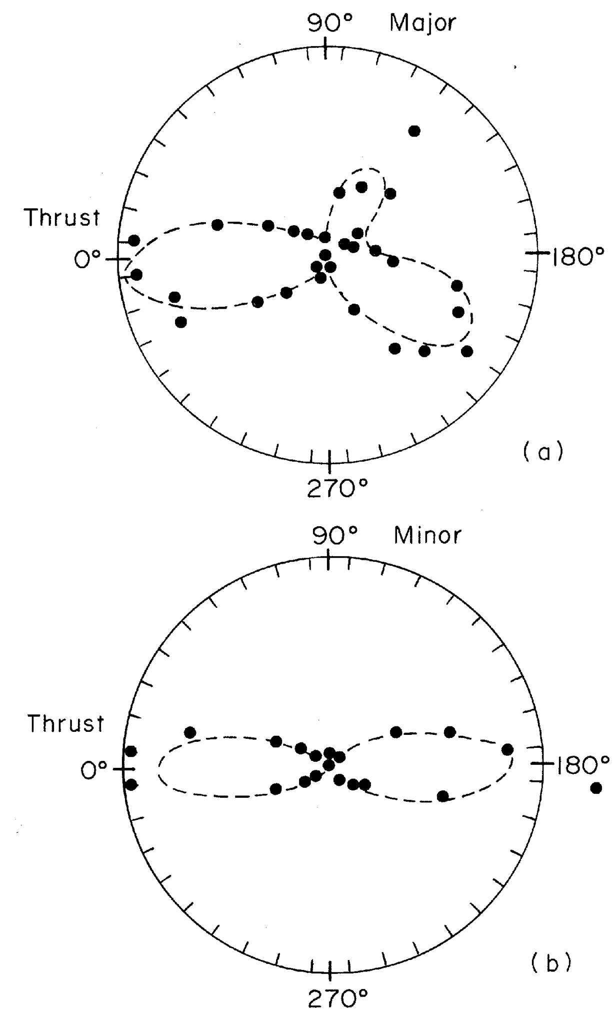
QCD and Jets

- Seminal contributions to the establishment of QCD from experimental study at lepton colliders

first evidence of three-jets and discovery of gluon jet



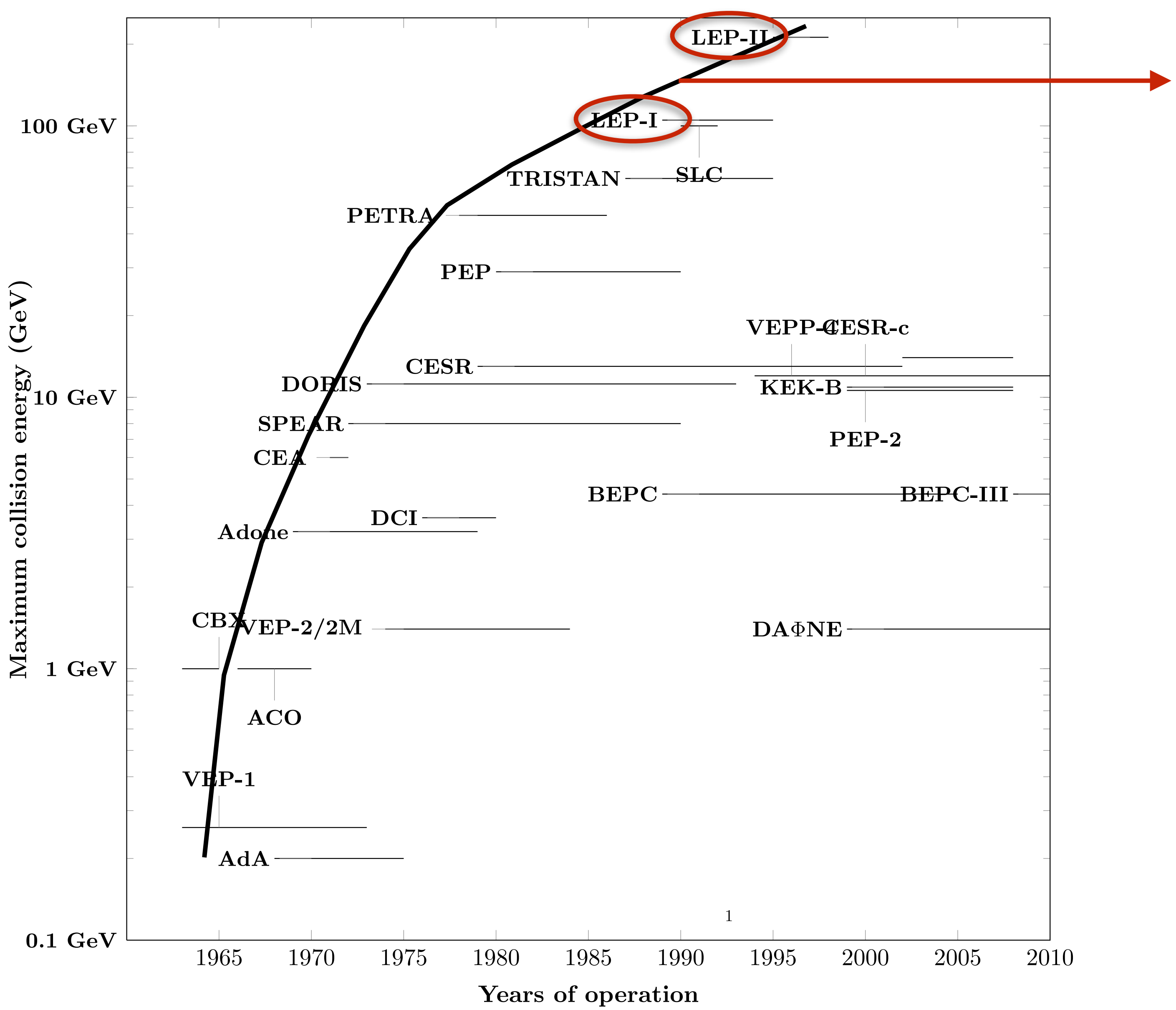
evolution of lepton colliders



RPL 43, 830 (1979), MARK-J

The Era of LEP

- LEP (highest ~209 GeV) studied multi-jet final states and jet properties over a large range in energy; foundation of precision QCD



evolution of lepton colliders

- measurement of α_s, asymptotic freedom, non-Abelian gauge structure of QCD
- difference of quark and gluon jet
- string effects, hadronization models, power correction
- multi-jet production, hadronic event shapes
- gluon splitting to heavy quarks, running b quark mass
- two photon physics

