Energy Frontier Workshop:
Open Questions and New Ideas

Forward Physics Facility: brainstorming session

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PHYSICS POTENTIAL

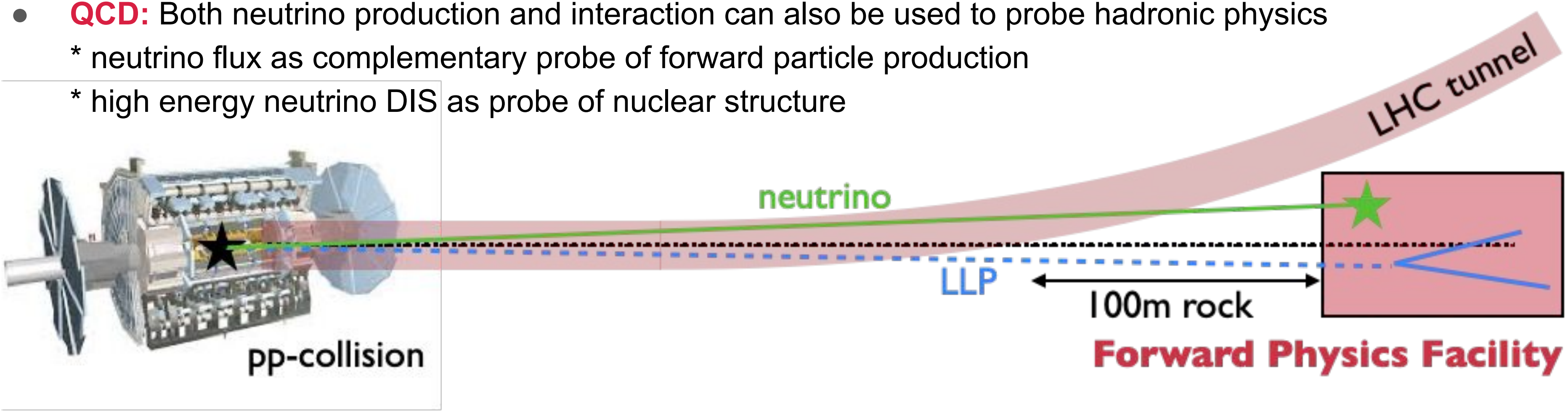
- As the LHC runs at higher energies and much higher luminosities in the next 15 years, how can its potential be maximally exploited?
- Attention has focused on high pT/ low cross section physics (~ fb - pb).
- But the total cross section is ~100 mb, and most of it (and most of the highest energy particles) is in the far forward region at low pT.
- In recent years, it has become clear that there is an **entire physics program that remains to be explored in the far forward region**, and this can be done with relatively small additional investment.
- **The proposal: create a Forward Physics Facility for the HL LHC.** Enlarge an existing cavern in the far forward region of ATLAS to house a suite of experiments with groundbreaking new capabilities for new physics searches, neutrinos physics, and QCD measurements.

PHYSICS POTENTIAL

- LHC experiments provide an intense neutrino beam along the beam collision axis
  * highly energetic: E~TeV
  * for all flavors: $\pi \to \nu\mu$, $K \to \nu e$, $D \to \nu\tau$

- **Neutrino Physics:** LHC neutrino experiments will open a new world of TeV neutrino physics

