Very Forward Particle Production and Searches (FPF, etc.)

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with input from J.L. Feng, F. Kling, S. Trojanowski
and many other authors of the FPF report [arXiv:2109.10905]

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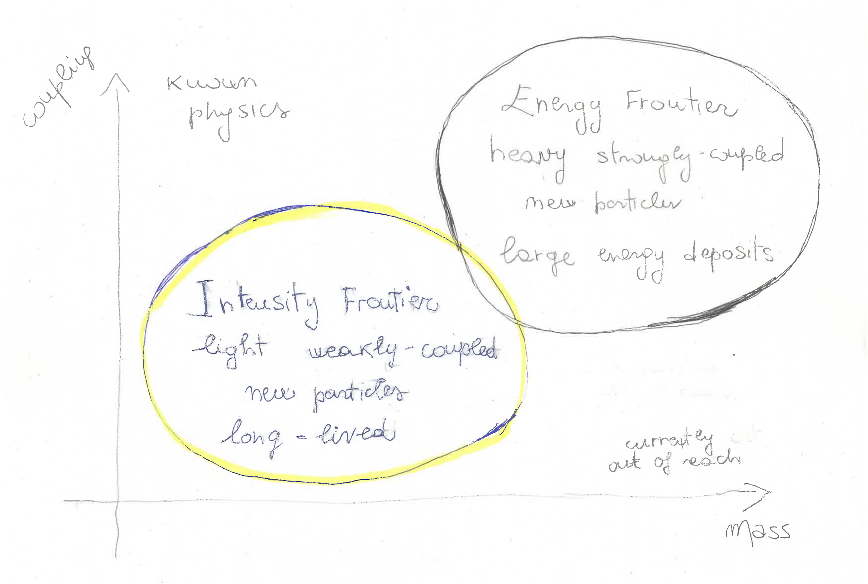
12th International Workshop on Multiple Partonic Interactions at the LHC
MPI@LHC
LIP Lisbon + zoom, October 11 - 15, 2021

Introduction: which particles can we better study in the forward region ?



Far-forward LHC experiments

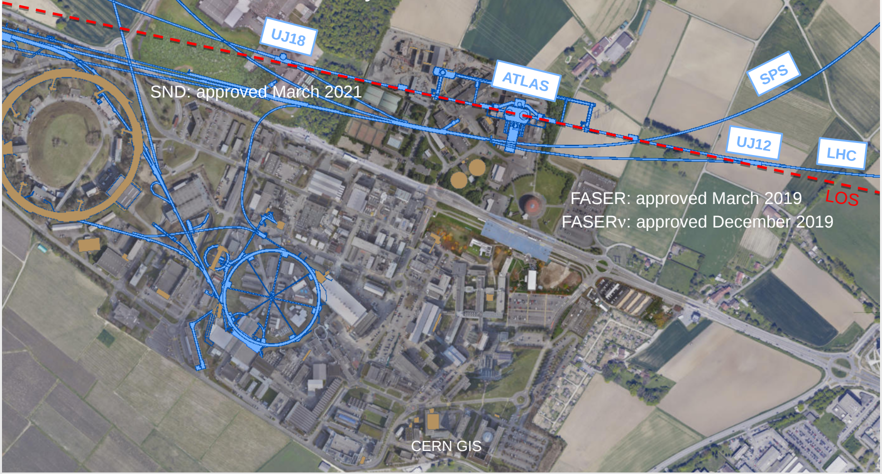
* Various projects to exploit beams of particles produced in the interactions points at the LHC, propagating in the direction tangent to the accelerator arc.

* Let these beams propagating for some distance, until they interact with the material of one or more detectors.

* Pilot experiments, on the tangent to the LHC beam line, at $\sim$ 480 m from ATLAS IP:
  - FASER, Faserν will take data during Run 3.
  - SND@LHC was approved last spring and is also supposed to take data during Run 3.

FAR FORWARD LHC EXPERIMENTS

The existing caverns UJ12 and UJ18 and adjacent tunnels are good locations for experiments along the LOS: 480 m from ATLAS and shielded from the ATLAS IP by ~100 m of rock.



Particle Fluxes at far-forward LHC experiments

$*$ Not all kinds of particles produced in the forward region of the LHC IP can be seen at the location of the experiments: LHC optical elements and rock are on the way.

