NA64 Status Report

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SPSC Open Session, CERN, June 20–21, 2017

Outline

- NA64 overview
- Status and results from the 2016 run
  - A´-> invisible decay, dimuon events
  - light X-boson from the ^{8}Be excess
- Conclusion, plans

NA64, July 2016

NA64

NA64 is designed to search for new, in particular Dark Sector physics in missing energy events. Broad research program with e^-, μ, π, K, and p beams at SPC (PBC'16/17)

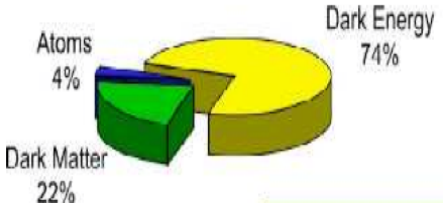
- e^- program approved in March 2016
- 2016: test run in July (2w), physics run October(4w)
- 2017: 5w run in autumn

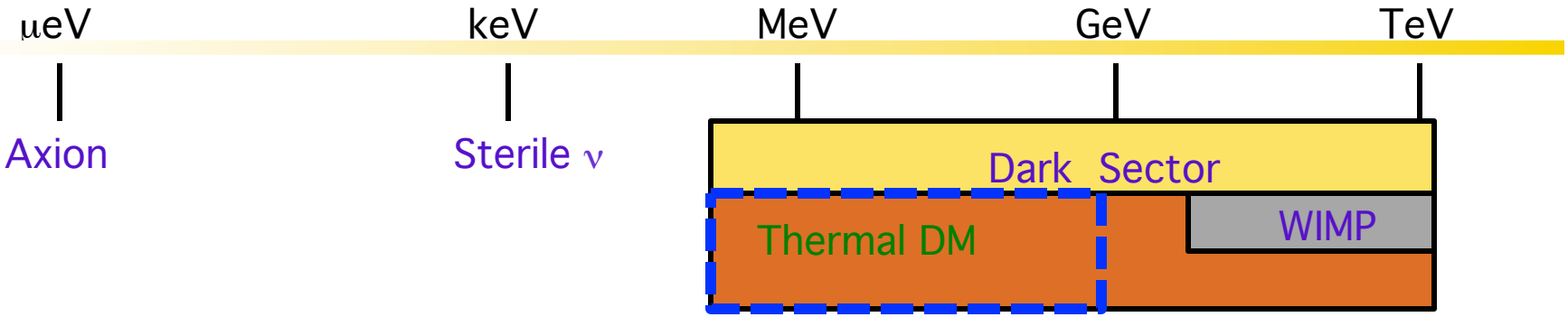
- Main goals for 2016:
- Search for invisible decay of the A´, in particular in the parameter space which could explain the muon g-2 anomaly
- Feasibility of the search for the light X-boson from the ^{8}Be excess

- ~ 40 participants from Chile, Germany, Greece, Russia, Switzerland and CERN

Sub-GeV Thermal DM from Dark Sector

What makes up most of the Universe's mass?





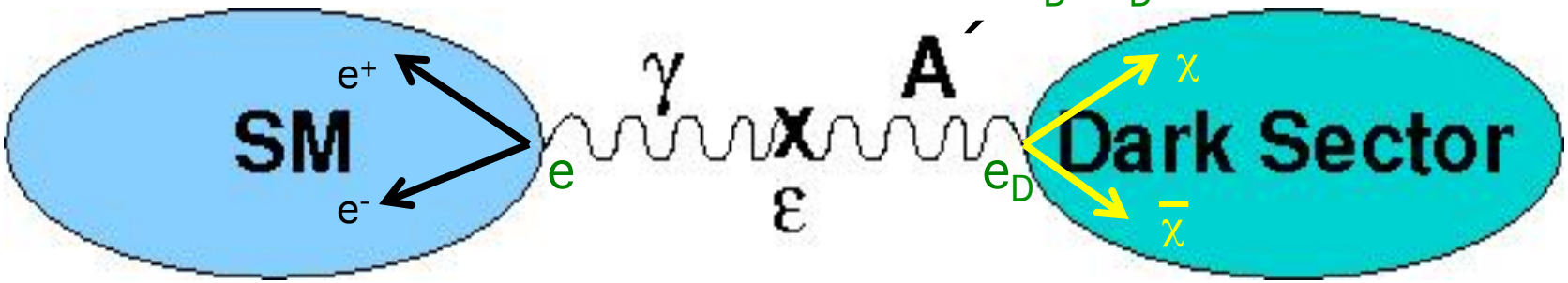
Various models motivate sub-GeV Thermal DM from Dark Sector:

- If DM is in sub-GeV range it must be SM neutral
- Thermal freeze-out motivate new interaction to mediate DM←→SM annihilation. New force in additional to gravity!
- The TDM candidates χ : scalars, Majorana, Pseudo-Dirac fermions.