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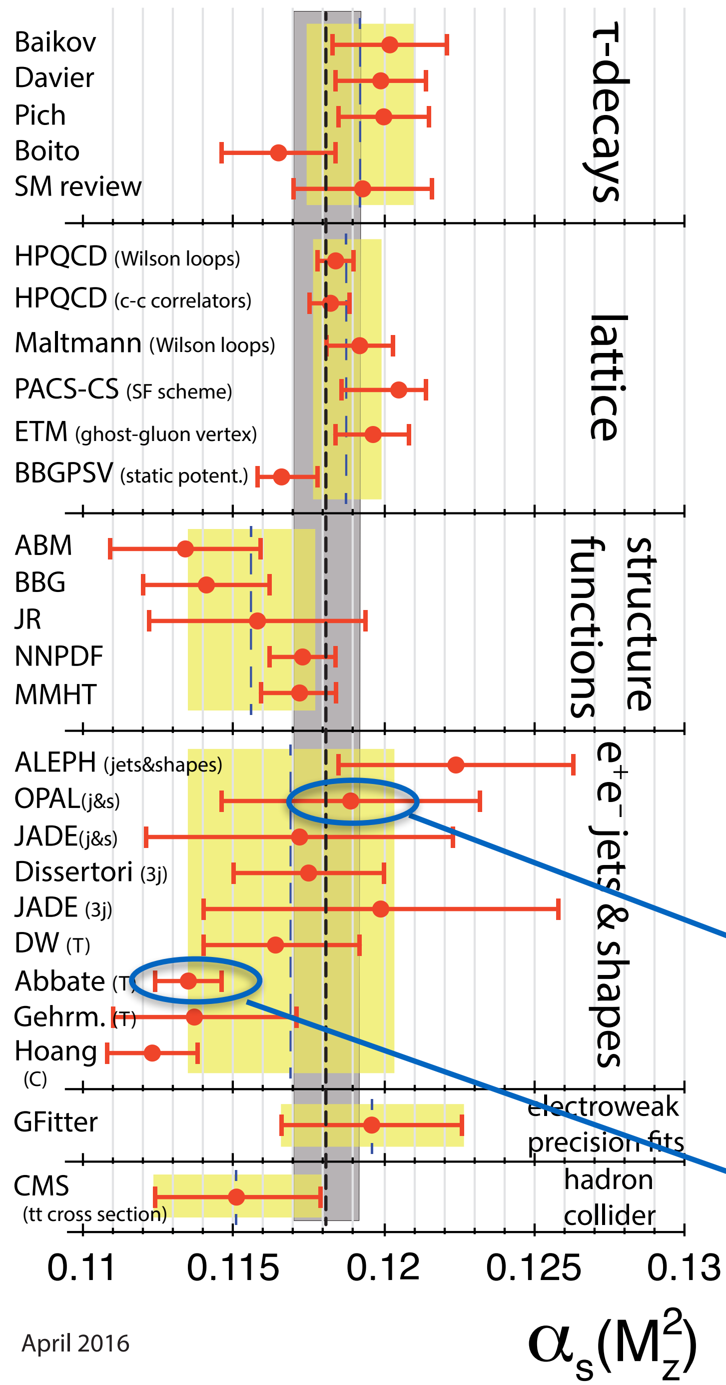
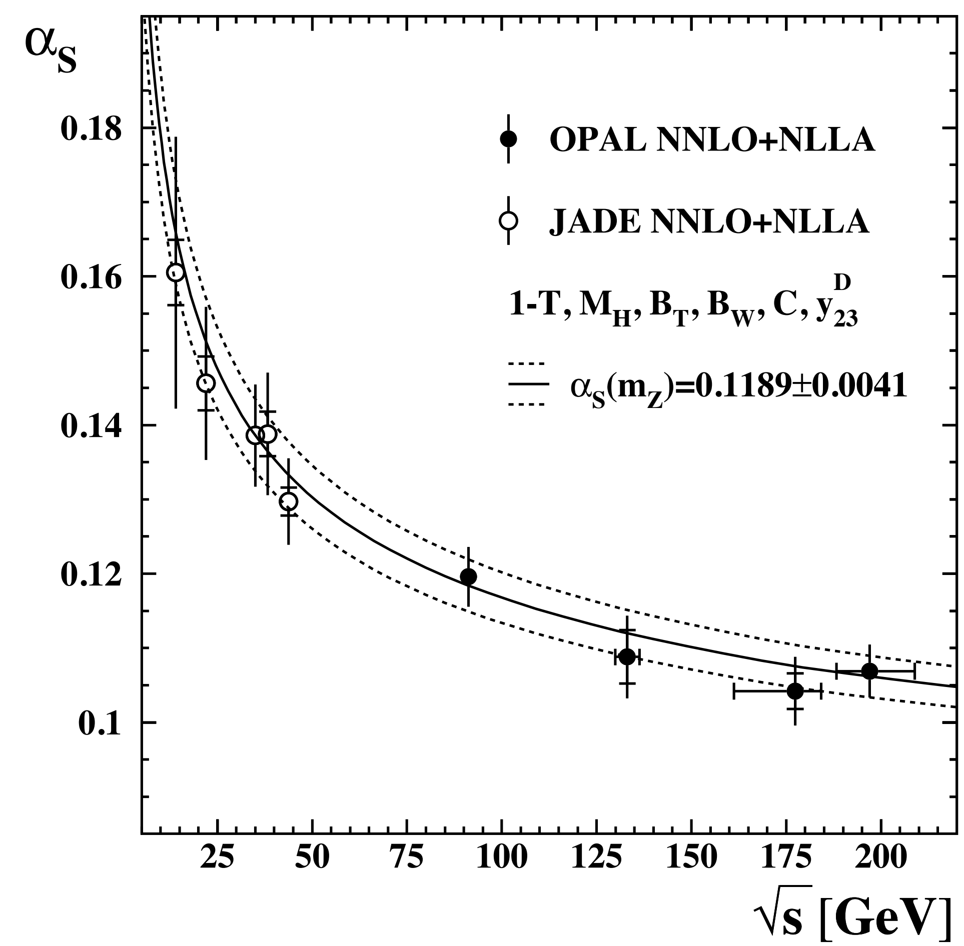




$$0.1189 \pm 8_{stat} \pm 16_{expt} \pm 10_{hadr} \pm 36_{theo}$$

OPAL, 1101.1470, hadr. event shapes (NNLO+NLLA)

$$0.1135 \pm 2_{expt} \pm 5_{hadr} \pm 9_{pert}$$

global analysis of thrust (NNLO+N3LL), 1006.3080

PDG 2016

CEPC vs. LEP

- CEPC with a much higher designed luminosity promises various QCD study at the highest precision, especially for high energies

sample in OPAL hadronic analysis, 1101.1407

Year	Range of $\sqrt{s}$ [GeV]	Mean $\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	Selected events
1996, 2000	91.0—91.5	91.3	14.7	395695
1995, 1997	129.9—130.2	130.1	5.31	318
1995, 1997	136.0—136.3	136.1	5.95	312
1996	161.2—161.6	161.3	10.06	281
1996	170.2—172.5	172.1	10.38	218
1997	180.8—184.2	182.7	57.72	1077
1998	188.3—189.1	188.6	185.2	3086
1999	191.4—192.1	191.6	29.53	514
1999	195.4—196.1	195.5	76.67	1137
1999, 2000	199.1—200.2	199.5	79.27	1090
1999, 2000	201.3—202.1	201.6	37.75	519
2000	202.5—205.5	204.9	82.01	1130
2000	205.5—208.9	206.6	138.8	1717

CEPC with a designed energy of 250 GeV and full luminosity of 5000 fb^{-1}

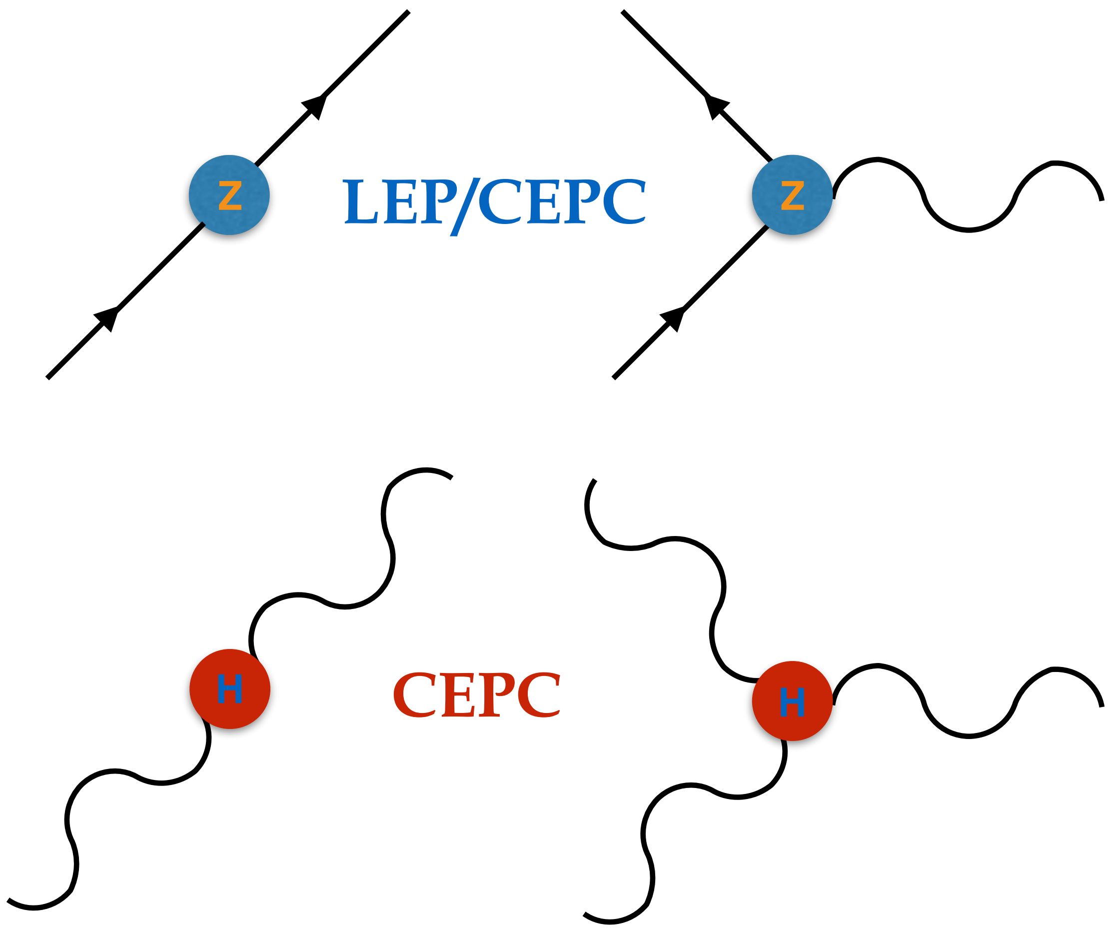
negligible statistical errors, reducing systematics; smaller power/hadronization corrections; allows precision study on high jet multiplicities