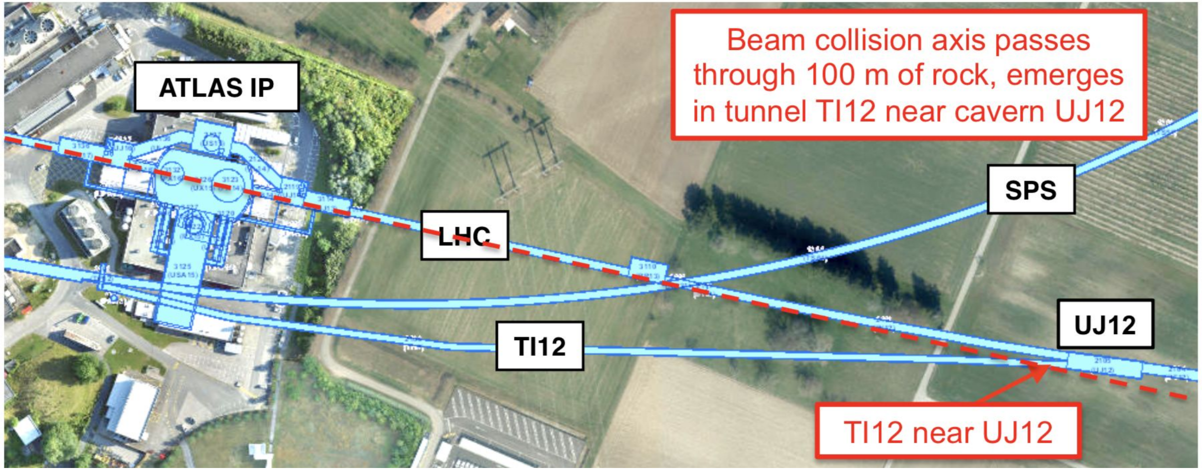
- **QCD:** Both neutrino production and interaction can also be used to probe hadronic physics
  * neutrino flux as complementary probe of forward particle production
  * high energy neutrino DIS as probe of nuclear structure



- **BSM Physics:** Many models of new physics predict MeV - GeV mass weakly interacting particles that are also preferentially produced along the beam collision axis.
  * light long-lived particles (dark photon)

see Forward physics and BSM discussion in BSM parallel session with Jonathan Feng