$*$ Among the particles produced at the IP or nearby, forward ν, and BSM LLPs will reach the detectors.

$*$ ν forward fluxes: intense and very energetic, with $\mathcal{O}$(TeV) particles (peak in the energy spectrum much larger than for fluxes seen in other accelerator neutrino experiments, like e.g. DUNE).
Unique energetic regime $\Rightarrow$ Unique Measurements $\Rightarrow$ Interesting SM physics program.

$*$ BSM LLPs: searches in the low mass / large $c\tau^0$ domain, complementary to searches at ATLAS/CMS/LHCb for which LLPs decaying beyond the spatial limits of the detector infrastructure are “missing energy”.

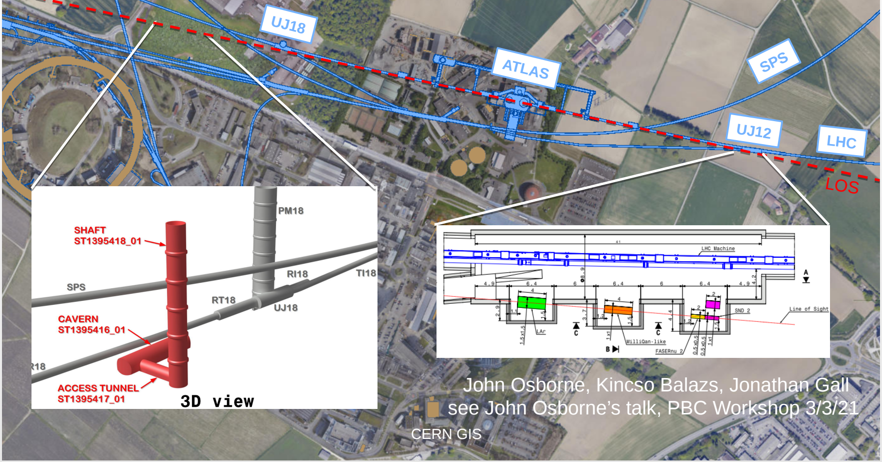
$*$ Present far-forward experiments limitations: space for positioning bigger detectors and increase sensitivity for SM and BSM searches is missing!

FPF LOCATION

Possibilities under active investigation:

(1) enlarge existing cavern UJ12 with alcoves for each experiment

(2) create a new shaft and cavern ~612 m from ATLAS past UJ18

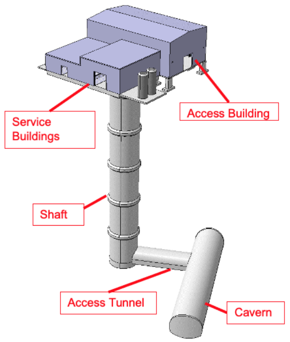


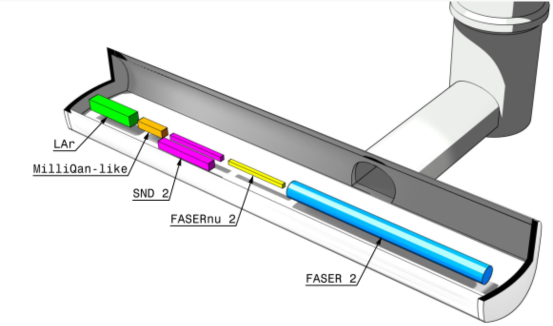
John Osborne, Kincso Balazs, Jonathan Gall

see John Osborne's talk, PBC Workshop 3/3/21

The Forward Physics Facility @ HL-LHC

A new large infrastructure, capable of simultaneously hosting a suite of experiments dealing with forward ν and BSM particles.





- Access possible during LHC operation
- Easier access than in LHC side caverns.
- It might be designed around the need of the experiments.

The Forward Physics Facility @ HL-LHC

A new large infrastructure, capable of simultaneously hosting a suite of experiments dealing with forward ν and BSM particles.

Questions currently under study:
- how far from the IP ?
- size and lenght ?
- at which angle positioning the various detectors ? ($6 \lesssim \eta \lesssim 10$)
- which detection technology and materials ?
- how to control the backgrounds ?

$\Rightarrow$ The answers partly depend on the physics one wants to explore, partly on the morphology of the experimental environment.

