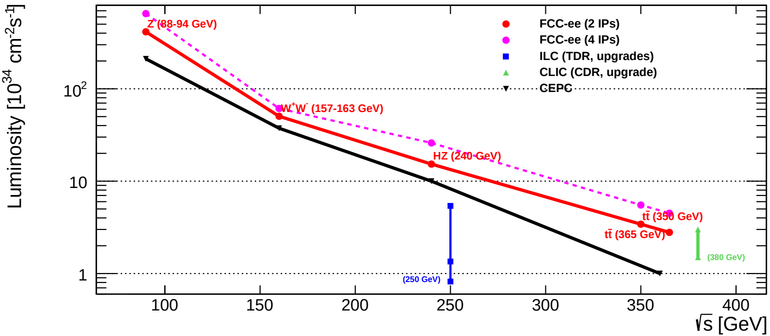
Electroweak precision at future e^+e^- colliders

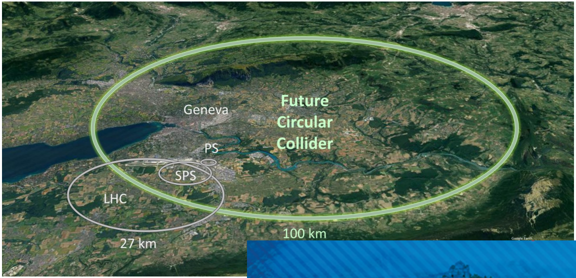
Marek Schönherr

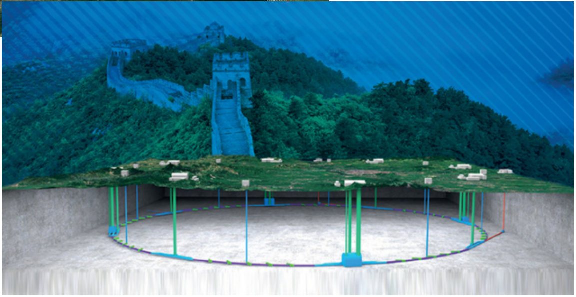
IPPP, Durham University

FCC Snowmass Report '22

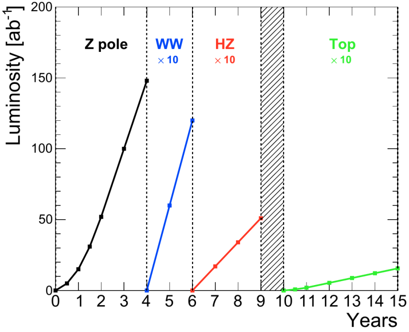


This talk will mainly focus on precision calculations for future e^+e^- colliders.


Future
Circular
Collider
Geneva
PS
SPS
LHC
27 km
100 km



Overview



Z pole

EW precision observables
$(m_Z, \Gamma_Z, \sin^2\theta_W^{\text{eff}}, \ldots)$
running couplings
$(\alpha(m_Z), \alpha_s(m_Z), \ldots)$

WW threshold

W spectroscopy
$(m_W, \Gamma_W, \text{couplings})$

$t\bar{t}$ threshold

top spectroscopy
$(m_t, \Gamma_t, \text{couplings})$

Zh threshold

Higgs spectroscopy
$(m_h, \Gamma_h, \text{couplings})$

Highest precision measurements need highest precision theory predictions to make full use of the data.

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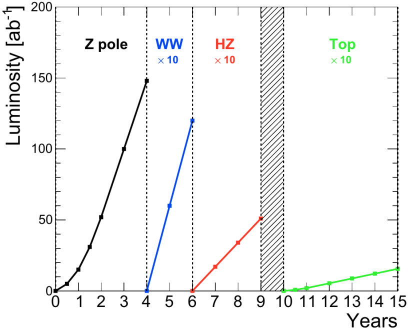

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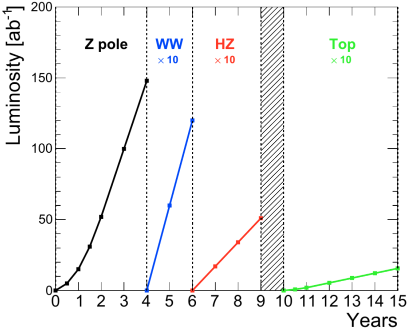