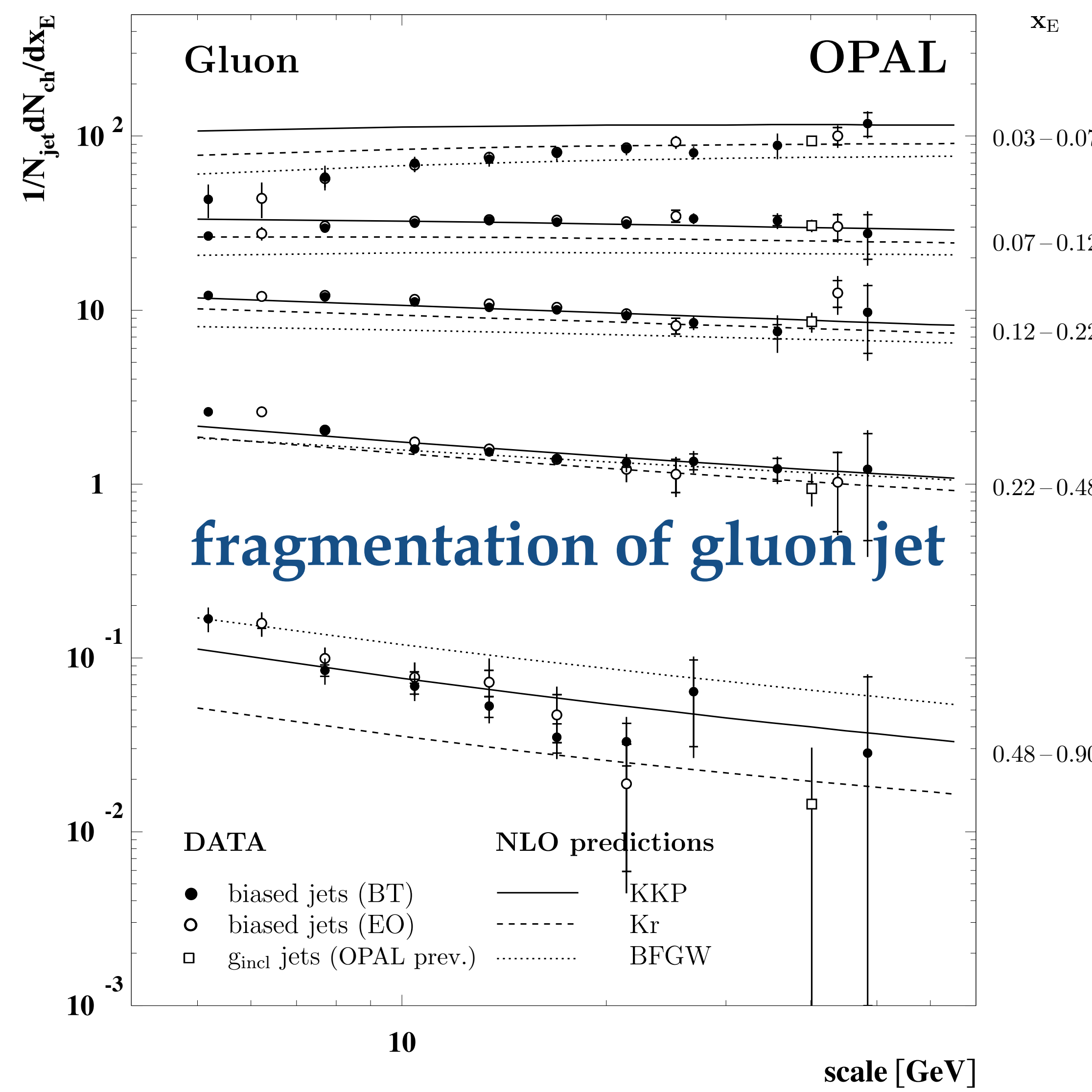
F_2^γ in γ-γ	$3.5\%_{\rm th} \oplus 3\%_{\rm exp} \approx 4.5\%$ (NLO only)	$1\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2\%$ ($\sim$2 yrs), $<1\%$ (FCC-ee) (NNLO. More precise new F_2^γ data)
e^+e^- evt shapes	$(1.5\text{–}4)\%_{\rm th} \oplus 1\%_{\rm exp} \approx (1.5\text{–}4)\%$ (NNLO+N$^{(3)}$LL, npQCD significant)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (+B-factories), $<1\%$ (FCC-ee) (NNLO+N^{3}LL. Improved npQCD via $\sqrt{s}$-dep. New data)
jets in e^+e^-	$(2\text{–}5)\%_{\rm th} \oplus 1\%_{\rm exp} \approx (2\text{–}5)\%$ (NNLO+NLL, npQCD moderate)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (few yrs), $<1\%$ (FCC-ee) (NNLO+NNLL. Improved npQCD. New high-$\sqrt{s}$ data)
W decays	$0.7\%_{\rm th} \oplus 37\%_{\rm exp} \approx 37\%$ (N^{3}LO, npQCD small. Low-stats data)	$(0.7\text{–}0.1)\%_{\rm th} \oplus (10\text{–}0.1)\%_{\rm exp} \approx (10\text{–}0.15)\%$ (LHC,FCC-ee) (N^{4}LO, $\sim$10 yrs. High-stats/precise W data)
Z decays	$0.7\%_{\rm th} \oplus 2.4\%_{\rm exp} \approx 2.5\%$ (N^{3}LO, npQCD small)	$0.1\%_{\rm th} \oplus (0.5\text{–}0.1)\%_{\rm exp} \approx (0.5\text{–}0.15)\%$ (ILC,FCC-ee) (N^{4}LO, $\sim$10 yrs. High-stats/precise Z data)

FCC-ee projection on as, 1512.05194

CEPC vs. LEP

- CEPC has the speciality of Higgs boson production with hadronic decays; producing the unique di-gluon final states and unbiased gluon jet





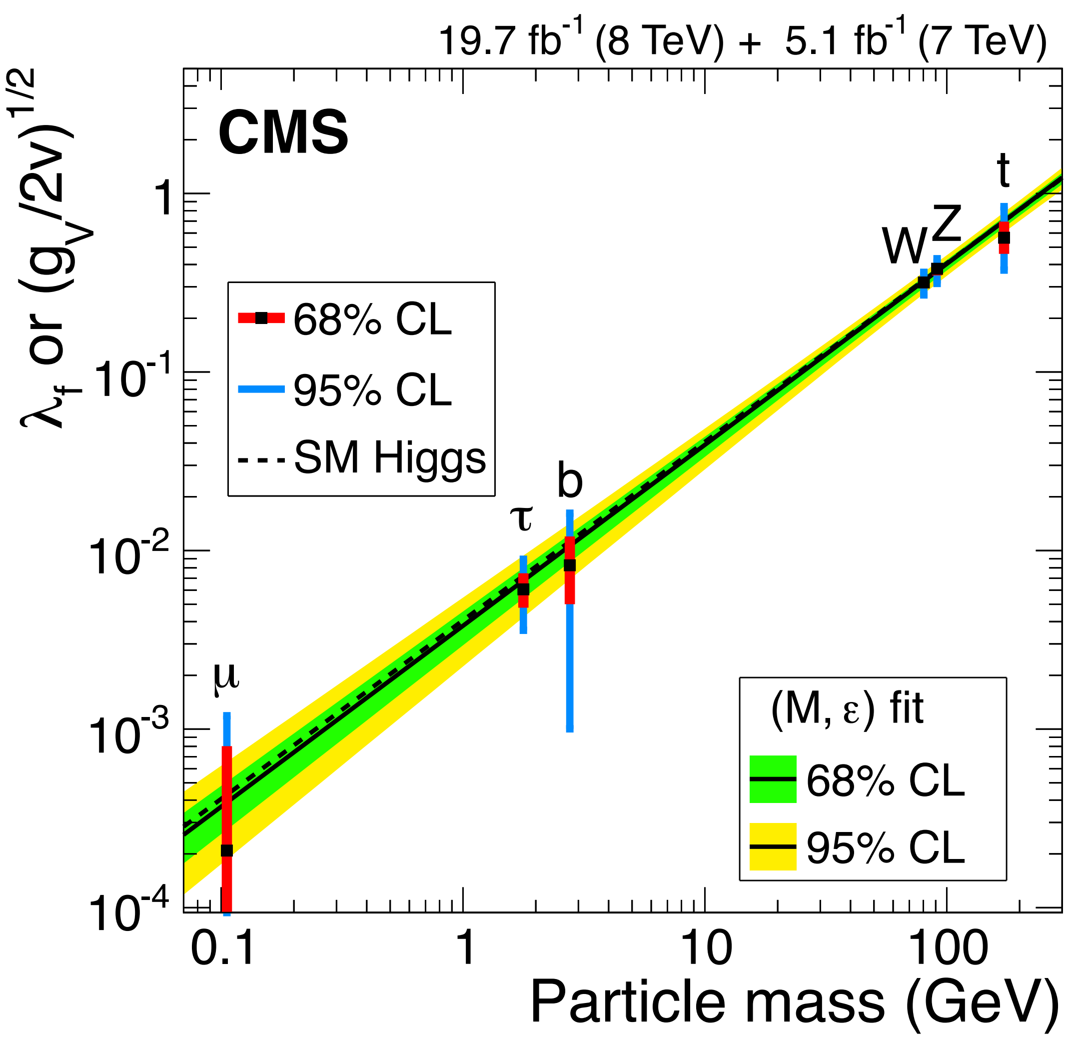
unique for study unbiased gluon jet at high energy

using Higgs boson to calibrate gluon jet and study event shapes

QCD and Higgs couplings

- Measurement on light-quark (u/d/s) Yukawa couplings are important but experimentally challenging