E.g. ν interactions are signals for SM searches, whereas act as a background for BSM searches!

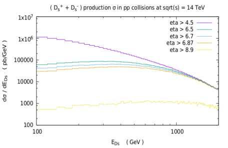
Experience built on top of experiments active during Run-3 will help!

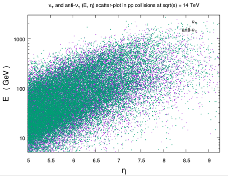
QCD opportunities with forward neutrinos during the HL-LHC phase

Maria V. Garzelli – University of Hamburg – II Institute for Theoretical Physics, `maria.vittoria.garzelli@desy.de`

New facility: Forward Physics Facility @ CERN capable of hosting a suite of experiments exploiting forward neutrinos produced at one of the LHC interaction points and propagating for several hundred meters in the direction tangent to the accelerator arc

New pilot experiments:
Faser2, Faser-ν, SND@LHC, MilliQan





Physics Opportunities:
* Proton Parton Distribution Functions
* Nuclear Parton Distribution Functions
* NP QCD and Tuning of Monte Carlo event generators
* Forward charged pions and kaons
* Forward heavy-flavoured hadrons

Forward heavy-flavour
* NP effects in heavy-flavour production
* Interplay with perturbative effects
* Universality of FF
* Intrinsic heavy-flavour and higher-twist

Open questions:
* how to disentangle SM and BSM effects ?
* how to measure forward lepton fluxes and disentangle them from cross-sections ?

See also W. Bai, M. Diwan, M.V. Garzelli, Y.-S. Jeong, M.H. Reno, *"Far-forward neutrinos at the LHC"*, hep-ph/2002.03012, JHEP **2006** (2020) 032.

Proton Parton Distribution Functions
* Low x **(**x < 10^{-6}) gluon at Q^2 > 1 GeV^2 not probed by other experiments so far!

Nuclear Parton Distribution Functions
* Measurements of CC and NC ν - *A and* $\bar{\nu}$ - *A* DIS cross-sections using various targets
* *u* and *d* quark flavour separation
* DIsentangling strange sea asymmetries
* Complementary to EIC *e-A* scattering studies

NP QCD and Tuning of MC event generators
* New data for testing the robustness of phenomenological models describing NP physics in MC (e.g. NP MPI, beam remnant effects, hadronization, branching fractions) and tuning their parameters.

Forward charged pions and kaons
* NP effects in light-flavour production
* Cosmic Ray EAS applications

Work supported by BMBF contract O5H18GUCC1

For further info:
* 2nd Forward Physics Facility Meeting online – 27 – 28 May 2021
`https://indico.cern.ch/event/1022352` !Registration open!
* Forward Physics Facility Kick-off meeting – 9 – 10 Nov 2020

presented at the APS Meeting "Quarks to Cosmos", April 2021

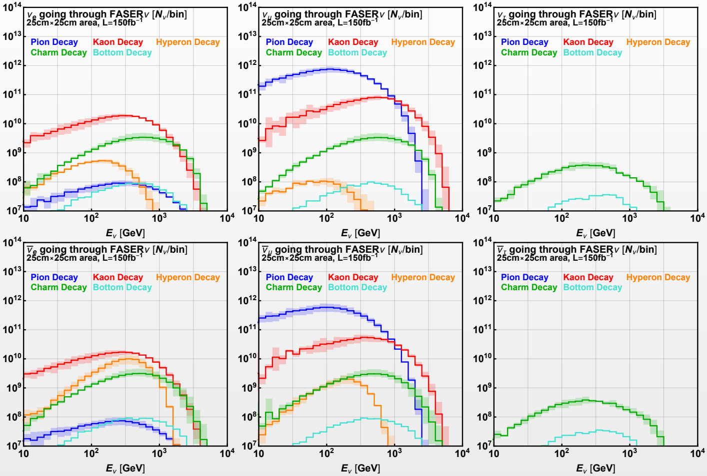
How to disentangle particle fluxes from particle cross-sections ?

* The detectors will measure observables from the **convolution** of **fluxes** (production + propagation) and **interaction** σ with target.

* Capability to distinguish might be more important for SM precision constraints than for BSM searches...