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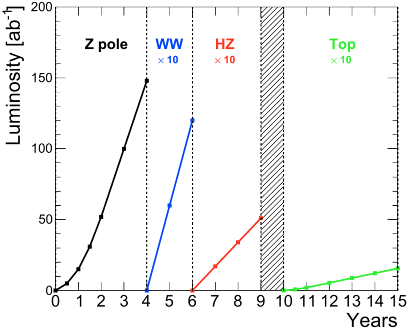

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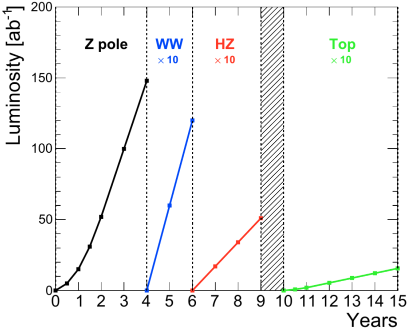

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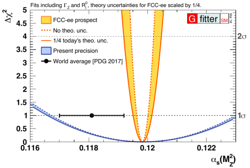
Z pole

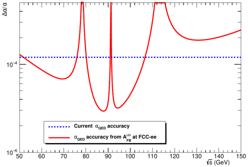
EW precision observables:

use on- and off-peak data to measure Z lineshape, $A_{\mathrm{FB}}(s)$, R_ℓ, ..., and determine m_Z, Γ_Z, $\sin^2\theta_W^{\mathrm{eff}}$, $\alpha(m_Z)$, $\alpha_s(m_Z)$, ...

To exploit full data precision theory predictions must keep pace, otherwise parameter extractions are severely theory limited.

- **NNLO EW needed throughout** ($\mathrm{N}^3\mathrm{LO}$ in some places) including ISR, FSR resummation and initial-final interference (IFI)
- need **highest precision Monte-Carlo event generators** to account for finite fiducial region, bremsstrahlung effects, hadronisation corrections, etc.





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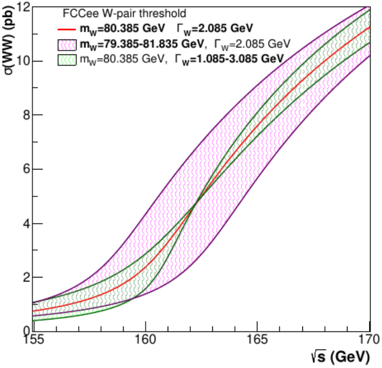
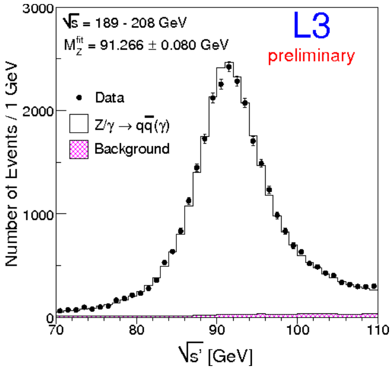


W mass and width determination

- needs precision calculation (NNLO QCD, QCD-EW, EW) and QED threshold resummation
- including implementation in Monte-Carlo event generators to account for finite fiducial region, colour reconnection, hadronisation, etc.
- highest precision calculations still from LEP (YfsWW and RacoonWW)
- $\Delta m_W \approx 0.7\,\text{MeV}$, $\Delta\Gamma_W \approx 1.5\,\text{MeV}$

Radiative return



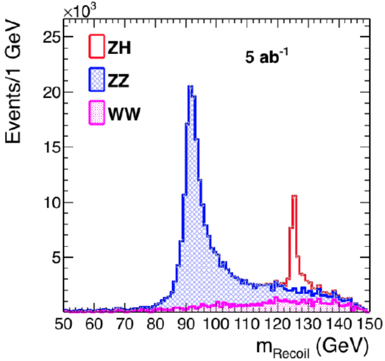
Mainly relevant to determine the invisible Z decay width through $R_\mu^{\text{inv.}} = (\text{inv.} + \gamma)/(\mu^+\mu^- + \gamma)$.