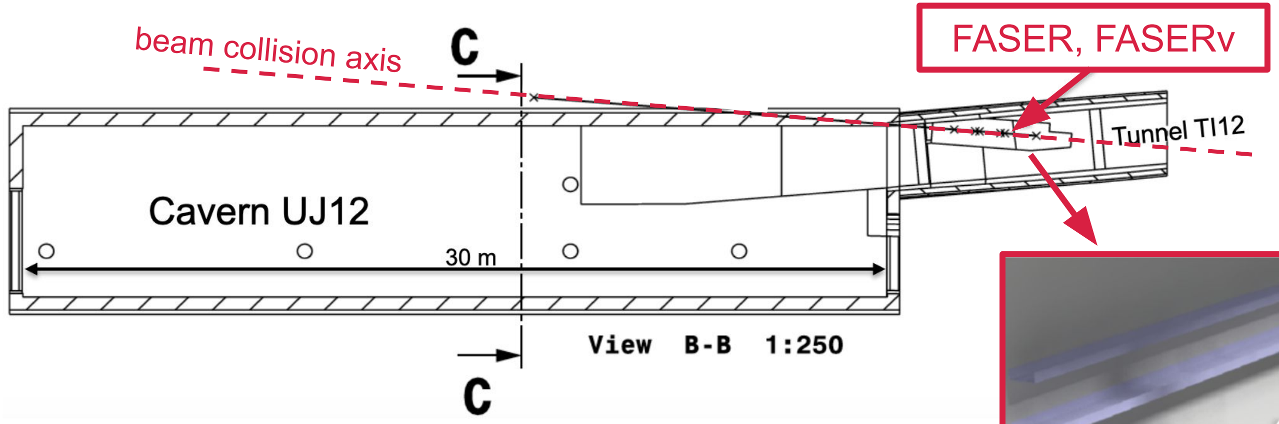
BEAM COLLISION AXIS

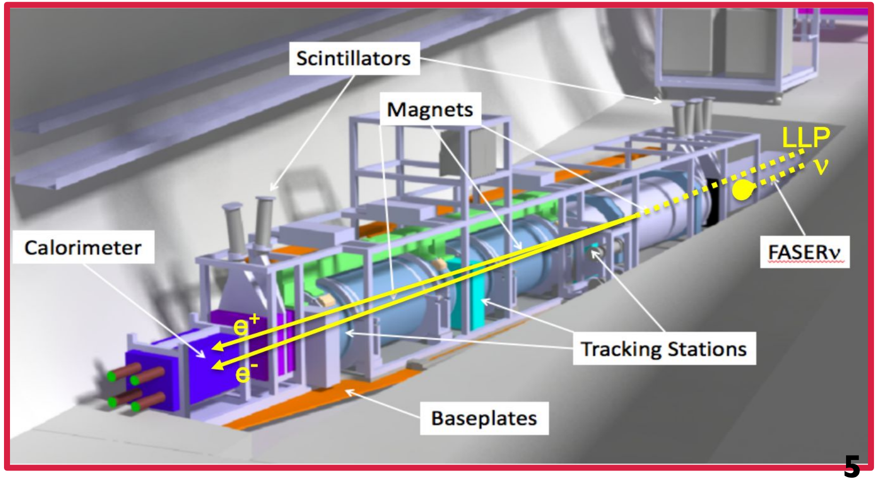


CURRENT EFFORTS

- A few experiments are under construction or proposed for this location. But they are severely limited by the tunnels and infrastructure that were created long before the physics potential of this space was appreciated.

Dougherty (2020)

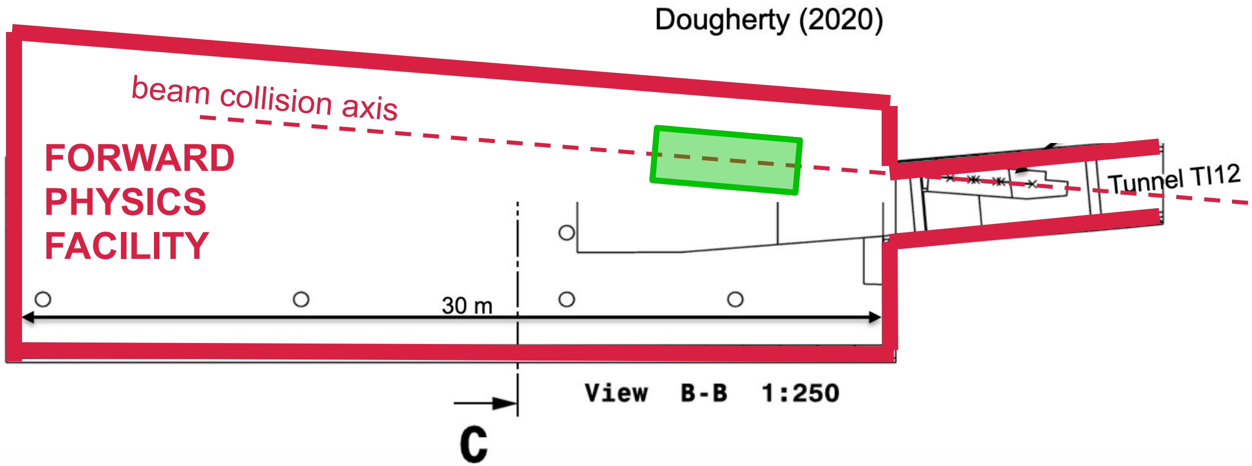




- The ~1ton FASERν detector will study high energy neutrinos at $\eta>9$ with ~10k ν_μ, ~1k ν_e, ~10 ν_τ events expected during LHC run 3.
- SND@LHC has also been proposed as a (slightly) off-axis neutrino experiment in TI18.

FUTURE EFFORTS & FORWARD PHYSICS FACILITY

- What experiments would we like to have at the HL-LHC era? Snowmass is great environment to investigate this question.



- This location could be upgraded to a **Forward Physics Facility** hosting a variety of far forward experiments.

- In particular, a possible ~10 ton neutrino experiment during HL-LHC could see ~1M ν_μ, ~100k ν_e, ~1k ν_τ events at TeV energies. This opens up many new opportunities for new physics searches, neutrino physics, QCD and cosmic ray physics, significantly extending the LHC's physics program.

Examples of QCD opportunities at a forward ν facility

Maria Vittoria Garzelli and Felix Kling

Snowmass 2021 EF Community Workshop - Open Questions and New Ideas, July 20th - 22th, 2020

Some examples of QCD opportunities at a forward ν facility, of interest for the Snowmass Energy Frontier

* EF05: new tunes of general purpose MC event gerators, insights on the interplay of pQCD and non-pQCD effects in hadron production

* EF06: new constraints on (g, c and s) distributions for new pPDF fits

* EF07: new νA CC inclusive (and less inclusive) DIS measurements for new studies of cold nuclear matter effects and nPDF fits

Assumptions
no BSM physics:
- no anomalous ν interactions
- no sterile neutrinos
- lepton flavour universality, no SM anomalies in τ, b and c physics
- etc....

