
FCC

Phenomenology Breakout Session

- Joint FCC-hh/ee/he session
- Important to work in close coordination

Contribution details

14:00 Perspectives at the Energy Frontier

Presenter(s): Chris QUIGG *(Fermi National Accelerator Lab. (US))*
Room: Basement - MS 050
Location: University of Geneva - UNI MAIL

14:30 Status and plans for the Heavy Ion physics studies

Presenter(s): Andrea DAINESE *(INFN - Padova (IT))*
Room: Basement - MS 050
Location: University of Geneva - UNI MAIL

15:00 QCD at the FCC: opportunities and challenges

Presenter(s): Giulia ZANDERIGHI
Room: Basement - MS 050
Location: University of Geneva - UNI MAIL

16:00 Status and plans for the physics studies of TLEP

Presenter(s): Jonathan R. ELLIS *(CERN)*
Room: Basement - MS 050
Location: University of Geneva - UNI MAIL

16:30 Summary of the BSM@100 TeV wshop, status and plans for the physics studies of FHC

Presenter(s): Michelangelo MANGANO *(CERN)*
Room: Basement - MS 050
Location: University of Geneva - UNI MAIL

17:00 Status and prospects of precise Higgs and BSM calculations for the FCC

Presenter(s): Michael SPIRA *(Paul Scherrer Institut (CH))*
Room: Basement - MS 050
Location: University of Geneva - UNI MAIL

17:30 Prospects for Higgs and BSM studies in ep collisions at the FCC

Presenter(s): Uta KLEIN *(University of Liverpool (GB))*
Room: Basement - MS 050
Location: University of Geneva - UNI MAIL

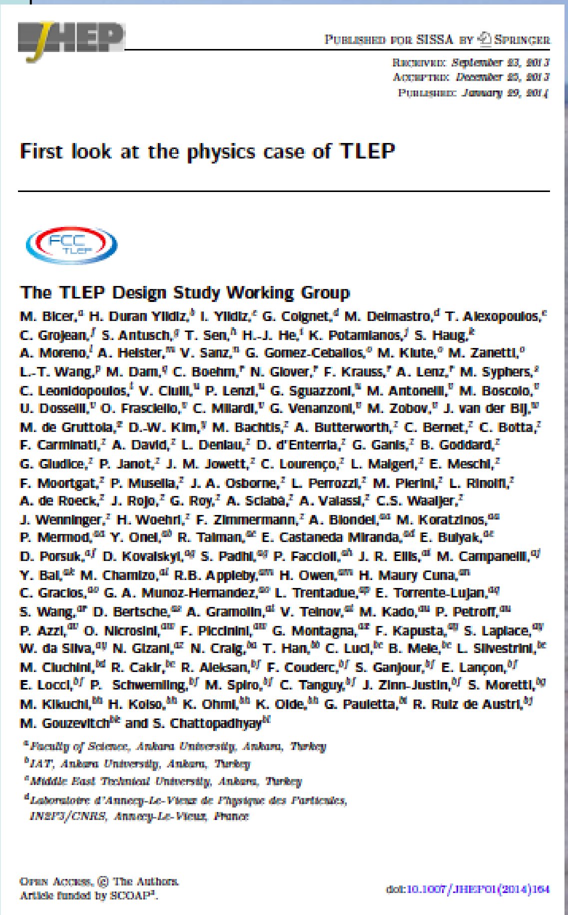
~~TLEP~~ FCC-ee Activities

- There have been a series of TLEP workshops, e.g., #6:

TLEP6

- https://indico.cern.ch/event/257713/
- A ‘First Look at TLEP Physics’ has been published:
- http://arxiv.org/abs/arXiv:1308.6176

  DOI: 10.1007/JHEP01(2014)164
- There are continuing TLEP Physics Vidyo meetings:
- https://indico.cern.ch/event/296628/
- Now integrated within the FCC structure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First look at the physics case of TLEP

The TLEP Design Study Working Group

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http://tlep.web.cern.ch/

The Twin Pillars of **FCC-ee** Physics

Precision Measurements

- Springboard for sensitivity to new physics
- **Theoretical issues:**
  - **Higher-order QCD**
  - **Higher-order EW**
  - **Mixed QCD + EW**
- Experimental issues
  - Patrick Janot