$R_\mu^{\text{inv.}}(s) \neq R_\mu^{\text{inv.}}(3\nu, \text{SM})$ can hint at DM candidates.

QED/EW corrections strongly dependent on precise experimental selection.

Needs **highest precision** fully exclusive **Monte-Carlo event generator** containing multi-loop higher-order QED and EW effects.

Zh threshold

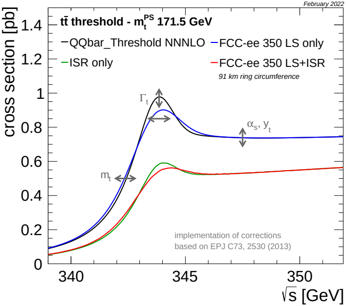


Higgs spectroscopy

- precise mass determination
- direct access to all Higgs decay channels incl. $h \to gg$ and $h \to$ inv.
- **precision fit of EFT parameters**

Monte-Carlo event generators with highest precision for both production mechanisms and Higgs decays necessary.

$t\bar{t}$ threshold – mass and width



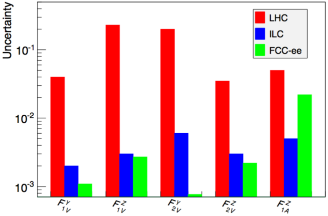
Determination of m_t and Γ_t

- measurement through kinematic reconstruction suffer large systematic uncertainties and ambiguous interpretation
- use shape of production cross section near threshold
  $\rightarrow \Delta m_{\text{top}} \approx 17\,\text{MeV}$,
  $\Delta\Gamma_{\text{top}} \approx 45\,\text{MeV}$

$t\bar{t}$ threshold – electroweak couplings

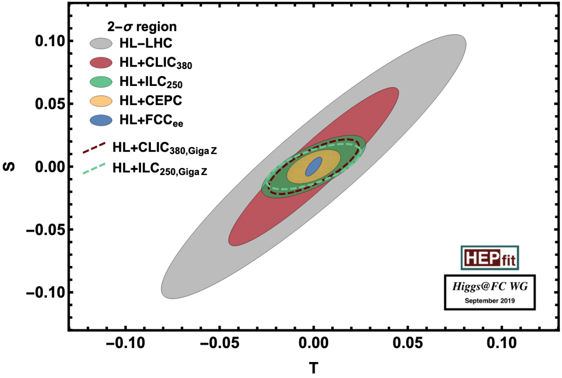
Determination of top quark electroweak couplings, $g_{tt\gamma}$, $g_{t_L t_L Z}$, $g_{t_R t_R Z}$, etc.

- typically using kinematical information above threshold (spin-correlations of final state leptons)
- needs precision Monte-Carlo event generators (NNLO QCD, QCD-EW) to account for finite fiducial region, top decay kinematics, colour reconnection, hadronisation, etc. $\rightarrow \delta g_{t_L t_L Z},\ \delta g_{t_R t_R Z} \approx 2\%$



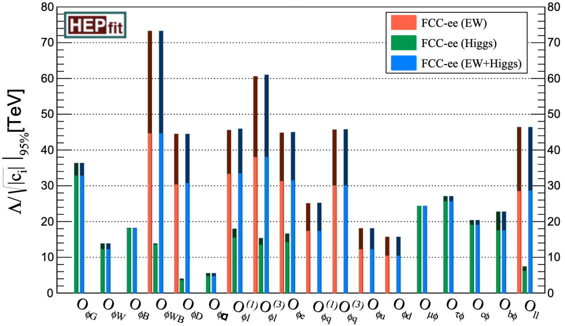
Barducci et.al. '15

EW precision fit



- vast improvements in uncertainties on EW precision data and theory may point towards inconsistencies in the Standard Model