Predictions of annihilation rate give important target for their (couplings;masses) parameter space which can be probed at SPS !

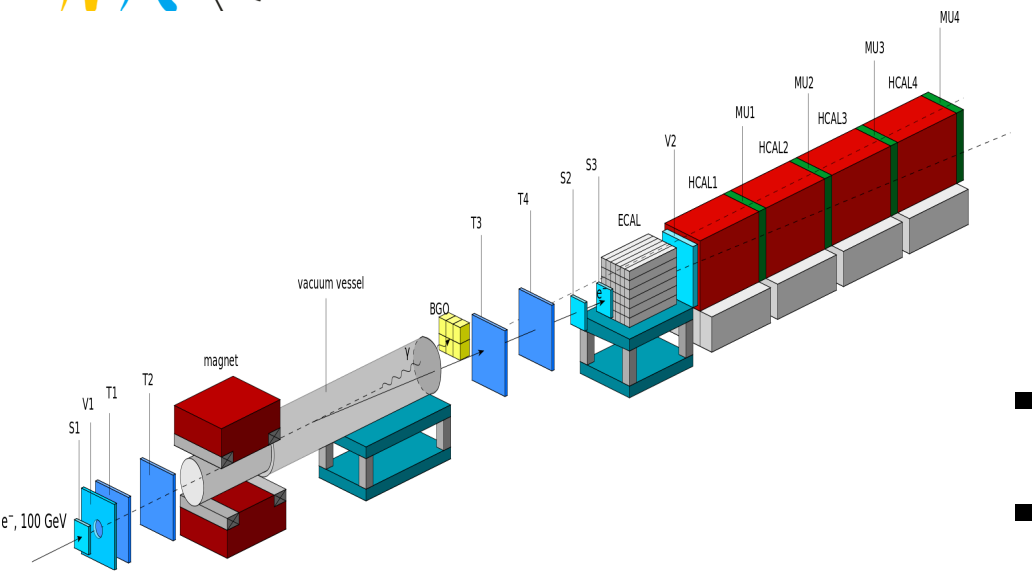
Vector portal to Dark Sector

Okun, Holdom' 86 .. $\alpha_D = e_D^2/4\pi$

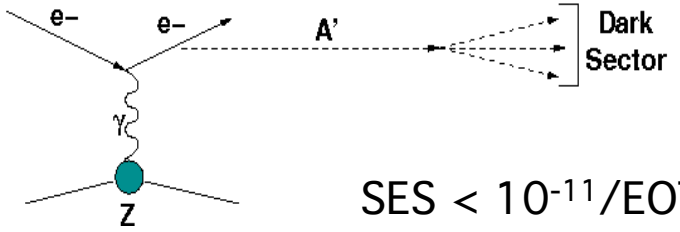


- new massive boson A´(dark photon) which has kinetic mixing with ordinary photon: $\Delta L = \varepsilon/2\ F^{\mu\nu} A'_{\mu\nu}$
- GUT prediction for the size of the γ-A´ mixing strength ($\varepsilon << 1$): 1-loop: $\varepsilon \sim 10^{-4} - 10^{-2}$; 2 loops: $\varepsilon \sim 10^{-5} - 10^{-3}$, $m_{A'} \sim \varepsilon^{1/2} M_Z$
- Production: A´- bremsstrahlung $e^- Z \rightarrow e^- Z A'$, $\sigma \sim Z^2\varepsilon^2/m_{A'}^2$
- Decays:
  - Visible: $A' \rightarrow e^+e^-, \mu^+\mu^-$, hadrons,..
  - Invisible: $A' \rightarrow \chi\chi$ if $m_{A'} > 2m\chi$, $\alpha_{DM} >> \varepsilon$
    Can explain $(g-2)_\mu$, astrophys. observations
- Cross section for χ–DM annihilation: $\sigma v \sim \overbrace{[\alpha_{DM}\, \varepsilon^2 (m_\chi/m_{A'})^4]}^{y}\ \alpha/m_\chi^2$

Search for A´->invisible decays at CERN SPS



S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)



SES < 10^{-11}/EOT

Signature:

- in: 100 GeV e- track
- out: $E_{ECAL} < E_0$ shower in ECAL
- no energy in Veto and HCAL

Main components :

- clean 100 GeV e- beam
- e- tagging system: tracker+SRD
- 4 π fully hermetic ECAL+ HCAL

Background:

- μ, π, K decays in flight
- Tail < 50 GeV in the e- beam
- Energy leak from ECAL+HCAL