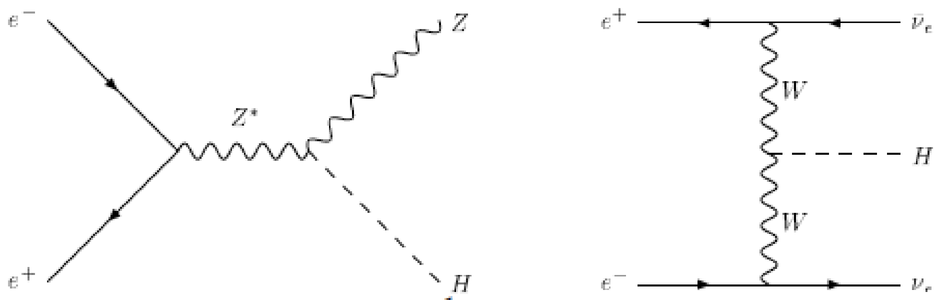
Rare Decays

- Direct searches for new physics
- Many opportunities
- **Z: 10^{12}**
- b, c, τ: 10^{11}
- W: 10^{8}
- **H: 10^{6}**
- t: 10^{6}

Higgs Production @ TLEP

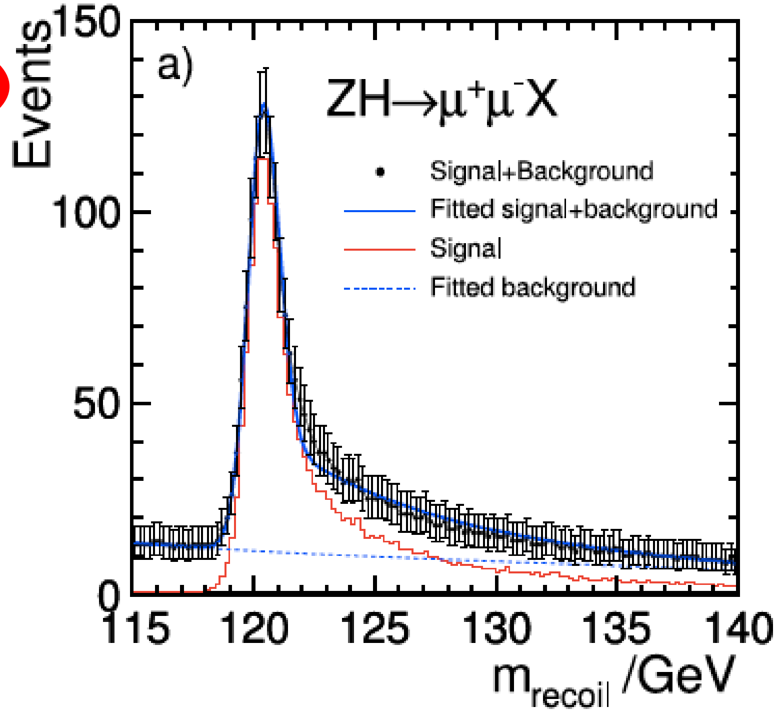
Spira

- Higgs boson production analogous to LEP2



- discovery up to $M_H \lesssim 0.7\sqrt{s}$
- elw. corrections $\mathcal{O}(10\%)$ Fleischer, Jegerlehner Kniehl Denner, . . .
- Higgs-strahlung $e^+e^- \to ZH$:
  Z monoenergetic
  $\Rightarrow M_H^2 = s - 2\sqrt{s}E_Z + M_Z^2$
  $\Rightarrow$ reconstruction from recoil mass