SM Higgs boson, y_s/y_b~0.1/5; u or d quarks negligible



F. Bishara et al., 1504.04022

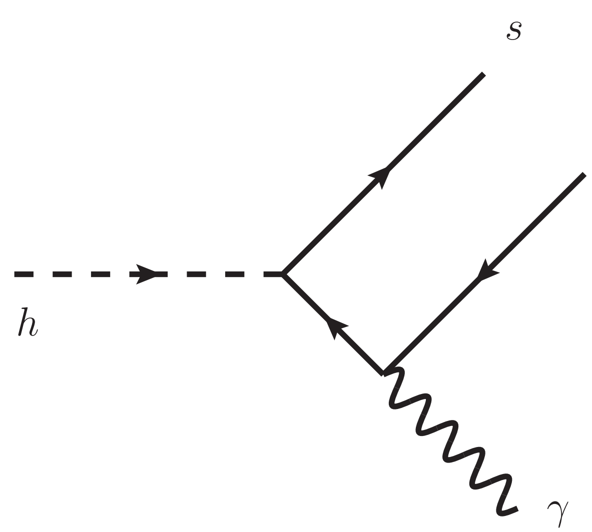
Model	κ_b	$\kappa_{s(d)}/\kappa_b$
SM	1	1
NFC	$V_{hd}\, v_W/v_d$	1
MSSM	$-\sin\alpha/\cos\beta$	1
GL	$\simeq 3$	$\simeq 5/3(7/3)$
GL2	$-\sin\alpha/\cos\beta$	$\simeq 3(5)$

interesting to test NP scenario where light-quark Yukawa couplings are enhanced

QCD and Higgs couplings

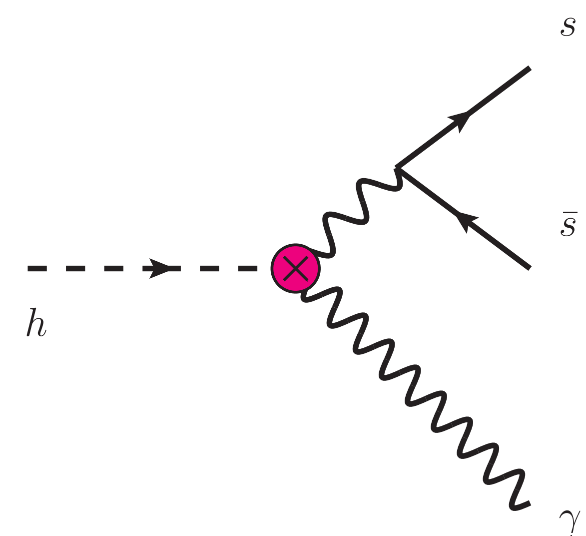
- Rare decays of the Higgs boson (BR~10^{-6}) measured at the LHC could be sensitive to the strange-quark Yukawa coupling

direct contribution



$$h \to \phi\gamma$$

indirect contribution



conventionally y_q are shown in unit of SM y_b

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\, dt$ [fb^{-1}]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
14	3000	770	0.39 (−0.97)	0.27 (−0.81)
33	3000	1380	0.36 (−0.94)	0.22 (−0.75)
100	3000	5920	0.34 (−0.90)	0.13 (−0.63)

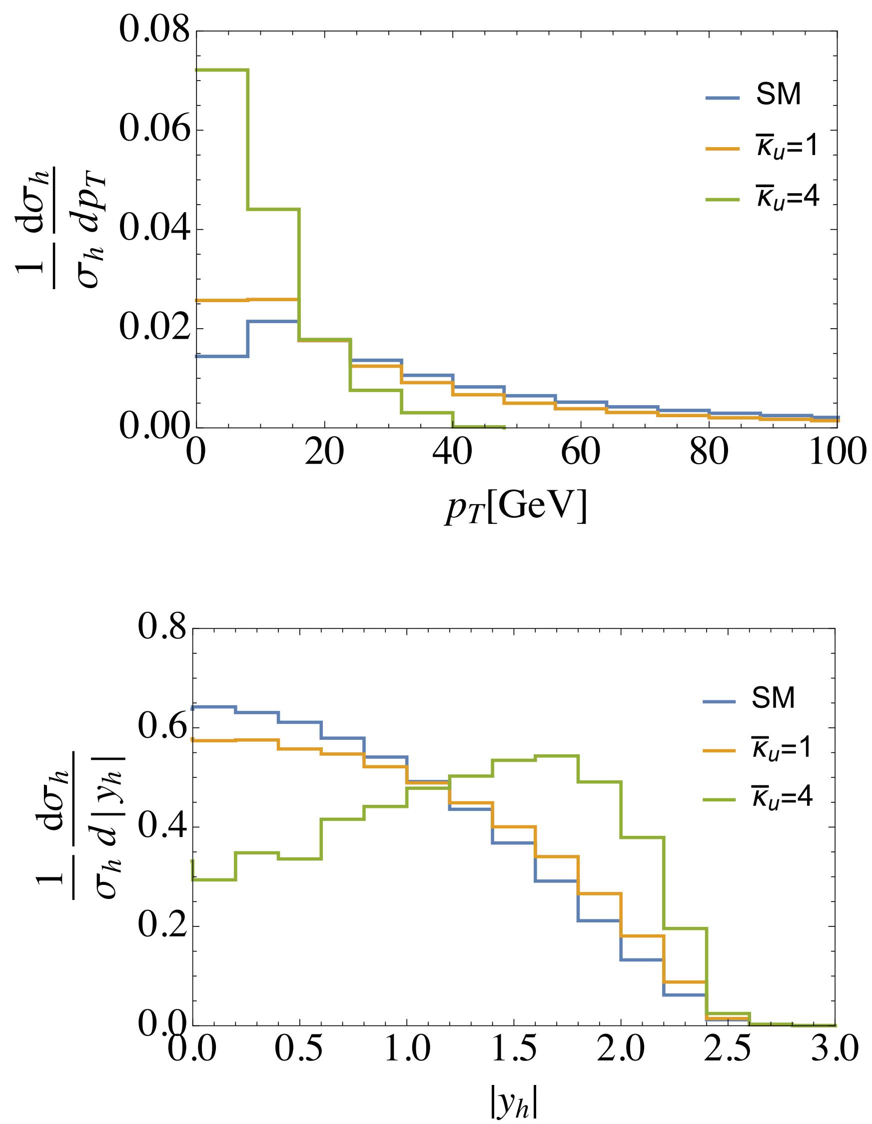
A. L. Kagan et al., 1406.1722

large theoretical systematics, e.g., from non-perturbative inputs; exp. unc. and BKs are large, 1505.06689 gives a number of ~20 instead

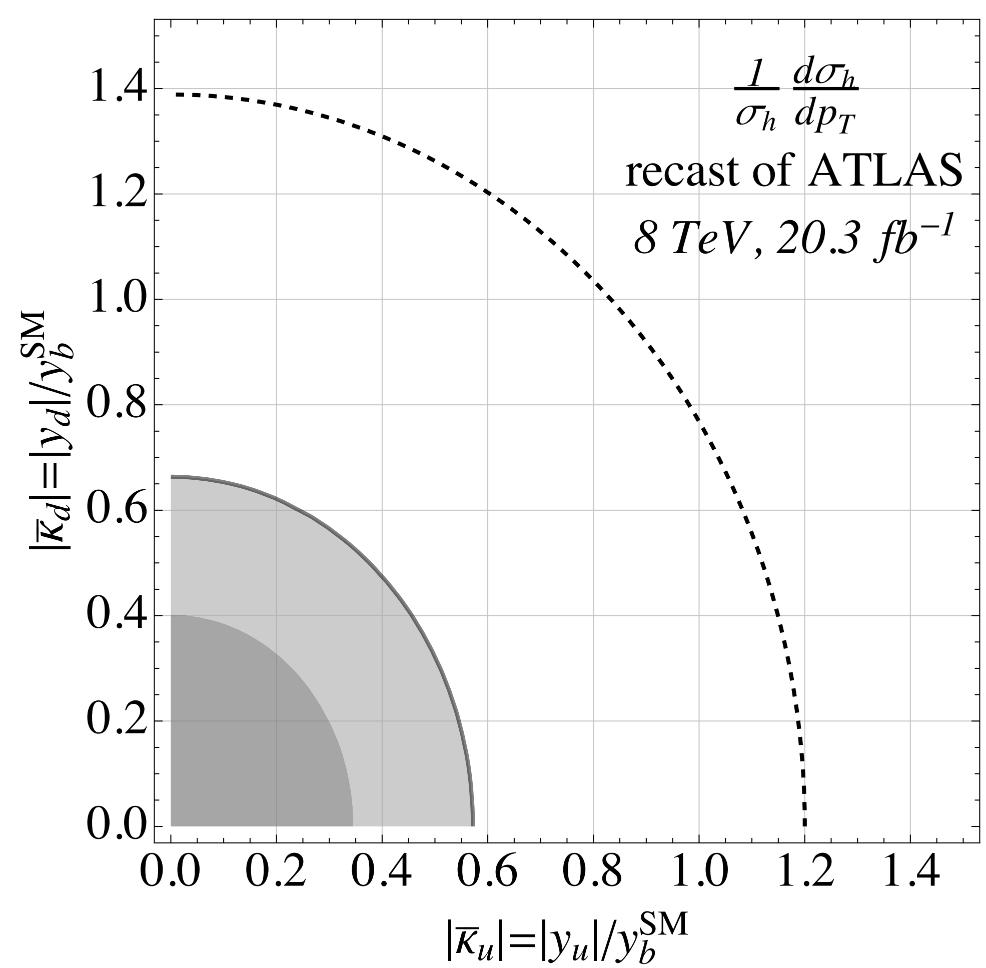
QCD and Higgs couplings

- Kinematic distributions of the Higgs boson measured at the LHC could be sensitive to the u/d quark Yukawa couplings