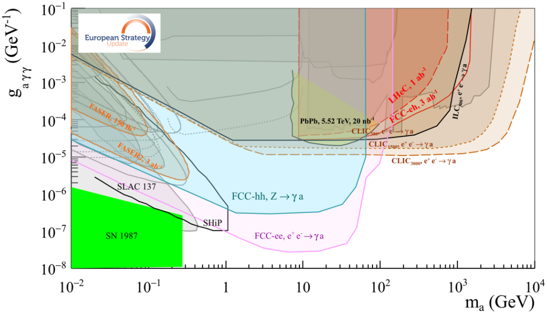
New Physics – EFT interpretation



- extraction from precision data through quantum corrections

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\,\mathcal{O}_i$$

New Physics – ALPs



- axion-like particles' (ALPs) masses and widths can be constrained mainly through $ee \to \gamma a$
- large parts of the parameter space (medium mass, small coupling) can be excluded thanks to high statistics of FCC-ee/CEPC
- complementary exclusion of high-mass ALPs for CLIC$_{3000}$

Precision event generation

Generally, lepton colliders allow for fewer processes/signatures to be studied compared to hadron colliders, but with much higher precision.

FCC-ee/CEPC statistics much larger than any other e^+e^- machine in history, allows for study of very interesting but rare processes

- $\gamma\gamma$ physics
- γ structure function (pert. and non-pert.)
- BFKL effects

Need precise electron structure functions which are also differential in the photon (and other partons at $\mathcal{O}(\alpha^2)$).

Needs precise calculation of Bhabha scattering for luminosity determination at a similar accuracy we have today for $(g-2)_\mu$.

The role of the electron structure function

Although the electron is a point-like object, it has a substructure (QED).

Bertone et.al. '19

Electron PDF

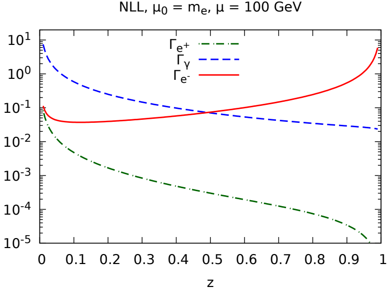
- access to complete partonic content of SM through QED+EW+QCD evolution

  $\mathcal{O}(\alpha)$ γ, $W^\pm$, Z, (h)

  $\mathcal{O}(\alpha^2)$ $e^\pm$, $\mu^\pm$, $\tau^\pm$, ν

  u, d, s, c, b, t

  $\mathcal{O}(\alpha^2\alpha_s)$ g



High luminosities allow to study rare process.
Photon luminosity of particular interest.

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Although the electron is a point-like object, it has a substructure (QED).

YFS soft-photon resummation

Yennie, Frautschi, Suura '61

- resums soft-photon logs
- photon radiation explicit
- most appropriate when $\sqrt{s}$ near resonance

Collinear structure function

Kuraev, Fadin '85

- resums collinear logs
- photon radiation integrated out
- most appropriate when $\sqrt{s}$ well above resonance

$\Rightarrow$ **in practice yield similar results**

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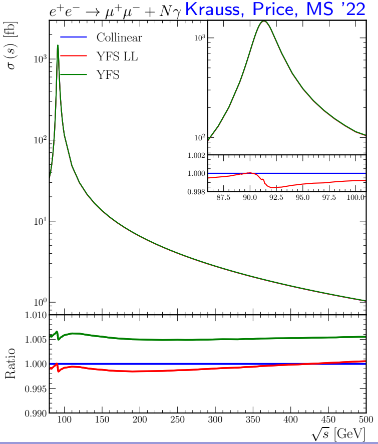
⇒ in practice yield similar results

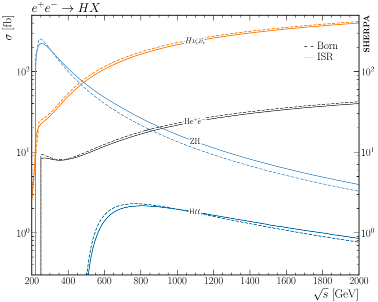


Soft-photon resummation

Krauss, Price, MS '22

Implementation in SHERPA

- YFS resummation in EEX scheme
- can be systematically completed with collinear corrs
- while most appropriate if $\sqrt{s}$ close to resonance, provides precise results over a very large range
- fully differential in photon kinematics
- full NLO EW to appear