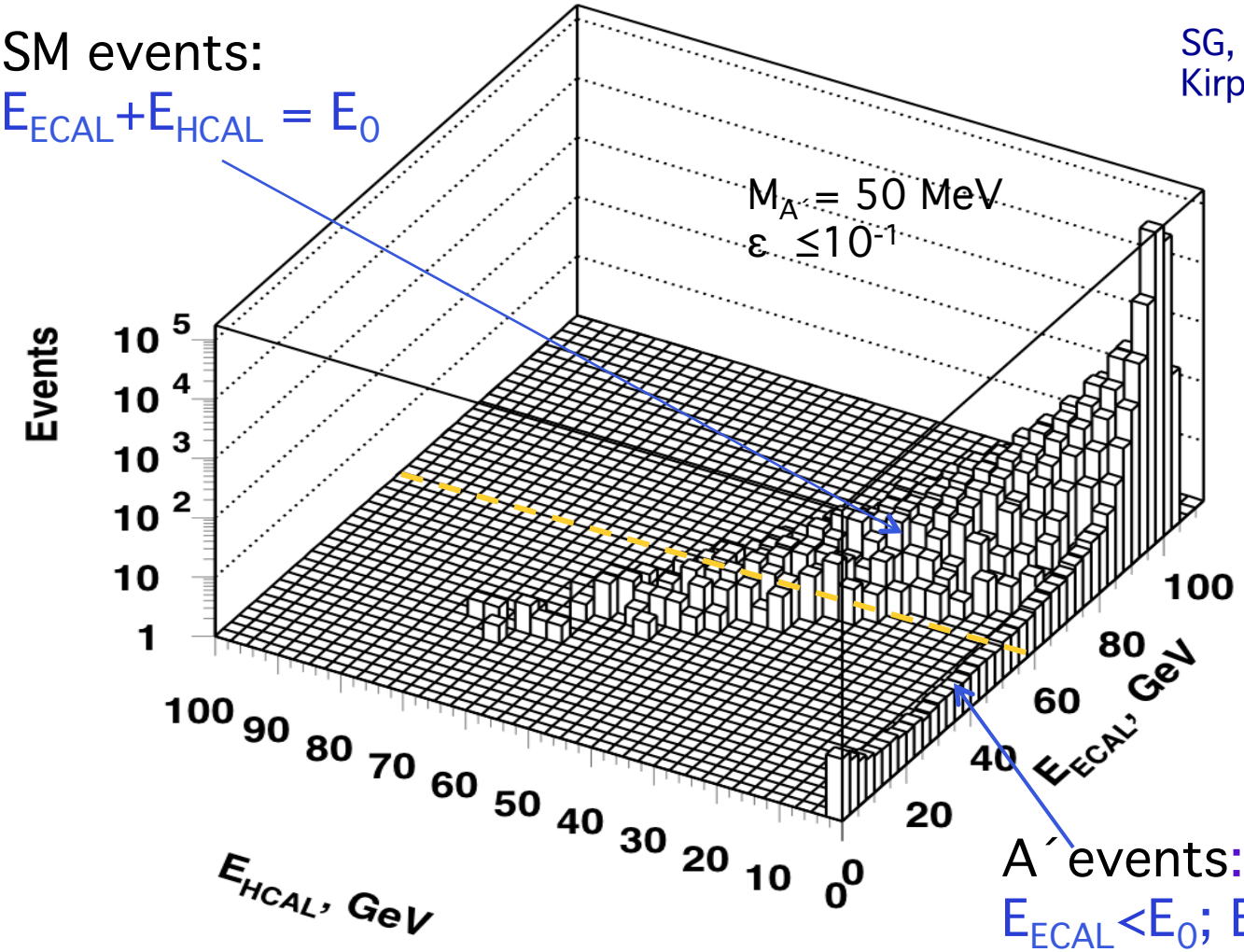
Signature for eZ->eZA´; A´-> invisible

GEANT4+code for A´emission in the process of e-m shower development σ(e^-Z->e^-ZA´) from Bjorken et al.`09

SM events:

$E_{ECAL}+E_{HCAL} = E_0$

SG, Kirsanov, Krasnikov, Kirpichnikov PRD(2016)



A´events:

$E_{ECAL}<E_0$; $E_{HCAL}=0$

Summary of the 2016 run

- First run period, 29.06–13.07, 2 w

  $Tr_{A'} = \Pi s_i \times V1 \times PS(E>E_{PS}) \times ECAL(E<E_{ECAL})$

  - 0.88×10^9 eot, 0.3×10^6 e^-/spill, BGO run
  - 1.87×10^9 eot, 1.3×10^6 e^-/spill, PbSc run
  - Total number ~ 2.75×10^9 eot