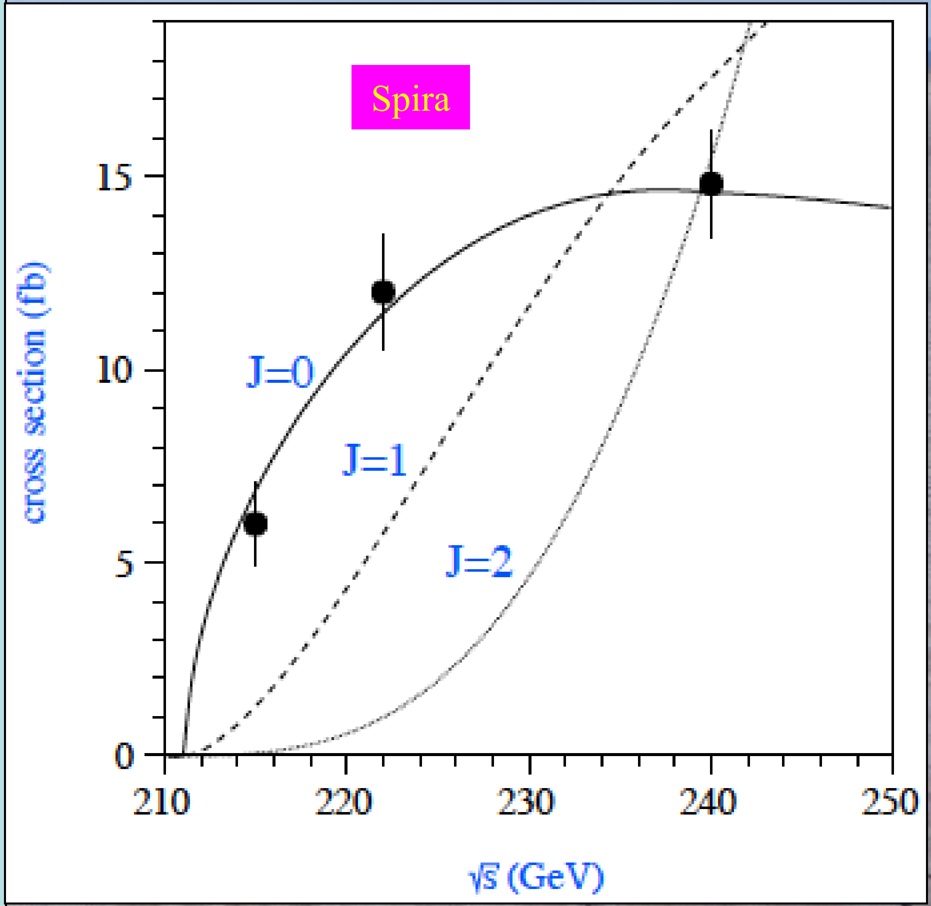
ILC TDR



$\Rightarrow$ mass, g_Z, g_W

Higgs Production @ TLEP

- Threshold sensitive to Higgs spin **KNOWN**
- Also sensitive to parity: 0^+ vs 0^-
- In presence of CP violation, could be a mixture
- **What sensitivity to 0^- admixture?**



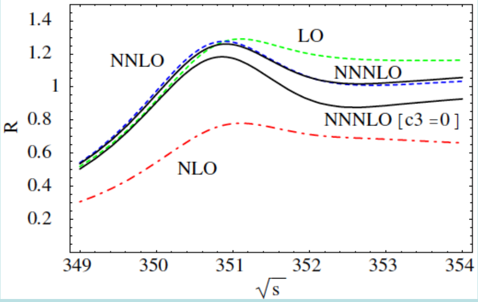
(Mainly) QCD Uncertainties

- Higgs Γ_b:
  - Higgs WG: $\Delta\Gamma_b = 7.5\%$
  - Should be 1.7%? 0.3% possible?
  - Higher-order QCD 0.25%
  - m_b uncertainty overstated by factor 4?
  - Error could be reduced by running SuperKEK-B above Υ
  - 5-loop running underway, need inputs from LE: m_b, m_c, α_{EM}, α_s

Higgs X-Section WG: Spira

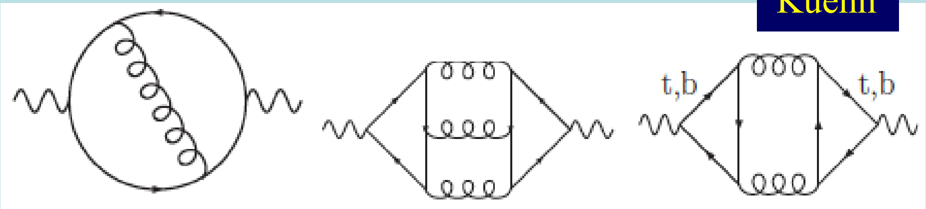
Kuehn

- M_W:
  - 4-loop uncertainty of 2.1 MeV insufficient: use $\overline{MS}$ m_t
  - Could do 4-loop mixed EW/QCD
- m_t:
  - calculation of σ at NNNLO underway

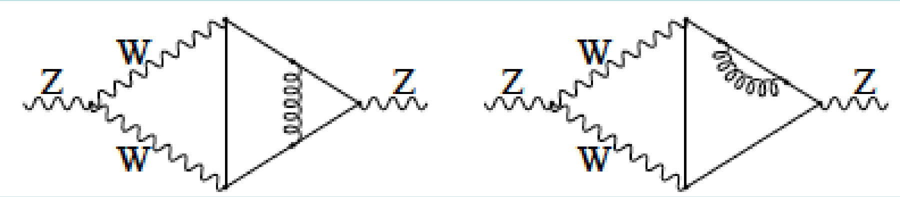


(Mainly) QCD Uncertainties

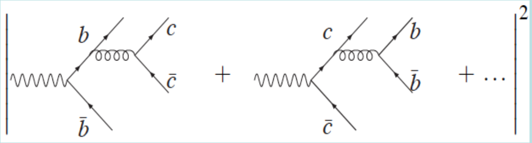
Kuehn



- Γ_Z:
  - Δ(non-singlet) = 101 KeV
  - Δ(singlet) V (3g) = 2.7 KeV, A (2g) = 42 KeV
  - Difficult to do next order