H. X. Zhu et al., 1606.09621



measured indirectly, induced by different production mechanisms

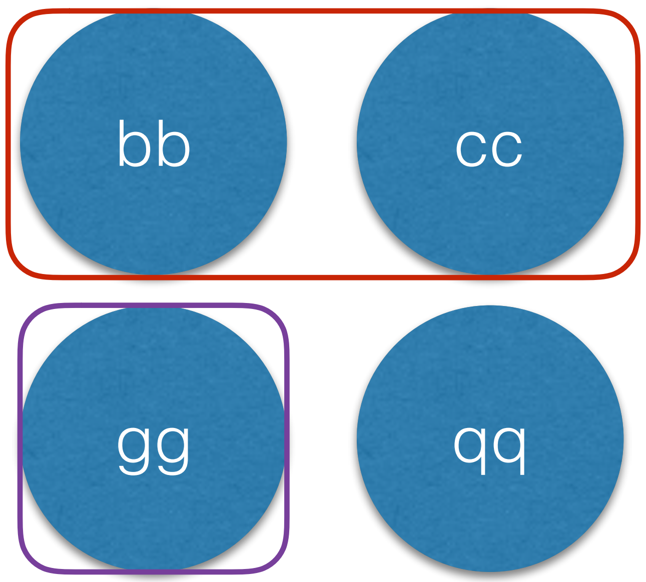


gluon luminosity is much higher than qqbar at the LHC, sensitivity will be largely limited by, e.g., theoretical uncertainties in gluon fusion

QCD and Higgs couplings

- CEPC is designed to measure the Higgs boson couplings with high precision which also applies to the light-quark Yukawa couplings

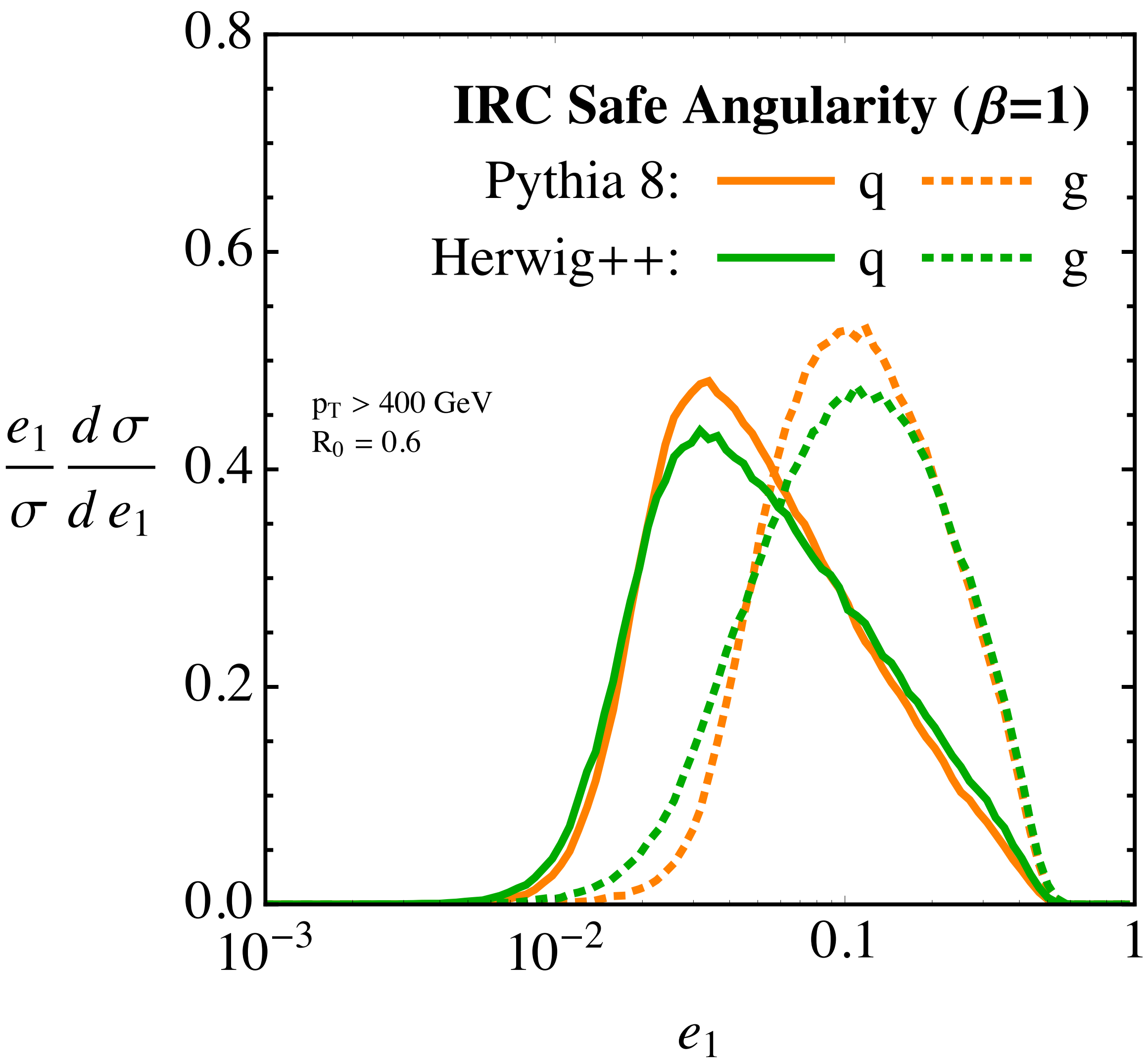
heavy-flavor tagging



gluon/quark disc.

using quark/gluon jet discriminator based on substructures, e.g., generalized angularities, net energy profile

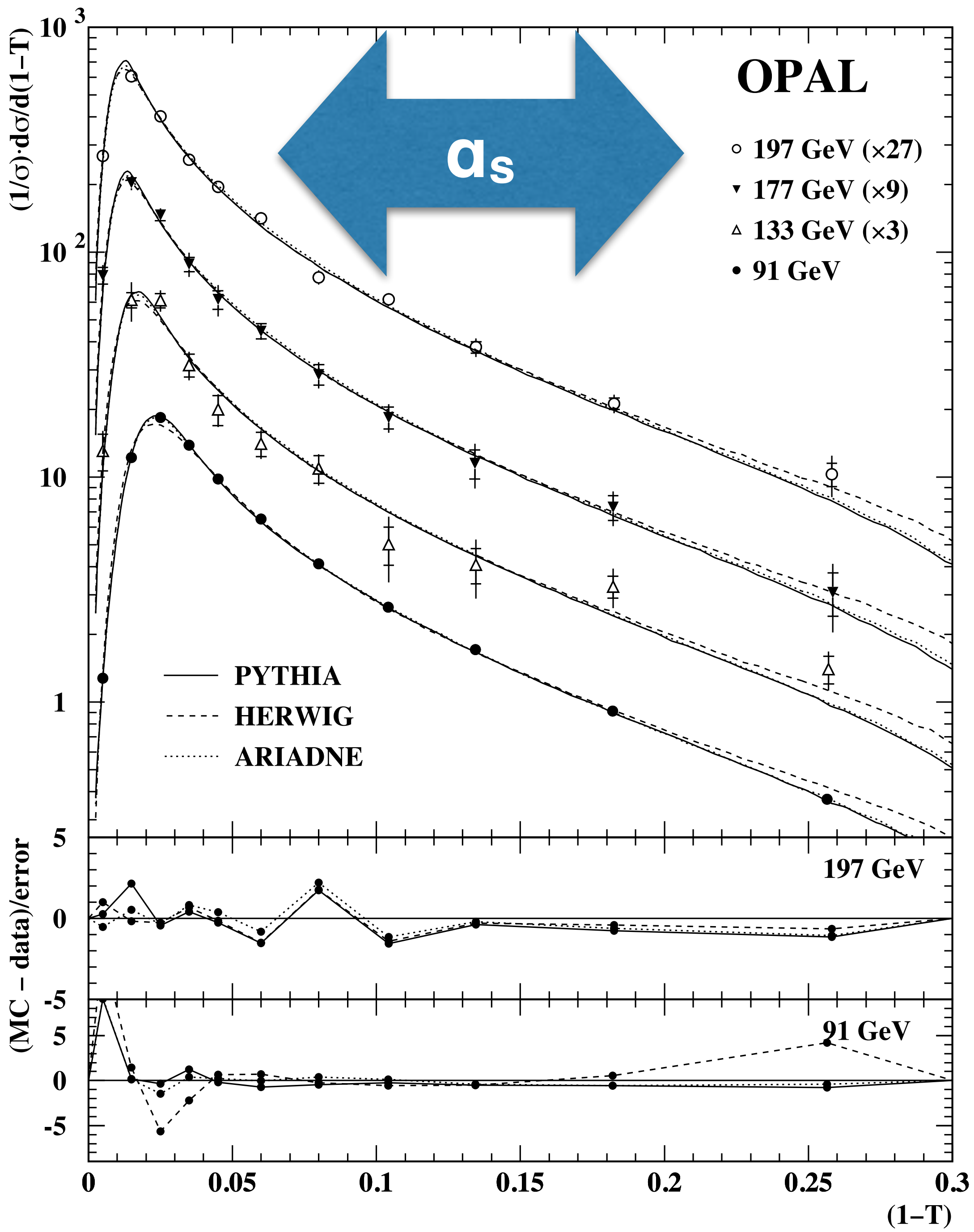
$$e_\beta \equiv \lambda^1_\beta = \sum_{i \in \mathrm{jet}} z_i \theta_i^\beta$$