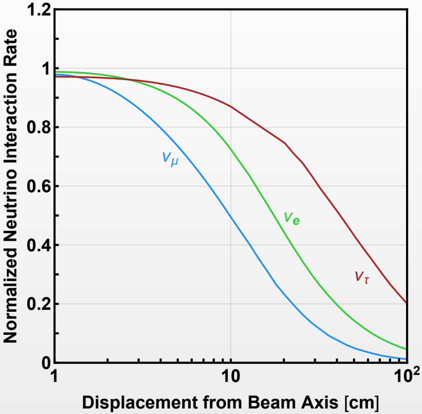
How much forward ?

* Faserν current approved project under construction covers $\eta_\nu \gtrsim 9$.
* New proposals cover: $7 \lesssim \eta_\nu \lesssim 8$, $8 \lesssim \eta_\nu \lesssim 9$, etc....

Tradeoff between the need to have an high ν flux (which would favour lower η values), the CC DIS interaction probability (which would favour more energetic ν, that are also the higher η ones), the necessity to control the backgrounds, and the geometry of the space available in the possible experimental locations.

For better understanding/testing QCD: cover different rapidity intervals, providing separate measurements for each of them, closing the gaps from such high rapidities towards lower rapidities, covered by other forward LHC experiments (LHCb ($2 < y < 4.5$), TOTEM ($5.3 < |\eta_{ch}| \lesssim 7$), CASTOR ($-6.6 < \eta_{had} < -5.2$), LHCf ($\eta_n > 8.81$). None of the existing LHC experiments, however, measures neutrinos!

Normalized ν interaction rate vs. detector radius

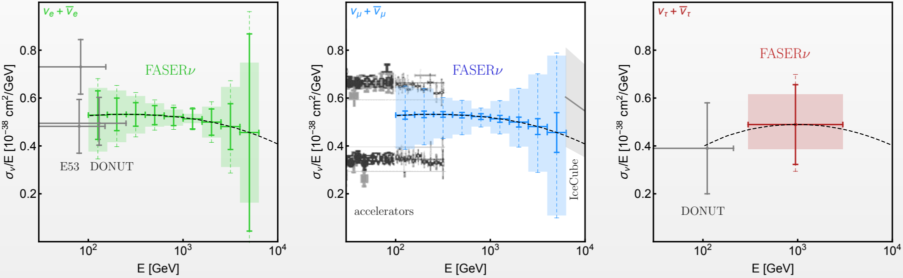


The neutrino interaction rate per unit area normalized to the prediction at the beam collision axis for a detector with radius $1 \text{ cm} < R < 100 \text{ cm}$.

from [arXiv:1908.02310]

We expect different flavour compositions at different energies and rapidities due to different ν sources $\rightarrow$ can be disentangled by detectors covering different η values.

Main measurement at a forward ν facility: average ν-induced DIS CC cross-section per (A-weighted) nucleon



from [arXiv:1908.02310]

$$\langle \sigma_A \rangle = \frac{\phi_\nu \sigma_{\nu A} + \phi_{\bar{\nu}} \sigma_{\bar{\nu} A}}{\phi_\nu + \phi_{\bar{\nu}}}$$

computed from the number of events that will be observed.
Good control on the fluxes (input) and on nuclear correction effects is necessary to infer separate precise info on $\sigma_{\nu p}$, $\sigma_{\bar{\nu} p}$, $\sigma_{\nu n}$, $\sigma_{\bar{\nu} n}$

ν production in pp collisions

Forward neutrinos are produced by the decay of hadrons produced in pp collisions.

Dominant contributions:
ν_e spectrum: K decay at low energy, c-hadron decays at high energy
ν_μ spectrum: $\pi^\pm$ decay at low energy, K at high energy
ν_τ spectrum: c-hadron decays at all energies

$\Rightarrow$ reliable ν_e, ν_μ flux estimates require not only reliable hadron production models, but even careful convolution with the beam optics. Solvable!
$\Rightarrow$ Synergy theory/experiment experts for performing useful simulations.