- Z Γ_b:
  - Correction @ $G_F m_t^2 \alpha_s^2$ = 0.1 MeV
  - Smaller corrections if use MSbar m_t, but need to know 4-loop conversion (underway)
  - Not well-defined at higher order: $b\bar{b}c\bar{c}$ final states!



- Γ_W:
  - Mixed EW/QCD calculated @ 2-loop: – 0.55 MeV
  - 3-loop $\alpha_W \alpha_s^2$ difficult but feasible

α_s status and prospectives

Zanderighi

Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2 dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, ~ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, ~ 10 yrs)
ep colliders	~ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ (~ 5 yrs [38])

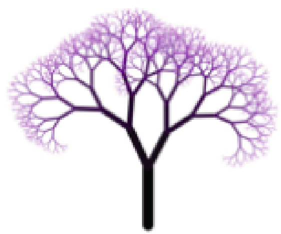
from Snowmass FCC-QCD report '13

QCD at FCC-ee

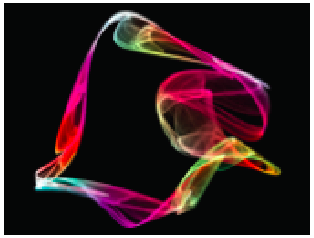
Skands

More than measuring α_s

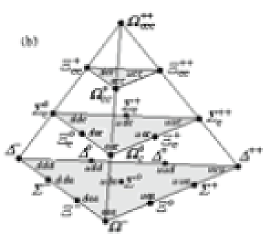
Emergent phenomena



Jets (the QCD fractal) ⟷ amplitude structures (in phase space) ⟷ fundamental quantum field theory. Precision jet (structure) studies.



Strings (strong gluon fields) ⟷ quantum-classical correspondence. String physics. Dynamics of hadronization phase transition.



Hadrons (incl excited states) ⟷ Spectroscopy, lattice QCD, (rare) decays, mixing, exotic states (e.g Ω_{ccc}, hadron molecules, …), light nuclei

Rare Leptonic Z Decays?

Silvestrini

- Upper limits from flavour-changing neutral currents (FCNC)

- Current and future bounds on LFV μ and τ decays:
  - $BR(\mu \to eee) < 10^{-12}$
  - $BR(\tau \to \mu\mu\mu) < 2\ 10^{-8}\ (10^{-9})$
  - $BR(\tau \to eee) < 3\ 10^{-8}\ (10^{-9})$
- These bounds imply:
  - $BR(Z \to \mu e) < 3\ 10^{-13}$
  - $BR(Z \to \tau\mu) < 4\ 10^{-8}\ (2\ 10^{-9})$
  - $BR(Z \to \tau e) < 6\ 10^{-8}\ (2\ 10^{-9})$

Opportunities

- Measuring $BR(Z \to \tau e)$ & $BR(Z \to \tau\mu)$ better than 10^{-9} would overcome future bounds on LFV decays

Rare Hadronic Z Decays?

Silvestrini

- Upper limits from flavour-changing neutral currents (FCNC)
- From present expts in B physics one gets

$|U_{bs}| <\sim 4\ 10^{-4}$ and $|U_{bd}| <\sim 10^{-4}$ Buras et al.