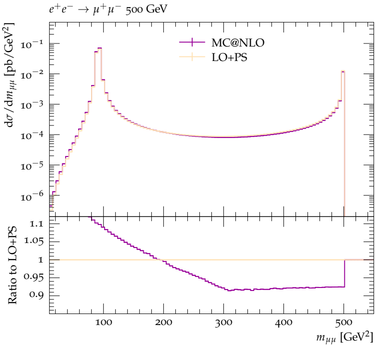


Collinear resummation

Flower, MS to appear

QED parton shower and MC@NLO EW matching in SHERPA

- ePDF/SF resums collinear $e \to e\gamma$ logarithms
- QED parton shower integrates the spectrum differentially in the e and γ kinematics
- matched to NLO EW corrs



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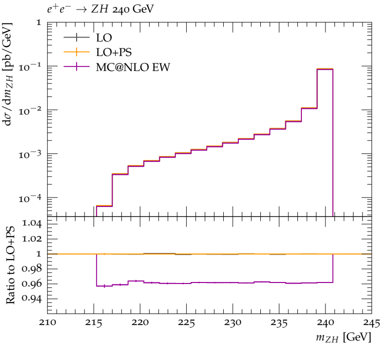


Precise electroweak corrections for the LHC

Electroweak corrections are also essential for precision physics at the LHC.

EW Sudakov logarithms at large momentum transfers.

Originate in the exchange of γ, W, Z, h bosons between legs i and j with large s_{ij}.
Large negative logarithms, KLN theorem is broken by the EW gauge boson masses and the distinguishability of the EW fermion doublets.

Captured in well-understood approximations
$\rightarrow$ EW_{sud} approximation — Denner, Pozzorini '01; Bothmann, Napoletano '20
$\rightarrow$ EW_{virt} approximation — Kallweit, Lindert, Pozzorini, MS '15

Precise electroweak corrections for the LHC

Inclusive NLO EW corrections are typically much smaller, but essential for precision observables.
Examples: m_W, A_i, $\sin^2\theta_w$

Particle level calculations essential to account for full experimental environment
Matching of fixed-order calculations to parton showers needed simultaneously for NLO QCD and EW corrections.

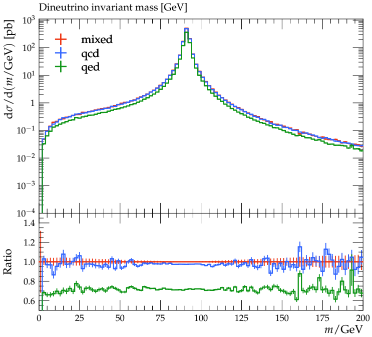
$\Rightarrow$ **MC@NLO QCD+EW**

Precise electroweak corrections for the LHC

Flower, Roper, MS to appear

Resonance aware parton showers and matching

- needed to preserve the shape of internal resonances beyond NLO
- essential for QED parton showers in the presence of W, Z, h, t
- QED subtraction has to be modified accordingly



MC@NLO QCD+EW for offshell W and Z production with SHERPA

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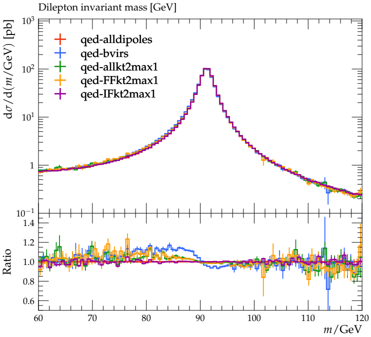

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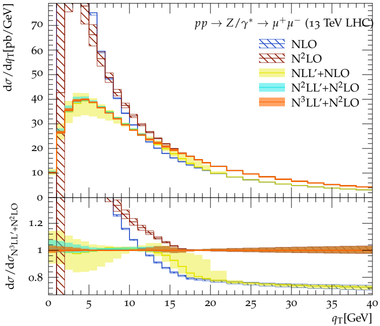
Precise electroweak corrections for the LHC

Ju, MS '21,'22,'23,'24



Analytic resummation of q_T and $\Delta\phi$ in off-shell W and Z prod.