* For example, SM objectives of the FPF experiments may include:
  - Constraining forward particle production in *pp* collisions (of interest for better modelling soft physics and tuning the related parameters in MC event generators): it works well under the assumption: *"we precisely know neutrino cross-sections"*.
  - constraining PDFs/nPDFs through neutrino DIS with target in detector (of interest for ALICE/ATLAS/CMS/LHCb SM and BSM programs at HL-LHC): it works under the assumption: *"we precisely know neutrino fluxes"*.

Examples of MC predictions of forward ($\nu+\bar{\nu}$) fluxes



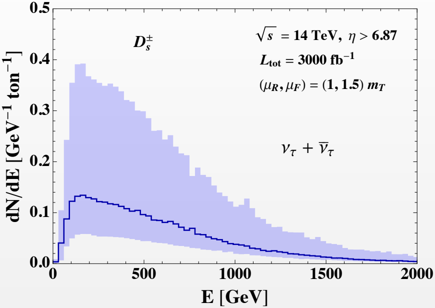
from Faserν collab. [arXiv:1908.02310]

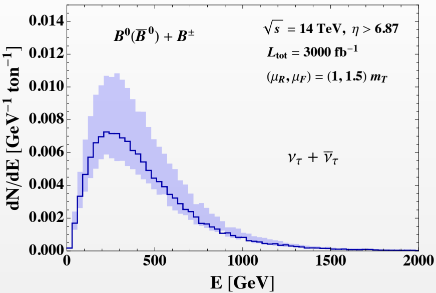
Estimated number of ν impinging on the transverse area of the FASERν detector.

Uncertainty band: envelope of the central predictions of different MC generators.

How to estimate a more reliable uncertainty band ?

Energy distribution of CC $(\nu_\tau + \bar{\nu}_\tau)$ events





, *from W. Bai et al. [arXiv:2002.03012]*

- ∗ Huge uncertainty band from state-of-the-art QCD calculations.
- ∗ Missing higher-order pQCD contributions are probably large.
- ∗ In case of bottom production, uncertainty is smaller (+60%, -20%) than for charm (+300%, -60%) in relation to the fact that $m_b > m_c$ $\Rightarrow \alpha_S(\mu_R = m_b) < \alpha_S(\mu_R = m_c)$.
- ∗ Additional uncertainties due to focus in forward region.

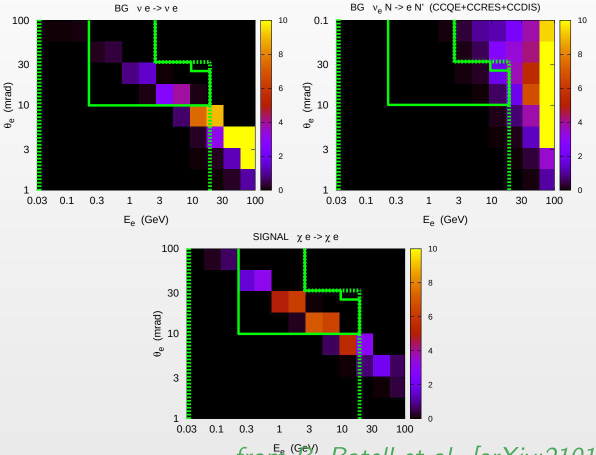
Light DM searches at the FPF: a simple testable model

* Hypothesis: DM particles χ in a hidden sector coupled to the SM through a dark photon A' with $m_\chi < m_{A'} << m_{EW}$.
  Parameter space $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$
* A' produced either by $pp \to ppA'$ (proton bremsstrahlung) or through $pp \to \pi^0, \eta, ... + X \to A'\gamma + X$
* followed by $A' \to \chi\,\chi$ decay.
* Signal at FPF detectors (LAr TPC or emulsion detector): $\chi e^- \to \chi e^-$
* Backgrounds at FPF detectors:
  - CC $\nu_e e^- \to \nu_e e^-$, $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$
  - NC $\nu_i e^- \to \nu_i e^-$, $\bar{\nu}_i e^- \to \bar{\nu}_i e^-$
  - CC and NC νN interactions.
  - $\mu \to \mu\gamma \to \mu e^+ e^-$

from B. Batell et al. [arXiv:2101.10338]