$\Rightarrow BR(Z \to bd) <\sim 10^{-9}$, $BR(Z \to bs) <\sim 2\ 10^{-8}$

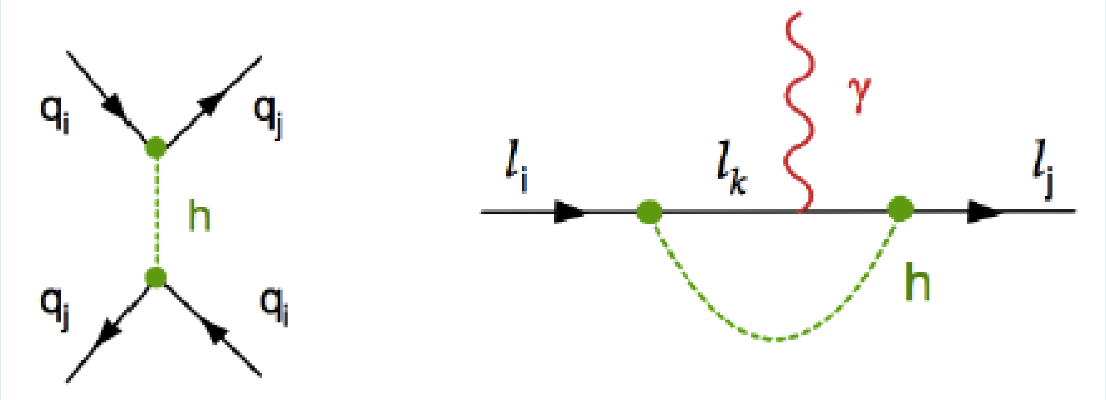
- How far can TLEP go? How will b id perform?
- From D mixing one gets $|U_{uc}| < \sim 2\ 10^{-3}$

$\Rightarrow BR(Z \to cu) <\sim 5\ 10^{-7}$

Opportunities

Rare Higgs Decays?

- Upper limits from FCNC, EDMs, …



- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

BR(τμ) or BR(τe) could be O(10)%

Blankenburg, JE, Isidori: arXiv:1202.5704

BR(μe) must be < 2×10^{-5}

Study on theoretical uncertaincies (QED) in the measurement of Z the invisible width from $e^- e^+ \to \nu + \bar{\nu} + \gamma$ using KKMC

S. Jadach, B.F.L. Ward and Z. Wąs

IFJ-PAN, Kraków, Poland

Partly supported by Polish Government grant
Narodowe Centrum Nauki DEC-2011/03/B/ST2/02632

To be presented somewhere sometime...

FCC-ee Work Breakdown Structure (Physics)

TLEP

Experimental / Physics Studies

- Electroweak Physics at the Z pole — Roberto TENCHINI
- Di-boson Physics and m_W measurement — Roberto TENCHINI
- H(126) Properties — TBA
- Top Quark Physics — Patrizia AZZI
- QCD and gg Physics — David d'ENTERRIA
- Flavour Physics — Stéphane MONTEIL
- Exp'tal signatures of New Physics — TBA
- Exp'tal Environment — Nicola BACCHETTA
- Offline Software and Computing — TBA
- Online Software and Computing — Ch. Leonidopoulos
- Detector Designs — Gigi ROLANDI

Phenomenology Studies

- Model Building and new Physics — TBA
- Precision EW calculations — Sven HEINEMEYER
- QCD and gg Physics — Peter SKANDS
- Flavour Physics — TBA
- Global Analysis, Combination, Complementarity — TBA ⇒ FCC-pp

The QCD coupling

- uncertainty on α_s propagates into all predictions
- e.g. for H → bb it is the dominant contribution to the uncertainty on the partial width ...

Generic target: *reduce uncertainty from to 0.1% i.e. 0.0001*

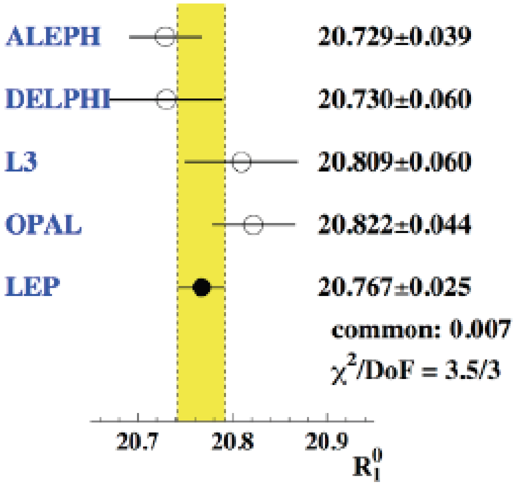
NB: this is a reduction by a factor 6-7, in comparison the uncertainty reduced by a factor 4 from 1992 to today

I will illustrate few possibilities in the following

QCD coupling from Z-decay width

Latest result from LEP:

$$R_l^0 = 20.767 \pm 0.025(0.12\%)$$



Need to improve the error by roughly 25-30

Error dominated by statistics. At TLEP with 10^{12} Z-events expect reduction by a factor of 200

At this level, subtle systematic uncertainties need to be taken into account ⇒ very promising, but requires dedicated analyses

Additional point: sensitivity to Zbb vertex which can be affected by New Physics (but constraint by direct extraction of R_b)

QCD coupling from W-decay?