A. Larkoski et al., 1408.3122; Zhao Li et al., 1107.4535

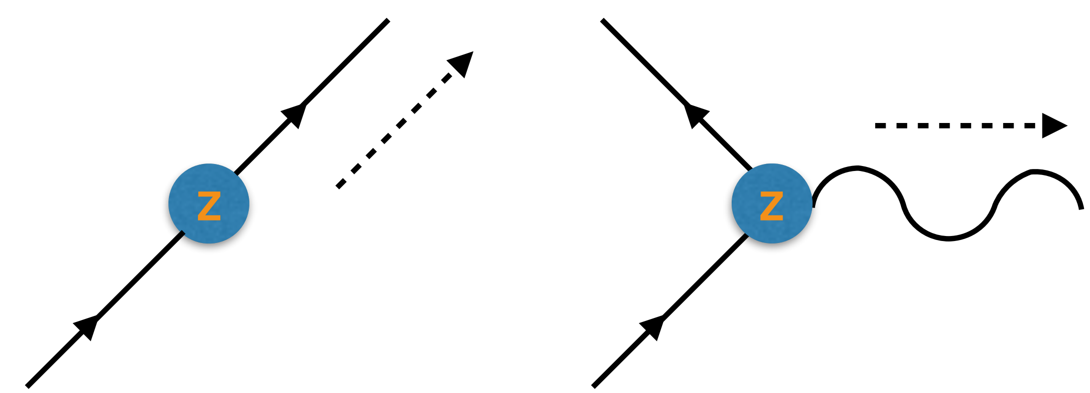
QCD and Higgs couplings

- A better way from theoretical point of view, utilizing global hadronic event shape observables, e.g., thrust distribution



OPAL, hep-ph/0503051

$$T = \max_{\vec{n}} \left(\frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right)$$

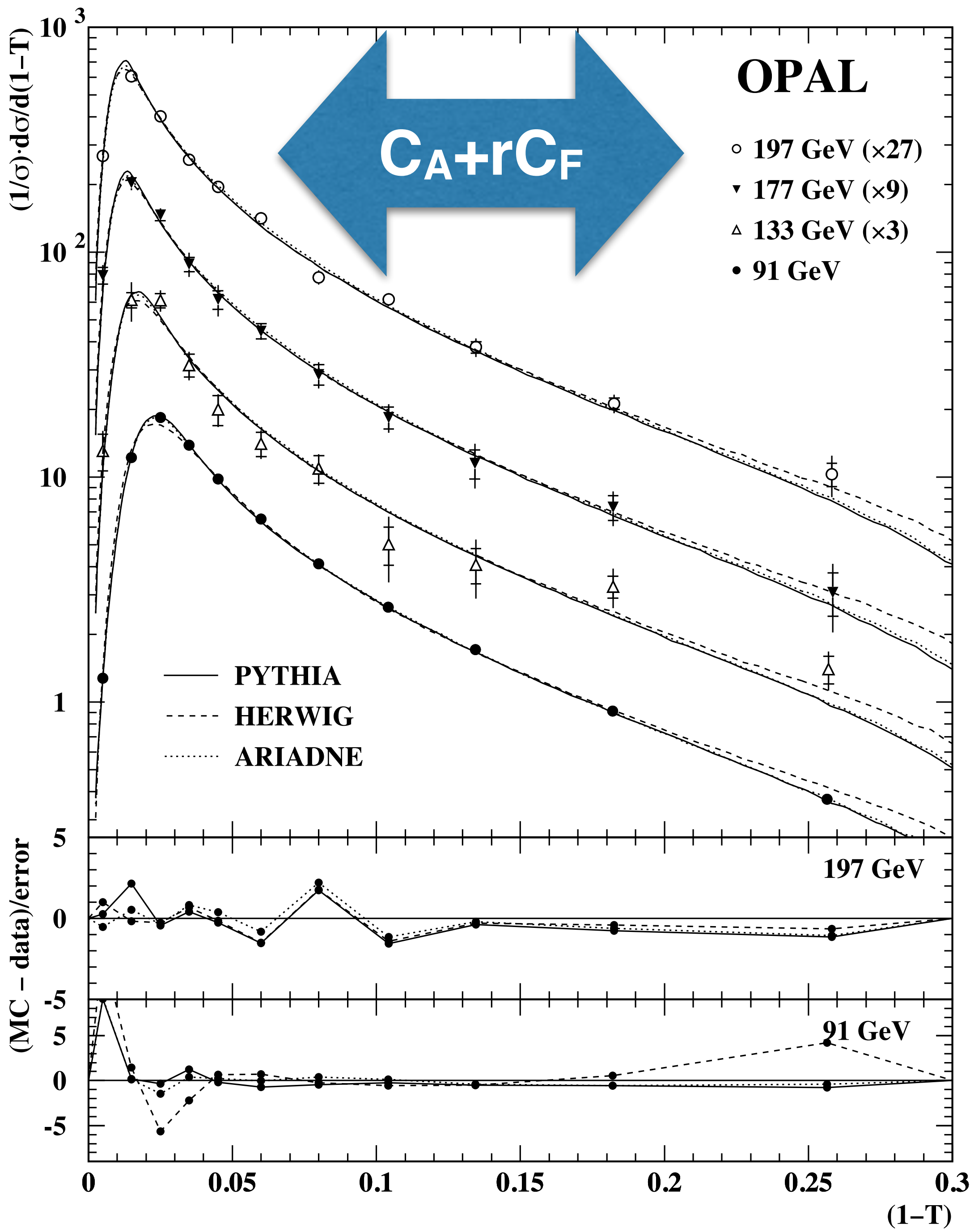


0.5<T<1, described by resummed prediction matched with fixed-order, plus additional non-perturbative corrections

sensitive to α_s

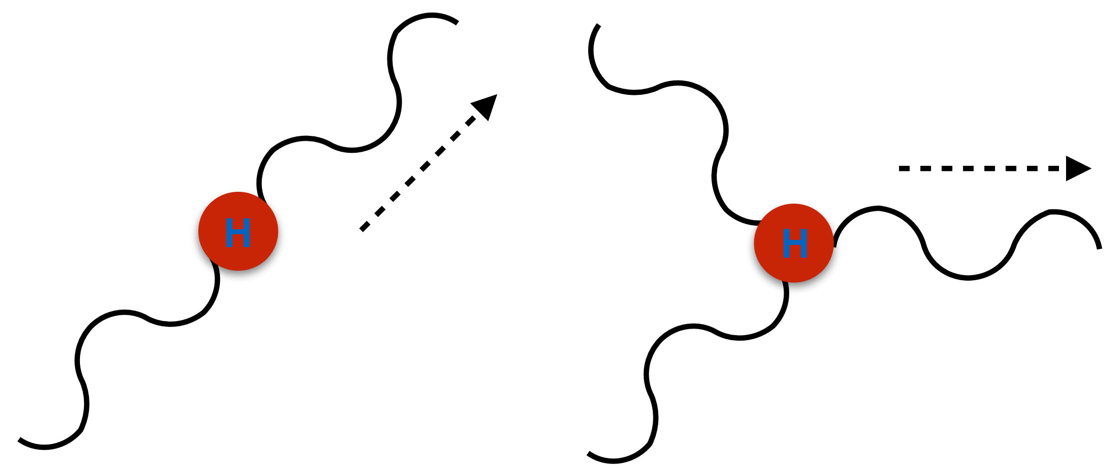
QCD and Higgs couplings

- A better way from theoretical point of view, utilizing global hadronic event shape observables, e.g., thrust distribution



OPAL, hep-ph/0503051

$$T = \max_{\vec{n}} \left(\frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right)$$



0.5<T<1, described by resummed prediction matched with fixed-order, plus additional non-perturbative corrections