ν_e and ν_μ flux predictons

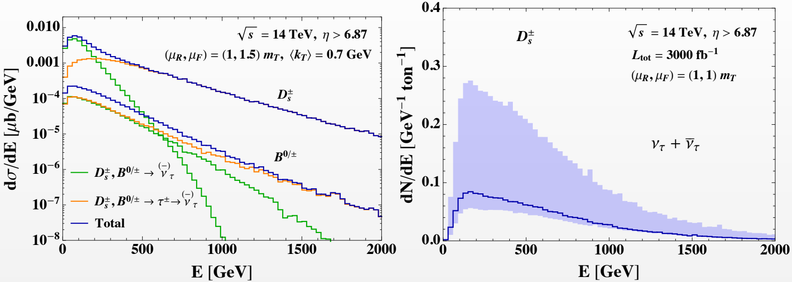
$*$ current predictions for ν_e, ν_μ energy spectra on the basis of minimum-bias event generators developed for EAS studies and tuned to LHC data: DPMJET, EPOS-LHC, QGSJET, SYBILL

$*$ PYTHIA8 predictions only in partial agreement with them and with available forward data (e.g. from LHCf): do we need to implement better physics or better tunes are enough ?

$*$ HERWIG7 and SHERPA ?

Theory uncertainties estimated by the experimental collaborations as differences between different generators: too rough!

ν_τ predictions



from [arXiv:2002.03012]

∗ NLO + FF + intrinsic $\langle k_T \rangle$, NLO matched to SMC

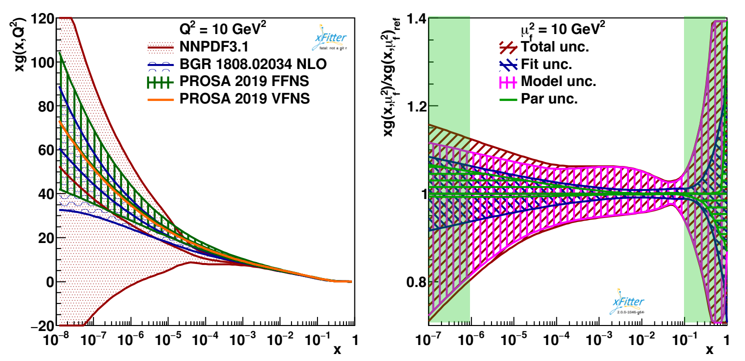
∗ direct decay and chain decay contribute to the total in different energy regions.

∗ Big uncertainties due to missing higher orders in pQCD: can we go beyond the present accuracy ?

∗ Forward (ν_τ + high-energy ν_e) measurements can help constraining forward heavy-flavour production and the interplay between perturbative and non perturbative effects.

Reducing gluon PDF uncertainties

$*$ Present-day gluon PDFs at low x are constrained using LHCb heavy-flavour data in the range $10^{-4} \lesssim x \lesssim 10^{-6}$

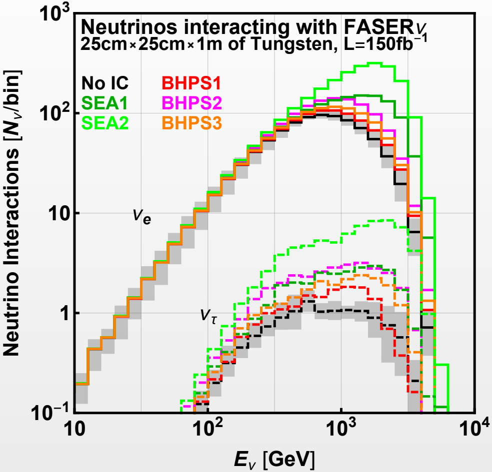


from [arXiv:1911.13164]

$*$ Production of forward high-energy ν_τ will be sensitive to even lower x ($5 \cdot 10^{-8} < x < 5 \cdot 10^{-6}$) and very large x ($x \sim 0.5$) gluon distribution for $Q^2 \sim$ a few GeV^2, further extending the constraints on gluon and sea quark PDFs.

$\Rightarrow$ Useful for future hadron colliders and for BSM searches at HL-LHC !