Measure branchings of WW to lvlv, lvqq, qqqq, extract

$$B_h \equiv \frac{\Gamma_{\mathrm{W,had}}}{\Gamma_{\mathrm{W,tot}}}$$

Latest LEP measurement (uses $4{\cdot}10^4$ WW events)

$$B_h = 67.41 \pm 0.27$$

With $5{\cdot}10^7$ WW events from TLEP (always assuming systematics scales with stat), reduce uncertainty on B_h by 70, and uncertainty on α_s to 0.0002

An interesting possibility that deserves further investigation

Hadronic τ width

More inclusive that R_Z (integrated over the mass spectrum). Interesting because of shrinking of error from the running

$$\delta\alpha_s(M_Z) \sim \frac{\alpha_s^2(M_Z)}{\alpha_s^2(Q)}\delta\alpha_s(Q)$$

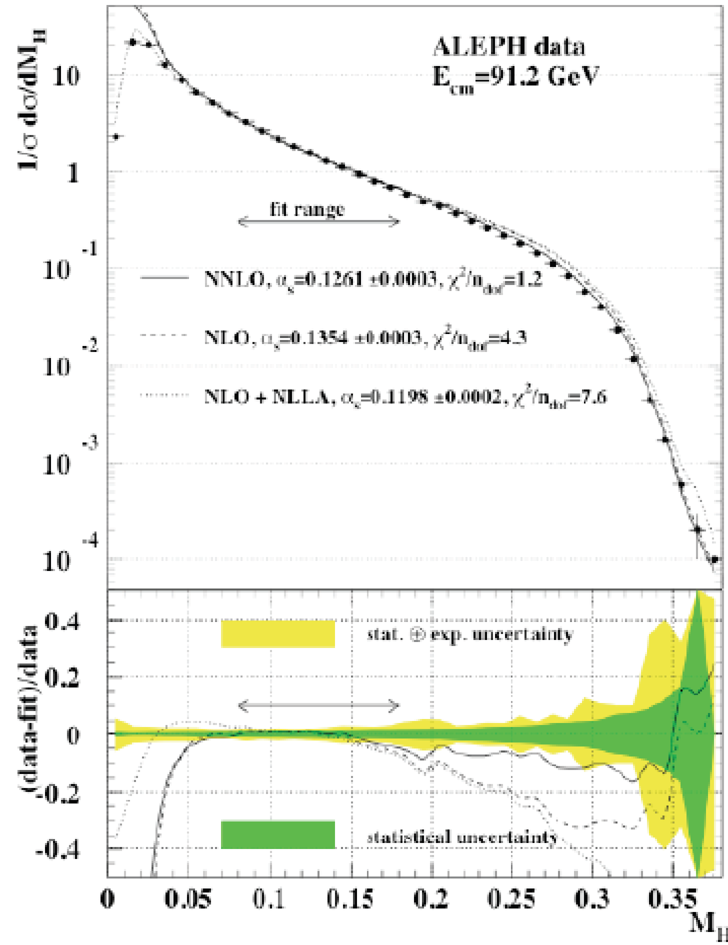
uncertainty on $\alpha_s(M_Z)$ about 3 times smaller than on $\alpha_s(m_\tau)$

Currently, methods of estimating impact of higher orders lead to differences in $\alpha_s(m_\tau)$ of $\lesssim$5% (i.e. on $\alpha_s(M_Z)$ of $\lesssim$1-2%)
Also non-perturbative corrections subject to debate

see e.g. 1303.6065 and 1303.2262

A better theory understanding needed to reduce error < 1%

QCD coupling from event-shapes



Theory predictions most accurate NNLO+NNLL

Still error budget dominated by theory uncertainty (3-5%)
Compare to experimental uncertainties (1%) and hadronization uncertainties (0.7-1.5%)
Going below 1% not realistic ?

<u>Challenge:</u>
can one design observables (e.g. combination of event-shapes) sensitive to α_s but with reduced uncertainties?

Future of QCD Models

Huge recent progress on theoretical side (not only cranking orders)

- Breaking through NLO (& automation) barrier
- Improving resummations and showers
- Better understanding of underlying principles (eg unitarity)
- Perturbative calculations combining different expansions

In 20 years, no one will be talking about "fixed order" calculations? → "perturbative" calculations, in form of:

- (N^nLO-corrected) (exclusive) (hadronized) Monte Carlos
- (N^nLO-matched) (inclusive) (analytical or numerical) resummations

These pQCD calculations will have very high precision

→ can see non-perturbative physics more clearly

Next generation models will have far better precision → need far better constraints. (And can probe far deeper! Reliably!)