sensitive to the average color charge

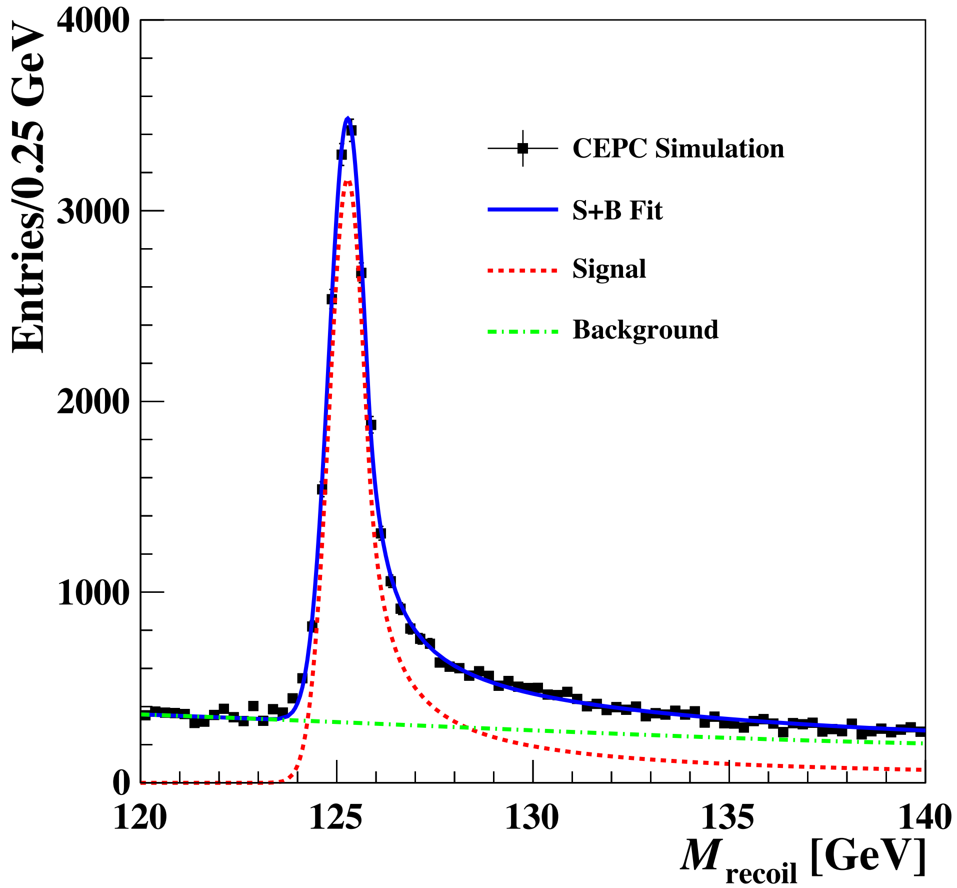
QCD and Higgs couplings

- Events of Higgs boson hadronic decay can be selected based on the recoil mass and be fully reconstructed

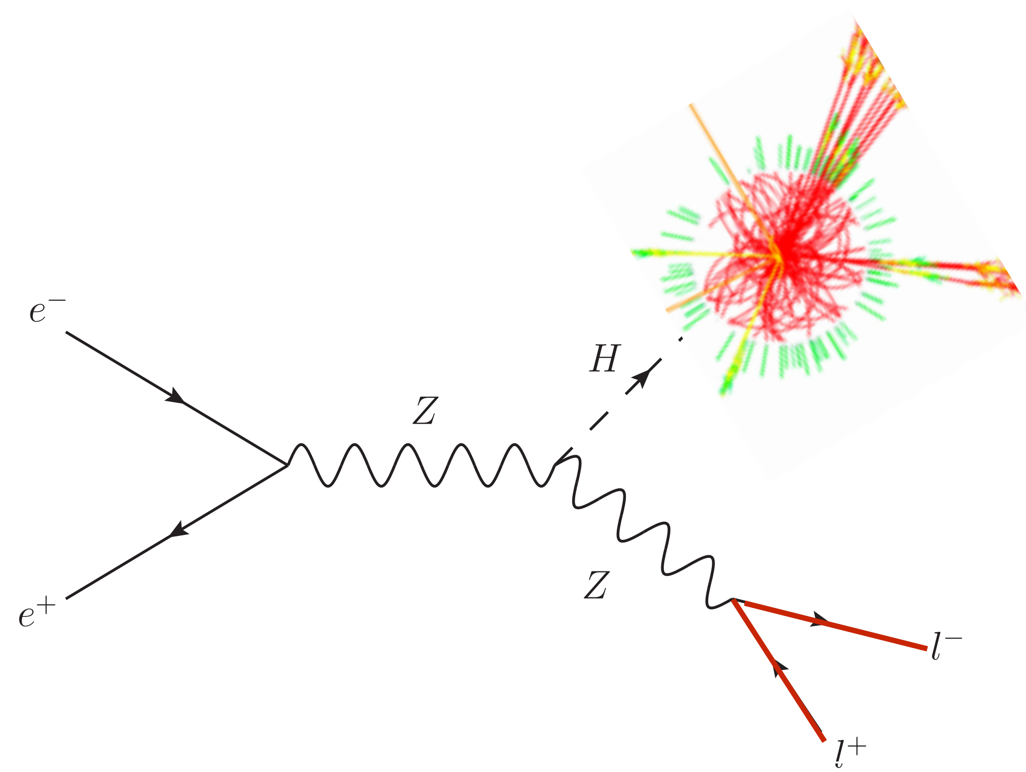
total event number assuming 250 GeV, 5 ab^{-1} and Z to electron and muon

$Z(l^+l^-)H(X)$	gg	$b\bar{b}$	$c\bar{c}$	$WW^*(4h)$	$ZZ^*(4h)$	$q\bar{q}$
BR [%]	8.6	57.7	2.9	9.5	1.3	~ 0.02
N_{event}	6140	41170	2070	6780	930	14

$$m^2_{\text{recoil}} = s - 2E_{f\bar{f}}\sqrt{s} + m^2_{f\bar{f}}$$



Man-Qi Ruan et al., 1601.05302

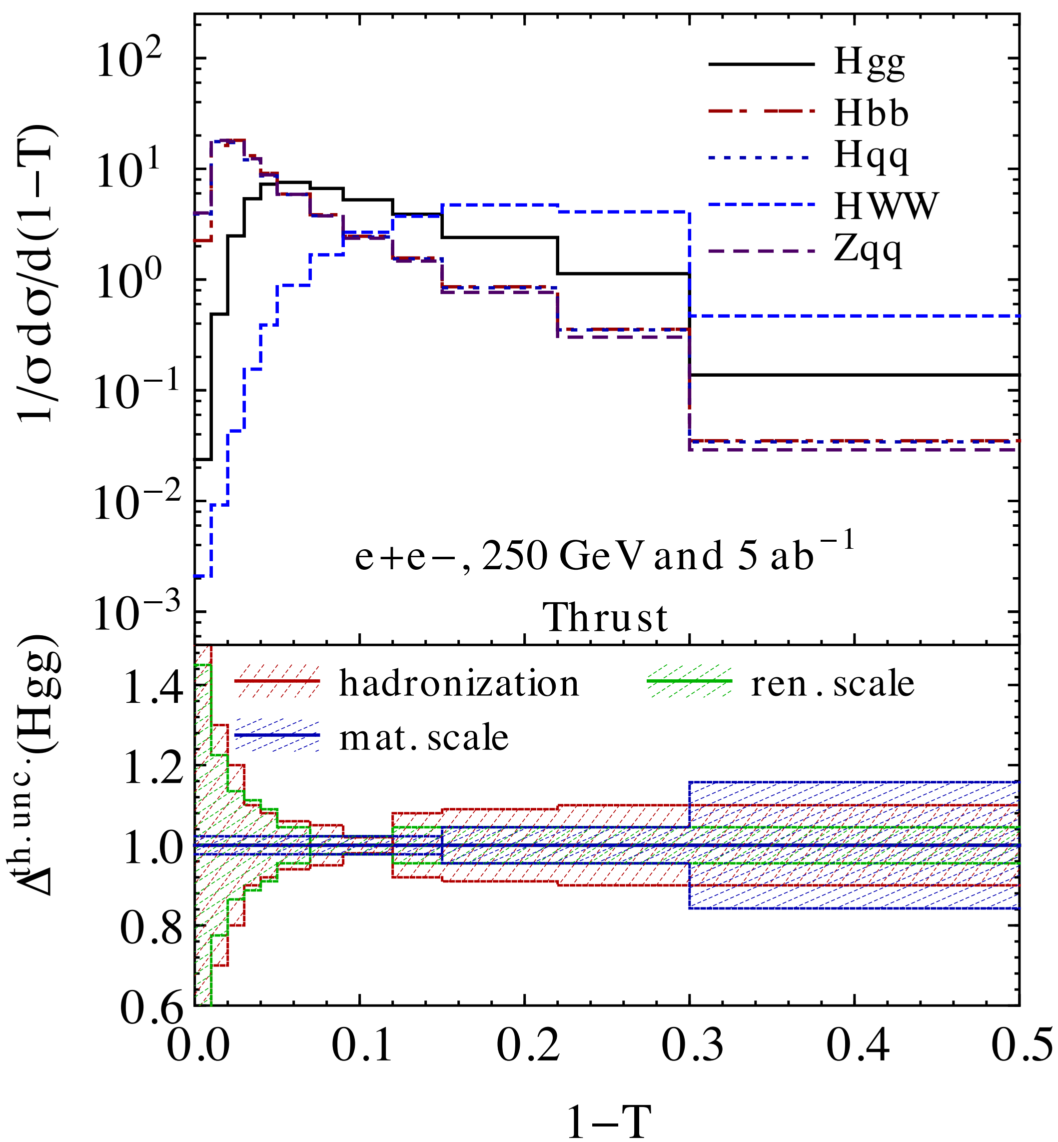


full kinematic informations allowing measurement of T in Higgs boson rest frame

Thrust distribution

- Di-gluon and di-quark initiated distributions show approximately a Casimir scaling on the peak position, $C_A/C_F=9/4$

normalized shapes of the thrust distribution from SHERPA



Jun Gao, 1608.01746

- N3LL +NNLO prediction available for SM Z->qq, T. Becher et al.; T. Gehrmann et al.
- N3LL+NNLO prediction in progress for H->gg, bb, qq
- effects of heavy-quark mass are small
- theoretical uncertainties include variation on ren. and mat. scales, and on hadronization effects

Sensitivity on light-quark Yukawa

- A projection on sensitivity on light-quark-Yukawa couplings is obtained using pseudo-data

$$\frac{dN}{dO} = N_S(r f_{q\bar{q}}(O) + (1-r) f_{gg}(O)) + N_{B,1} f'_{q\bar{q}}(O) + N_{B,2} f_{WW}(O)$$