Constraining Intrinsic charm

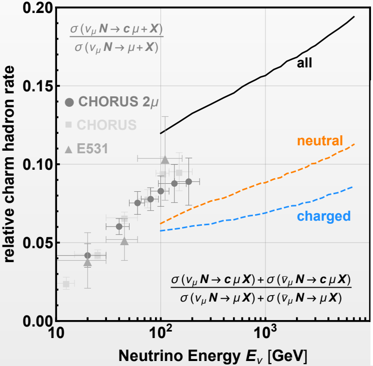


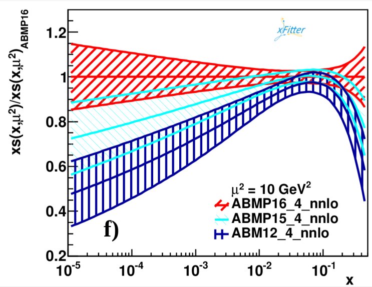
∗ At large energies spectrum of CC events enhanced by the presence of intrinsic charm with respect to the perturbative charm case.

⇒ Preliminary, more realistic evaluations are needed!

Constraining strange sea PDFs

Strange sea PDFs can be constrained thanks to the possibility offered by emulsions of detecting not only the lepton but even the charm hadrons emitted in CC DIS according to $\nu_\ell N \to \ell^- X_c + X$, $\bar{\nu}_\ell N \to \ell^+ X_c + X$





∗ This will extend the dimuon results of CCFR/NuTeV/NOMAD and charm-hadron results of CHORUS, E531 (emulsion) experiments.

∗ Emulsions will also allow to update the charm muonic B.R. that is a key input (and a source of uncertainties) for dimuon experiments.

∗ Nuclear uncertainties reduced by the ratio of cross-sections.

Nuclear PDFs / nuclear matter effects for pPDF

$*$ The target of Faserν is made by W nuclei ($A = 184$, $Z = 74$), other experiments consider Pb to maximize the number of CC events.

$*$ It is indeed possible to use lighter targets without loosing statistics if one has the possibility to build a detector large enough. This will probably be possible at a HL-LHC forward neutrino facility. In that case target of various A values can be used, considering A as small as Fe and light metals.

$*$ Target replacement is an easy operation for this kind of detectors and is in any case planned, due to progressive accumulation of tracks on the emulsions (which makes progressively more difficult their reading).

$*$ These measurements will be useful to increase the small amount of data presently available for nPDF fits and better understanding their A-dependence.

Which detector requirements are needed to do precision QCD studies ?

$*$ What is the energy resolution we should aim at for getting precise QCD constraints ? In emulsions $E_\nu = E_\ell + E_{had}$ present energy resolution of 30%, reconstructed using as input topological quantities extracted from emulsion reading. Knowledge of (E_ν, E_ℓ, $\theta_{\ell,\nu}$) allows to derive (Q^2, x_{Bj}).

$*$ Distinguishing ν and $\bar{\nu}$:
this will be e.g. possible by coupling Faserν to Faser spectrometer.

$*$ Extension to NC DIS studies: probably desirable, but reconstruction of events more difficult, because the emitted ν escapes the emulsion.

$*$ Backgrounds (e.g. from neutral hadrons from μ interacting in rock, reaching and interacting with the target): they increase when going less forward $\rightarrow$ controllable

$*$ How often will the emulsions need to be replaced during HL-LHC ?
Is a change of detector technologies needed ?

SNOWMASS PLANS

- Bring together physicists with diverse interests in new physics searches, neutrino physics and QCD to study the physics potential and feasibility of the Forward Physics Facility at the HL LHC.

- In particular, the potential for QCD needs to be studied in more detail. Maria presented examples of QCD opportunities at a forward LHC neutrino detector.
  → What are the detector requirements needed to do precision QCD measurements?

- We will submit a Snowmass LOI on the Forward Physics Facility:
  → LOI will include a paragraph on QCD physics potential, summarizing results of our discussion.
  → Everyone is invited to join the Forward Physics Facility LOI, email felixk@slac.stanford.edu.

- This is a brainstorming session: your feedback and new ideas are welcome!