“Neutrino Counting”

Blondel

- **On Z peak:** $N_\nu = 2.984 \pm 0.008$

  - 2 σ :^) !!

- Error ΔN_ν dominated by ΔL, theory dominated:
- Bhabha uncertainty $\pm$ 0.0046
- Building blocks available to bring perturbative error < 0.1%
- **Radiative return:** $N_\nu = 2.92 \pm 0.05$

Piccinini

- EW corrections!
- Useful to study WWγ vertex: EW NLO

Conclusions

From this limited study using KKMC at 161GeV we conclude that:

- QED effects are sizeable $\sim 2\%$.
- t-channel contrubution is $\sim 10\%$ near Z peak in photon energy.

To be studied further most urgently:

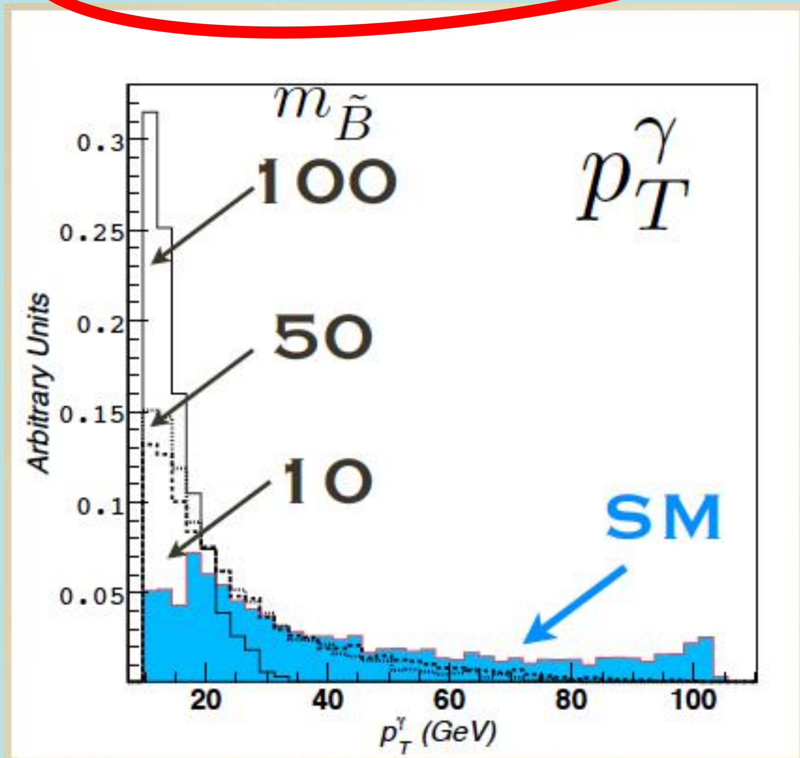
- The dependence on $\sqrt{s}$
- The dependence on $\theta_{\rm min}$ and other cutoffs
- Where from normalization?
  Bhabha? Or may be $e^- e^+ \to \mu_- + \mu_+ + \gamma$?
  And how uncertain?

Direct Searches for New Particles?

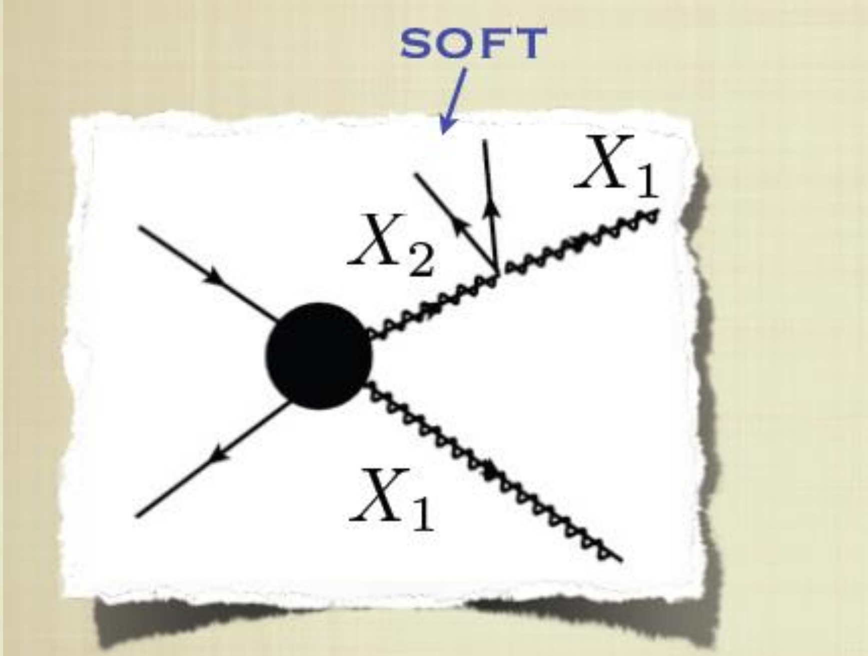
Sanz

- Best chance may be pair-production of dark matter particles + soft γ, …
- Way to get "$N_\nu > 3$"