Jun Gao, 1608.01746

- r, defined as BR(qq)/BR(jj), j=g,q
- N_S, total signal events of ZH(jj), assuming an efficiency of 50%
- N_{B1}, BKs from ZZ(qq) and ZH(bb,cc), ~30% of N_S(SM) using recoil mass selection and heavy flavor tagging
- N_{B2}, BKs from ZH(WW*,ZZ*), ~60% of N_S(SM), (effects are small since far away from signal region)
- f(qq),f'(qq),f(WW),f(gg), normalized shapes, can be obtained from theoretical calculation(simulation) or via data in a controlled region

Sensitivity on light-quark Yukawa

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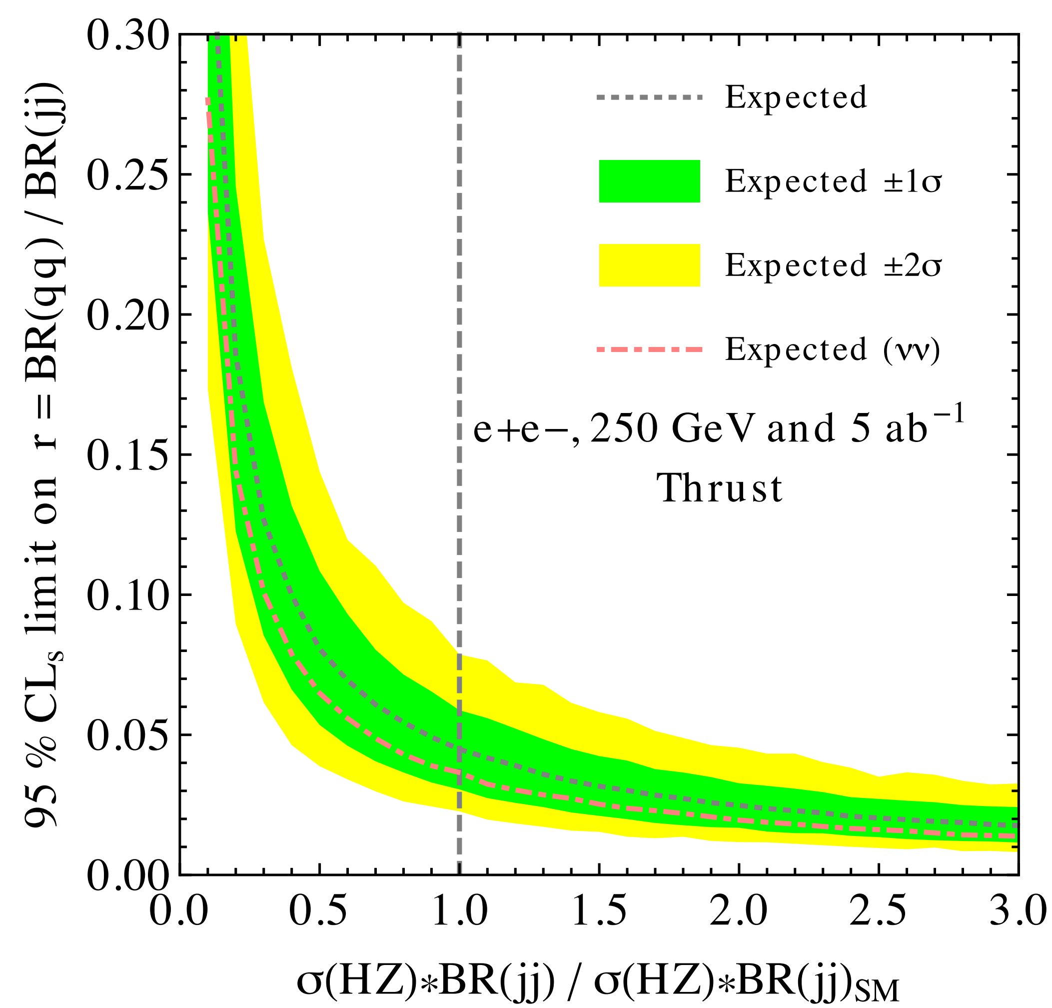
$$\frac{dN}{dO} = N_S(r f_{q\bar{q}}(O) + (1-r) f_{gg}(O)) + N_{B,1} f'_{q\bar{q}}(O) + N_{B,2} f_{WW}(O)$$

Jun Gao, 1608.01746

- N_S can be measured independently to ~3% via hadronic Z decays (CEPC TDR)
- Systematics on N_{B1}, N_{B2} estimated to be 4%
- Also including three systematics on theoretical predictions of f(gg)
- Expected exclusion limit on r are obtainted via psedu-data and by using profiled log-likelihood ratio with the CL_S method

expected exclusion limit



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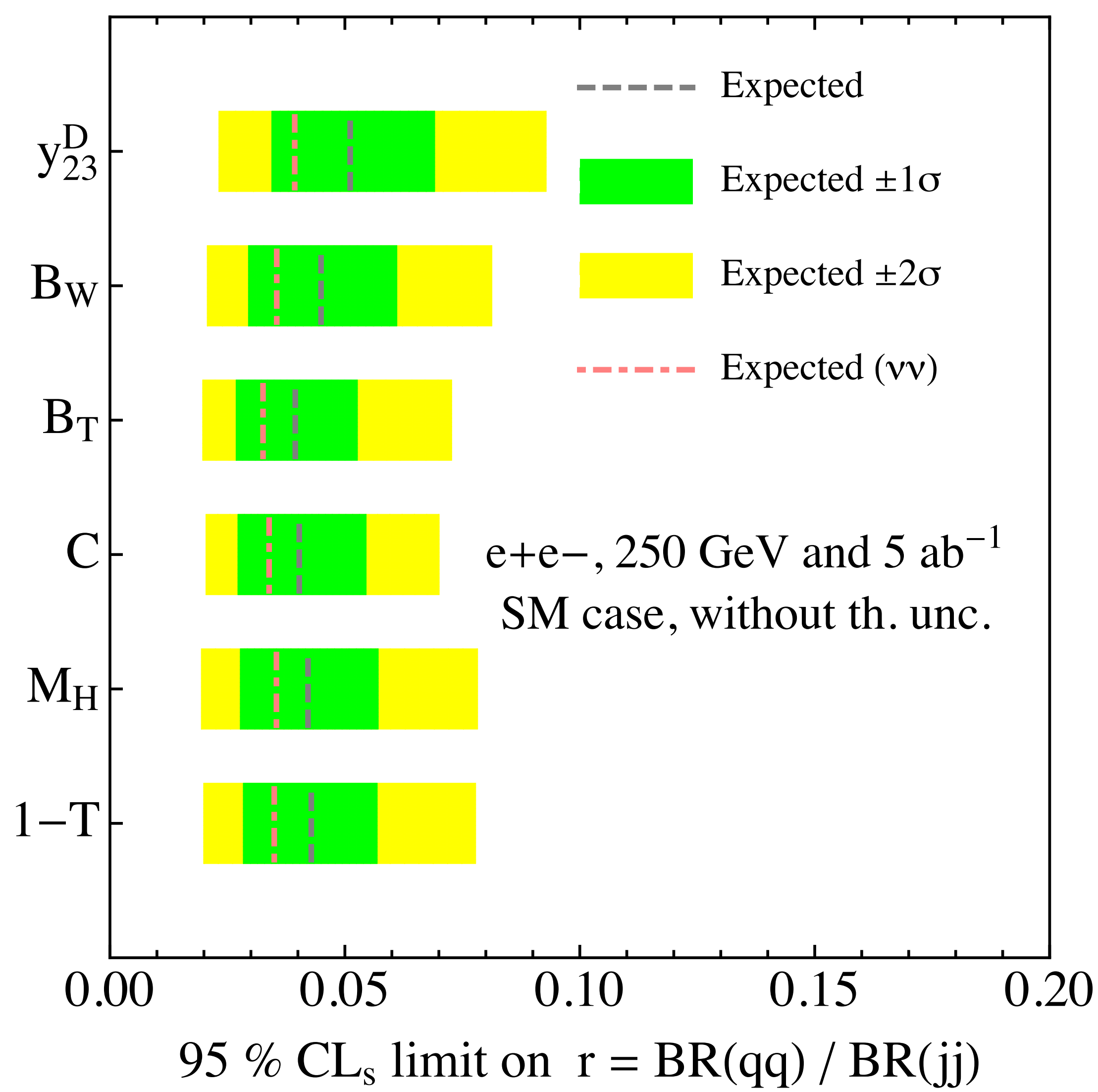

Jun Gao, 1608.01746

an exclusion limit on r of 0.05, corresponds to a decay BR(qq) of 0.4% to any of u/d/s, a Yukawa coupling of 8% of SM y_b, or 5 times of SM y_s

comparison with LHC

best projected LHC limit from exotic decay on s quark is ~30% (optimistic) of SM y_b, from kinematic distribution on u/d is ~50%

Summary

- CEPC offers a great opportunity on precision study of QCD

- The higher energy and luminosity allow further refined study on QCD topics studied at LEP

- The unique Higgs boson production allows detailed study on QCD gluon jet, fragmentation and event shapes

- On the other way around, QCD study can be important for measurements on Higgs couplings, especially providing best sensitivity on light-quark Yukawa couplings