Light DM searches: signal/background discrimination

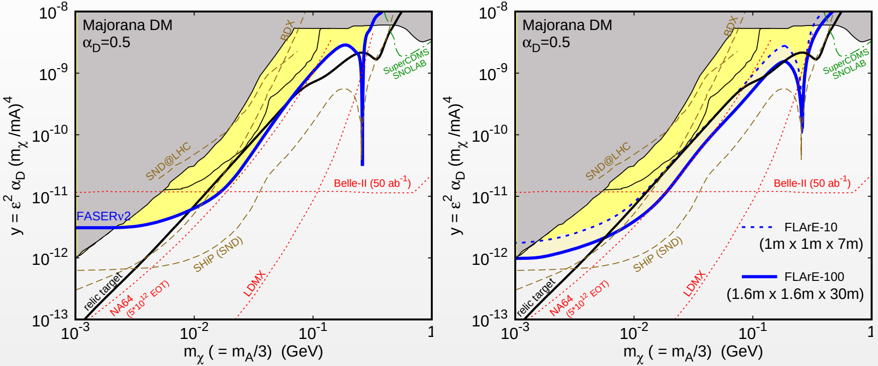
- ν induced background can be eliminated because signal and background occupy different regions of the $(E_{e,rec}, \theta_{e,rec})$ plane.



from B. Batell et al. [arXiv:2101.10338]

- μ induced background can strongly be reduced by sweeper magnets or active μ vetos.

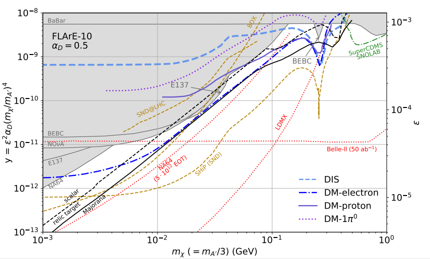
Exclusion bounds for light Majorana DM search

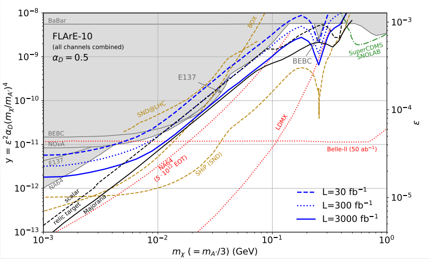


from B. Batell et al. [arXiv:2101.10338]

- ∗ LArTPC 10-ton detector increases exclusion bounds w.r.t. emulsion (Faserν2).
- ∗ Sensitivity to the region where χ has the correct thermal relic density.
- ∗ Complementary info w.r.t. missing energy experiments, that do not see χ scattering.

Exclusion bounds for light Majorana DM search





from B. Batell et al. [arXiv:2107.00666]

∗ Extension of the previously considered exclusion bounds in the large m_χ region, thanks to the additional identification and analysis of $\chi + A$ collisions.

PBC BSM Benchmark Cases

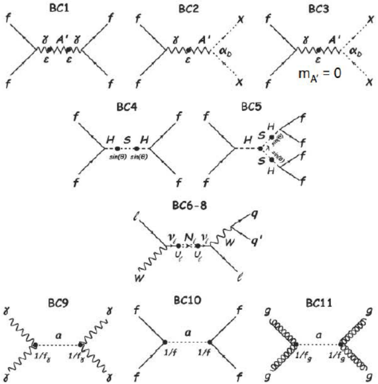
The BSM WG selected a set of theoretically and phenomenologically motivated target areas used as benchmarks models to explore the physics reach of the received proposals and put them into the worldwide landscape.

Dark Photons, Dark Matter & millicharged particles

Dark Scalars

Heavy Neutral Leptons

Axion-Like Particles



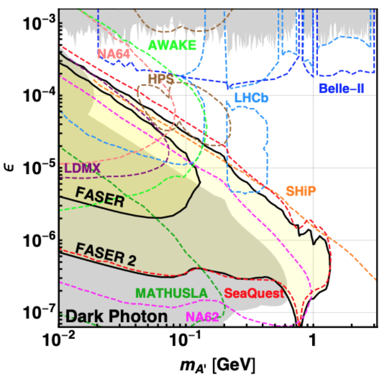
from M. Lamont, PBC presentation @ MITP, november 2020