- currently N^{3}LL+N^{2}LO QCD accuracy
- NLL QED corrections comparable to N^{2}LL QCD, but still unkown
- EW corrections relevant for precision observables m_W, $\sin^2\theta_w$, A_i

$\to$ towards N^{4}LL+N^{3}LO QCD + NLL+NLO EW for offshell W and Z production

QCD aspects at e^+e^- colliders

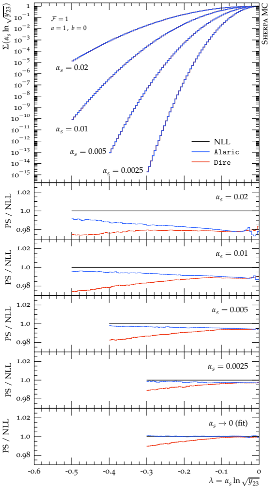
Inclusive QCD production, *ee* $\rightarrow$ jets

- integrated over individual hadron properties
- event shapes are an excellent testbed for precision QCD calculations (higher orders, analytic resummation, parton showers) $\rightarrow$ extract α_s

Need a **fully differential higher-order parton shower resummation**, beyond simple K-factor modifications of LO showers.

First step: NLL accurate parton showers.

NLL accurate parton shower – ALARIC



Constructed to cure defects in current showers and be demonstrably NLO accurate.

limit: $\alpha_s \to 0, \lambda = \alpha_s \log \mathcal{O} = \text{const.}$

Durham jet rate y_{23}	$\beta = 0$
Total jet broadening B_T	$\beta = 0$
Durham jet rate $FC_{1/2}$	$\beta = \frac{1}{2}$
Thrust $1 - T$	$\beta = 1$

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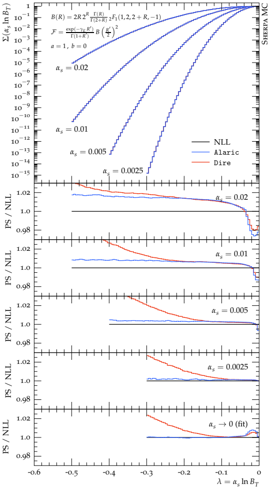

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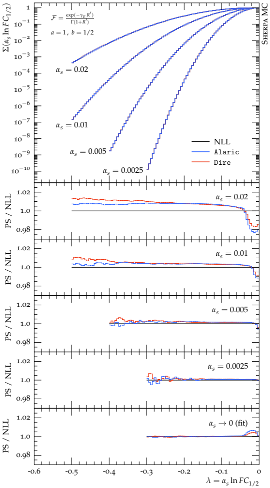

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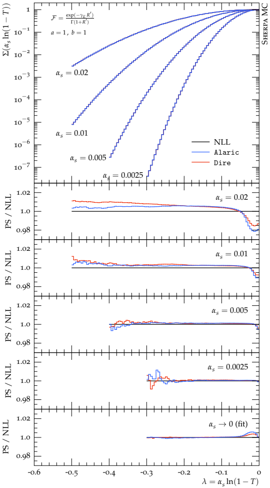

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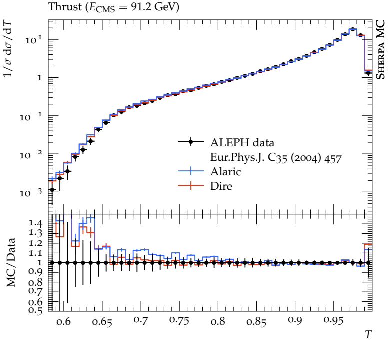
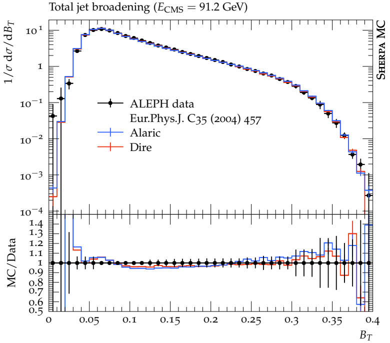
ALARIC – LEP phenomenology

- apply in realistic LEP scenario
- compare with existing DIRE shower (not NLL)





Conclusions

e^+e^- colliders, FCC-ee and CEPC in particular, offer great physics opportunities, however

- demands high-precision calculation of a number of signatures
- Monte-Carlo event generator development indispensable
  - many new developments on the precision frontier in SHERPA
  - some are already available in SHERPA-3.0.1, some are currently developed for future versions

http://sherpa.hepforge.org

Thank you!

Backup