Compressed spectra



$$\Delta m = m_{X_2} - m_{X_1} \ll m_{X_1}$$



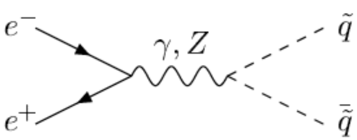
Sparticle Production?

- Unlikely? But cross-sections under control

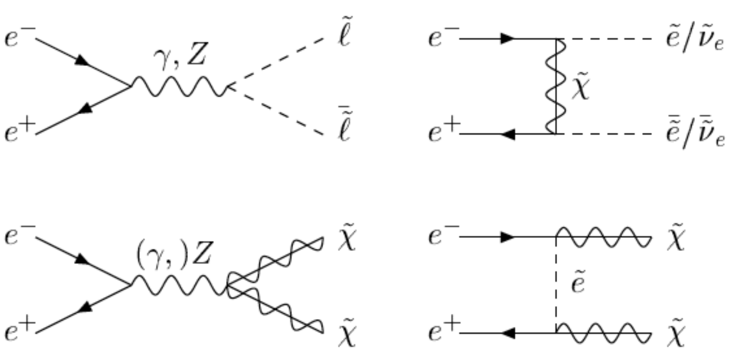
Spira

2 classes of SUSY particle production processes:

(i) strongly interacting particle pairs:



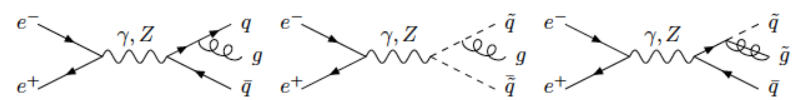
(ii) weakly interacting particle pairs:



- NLO [QCD &] elw. corrections known

- $e^+e^- \to \tilde{\chi}^+\tilde{\chi}^-, \tilde{\chi}^0\tilde{\chi}^0$: test g, g' equality Choi, Kalinowski, Moortgat–Pick, Zerwas

$e^+e^- \to q\bar{\tilde{q}}\tilde{g}, \tilde{q}\bar{\tilde{q}}g, \tilde{q}\bar{q}\tilde{g}$



- possibility to test equality of strong couplings ← NLO required
Brandenburg, Maniatis, Weber, Zerwas

- SUSY particle decays: most SUSY-QCD & SUSY-elw. corr. known
⇒ public codes:
SDECAY, SOFTSUSY, SPHENO, MICROMEGAS
Djouadi, Mambrini, Mühlleitner
Allanach
Porod
Belanger,. . .

FCC-ee Design Study Mandate (Physics)

- Conveners and Working Group Mandate
  - All conveners (or candidates) have been sent a mandate
- Their charge include
  - The proposal of one/two co-conveners within a timescale of a year
    - Targeting global effort and international collaboration
  - The nomination of sub-group conveners, for the various work areas
    - ibid
  - Start the group activities, with regular reports to physics coordination
    - Attract people for the studies relevant to their group
  - Seeking synergies with Linear Collider studies and teams, in particular
- They were asked to produce a document, based on this mandate
  - With work areas, timeline, and specific deliverables, at least for FCC Phase 1
    - And to present/discuss their plans at the FCC Kick-off break out session
  - Concluded with a "Phase 1" written report, in Spring 2015
- First publication of the TLEP Design Study Group
  - "First look at the physics case of TLEP"
    - Reference: Journal of High Energy Physics JHEP01(2014)164.

Z the invisible width from $e^- e^+ \to \nu + \bar{\nu} + \gamma$ at TLEP

- Z invisible width in terms of number of neutrinos from LEP
  $N_\nu = 2.984 \pm 0.008$
- According to "The TLEP Design Study...", page 29
  `http://arxiv.org/abs/arXiv:1308.6176`
  could be measured 10 times better.
- TLEP run near WW threshold 5pb would ensure 3M events with visible photon and invisible $Z \to \nu\bar{\nu}$ decay.
- No reliable estimate of the theoretical (QED) uncertainties at this precision level – only hope that this process is possibly better that Z peak cross section.
- Let us 1st step in working out such an estimate...