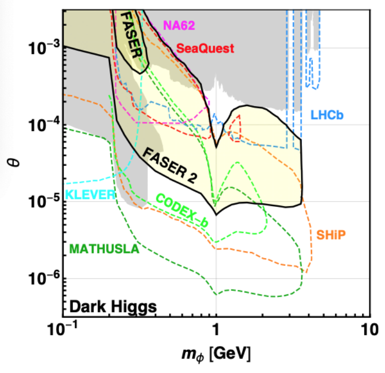
- 11 models for light, weakly-interacting particles (LLPs, FIPs)
- BC1, BC4-11 covered by FASER, FASER2; BC2 and BC3: FPF.

BCs 1, 4-11: LLPs at FASER and FASER2

* Run-3 integrated luminosity is enough for FASER to discover new physics for some of the Benchmark Cases.

* FPF will provide space to upgrade FASER (R = 10 cm, L = 1.5 m) to FASER2 (R = 1.0 m, L = 5 m), either greatly enhancing sensitivity (e.g. for A' - visible mode) or by providing new prospects (e.g. for S), complementary to other experiments.

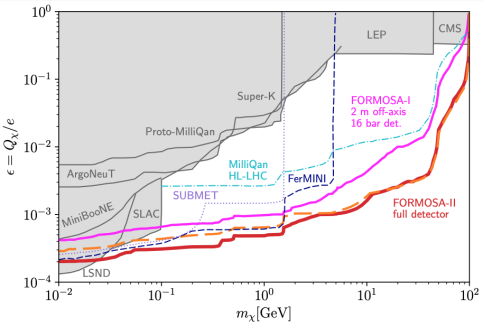




from FASER Collaboration, [arXiv:1811.12522]

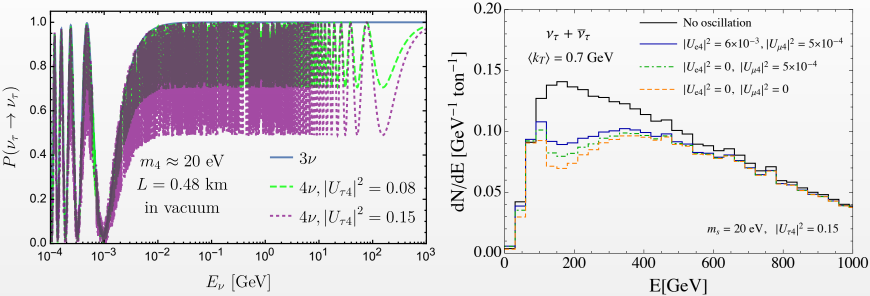
BC3: Milli-charged particles

- ∗ This is currently the target of the MilliQan experiment, near the CMS IP.
- ∗ MilliQan Demonstrator already probes an otherwise uncovered region. Full MilliQan planned to run in the same location at HL-LHC. However, sensitivity can be improved significantly at the FPF (FORMOSA)



from MilliQan/FORMOSA

Other physics opportunities/complications for HNL searches: ν oscillations



from W. Bai et al. [arXiv:2002.03012]

∗ For the baseline and the neutrino energy range of the Forward Physics Facility, oscillations between active neutrinos in the SM are suppressed.

∗ Oscillation of ν_τ in heavy sterile neutrinos ($m_4 \sim 20$ eV) can be probed, by looking at deficit or excess in the observed event spectrum.

Conclusions

$*$ Far-forward experiments offer the opportunity for a reach BSM (and SM) program, exploiting the production of LLPs at the LHC IPs, their decay in DM, and DM + e and DM + A scatterings in the detectors.

$*$ FASER/FASERν/SND@LHC already able to provide competitive limits in exclusion plots during Run 3.

$*$ A Forward Physics Facility, ready for the HL-LHC phase, can offer a unique opportunity to expand the program of LLP/FIP searches in the "forward" direction.

$*$ Civil Engineering studies and cost estimate under way.

$*$ Crucial questions, considering the BSM LLP production mechanisms:
- how well do we control forward SM particle production ?
- how well do we control SM ν + e and ν + A backgrounds ?

For further info and contributing to answer:
3rd Forward Physics Facility meeting - 25-26 October by zoom
https://indico.cern.ch/event/1076733