- Second run period, 12.10–09.11, 4 w

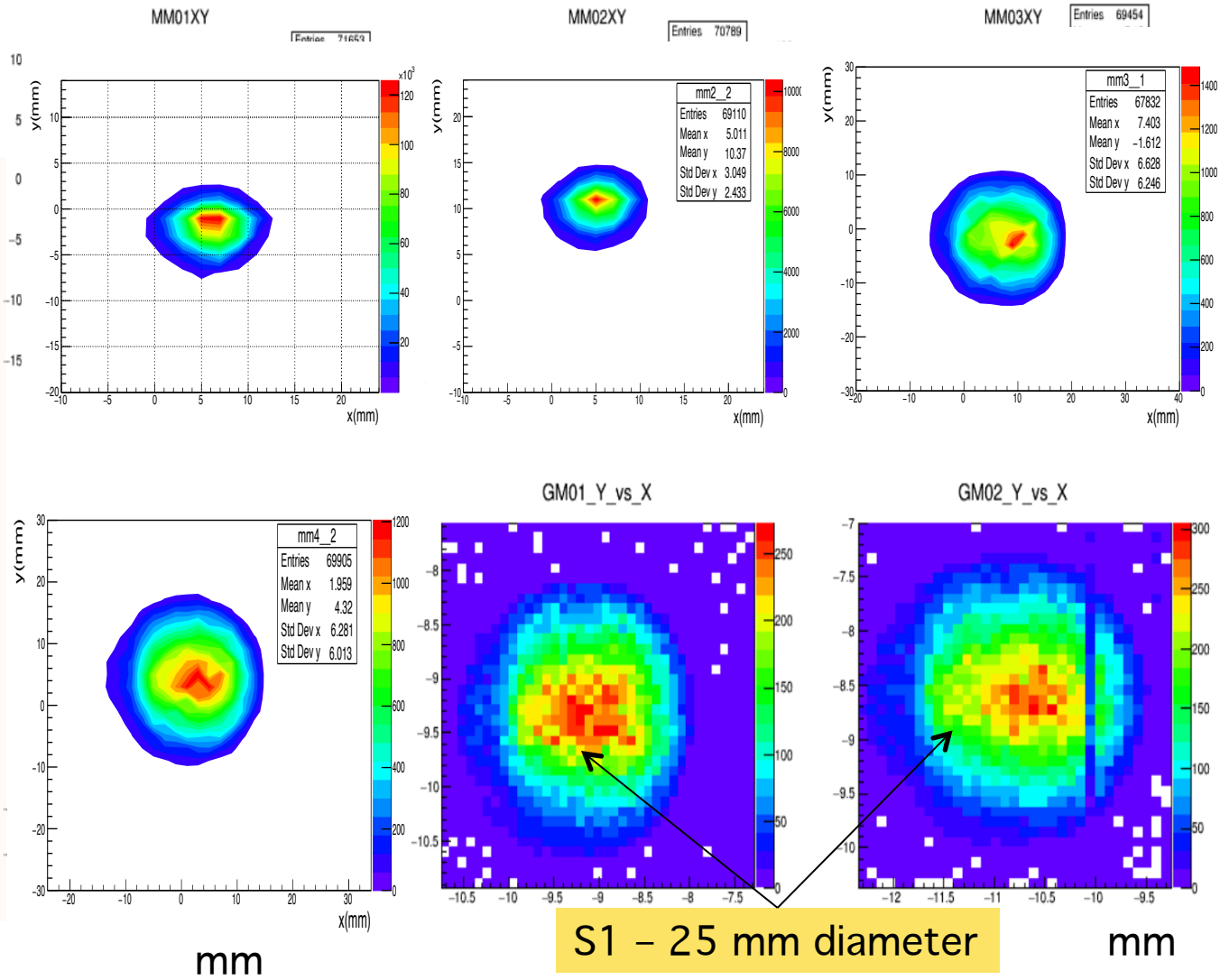
  - 23 October → start data taking;
  - Total accumulated electrons ~2×10^{10}, S_0 rate $1.5 \div 2.2 \times 10^6$;
  - Total accumulated electrons ~1.5×10^{10}, S_0 rate $2.4 \div 3.2 \times 10^6$;
  - Total accumulated electrons ~1.0×10^{10}, S_0 rate $4.6 \div 5.0 \times 10^6$; ~0.6 day
  - Total number ~ 4.5×10^{10} eot

  05.11–09.11 ^{8}Be anomaly test

  - Test visible mode, second tungsten electromagnetic calorimeters, additional veto counters were installed downstream of vacuum pipe;
  - Data taking, ~ 5×10^9 eot, $2.8 \div 3.0 \times 10^6$ e-/spill (2 days)

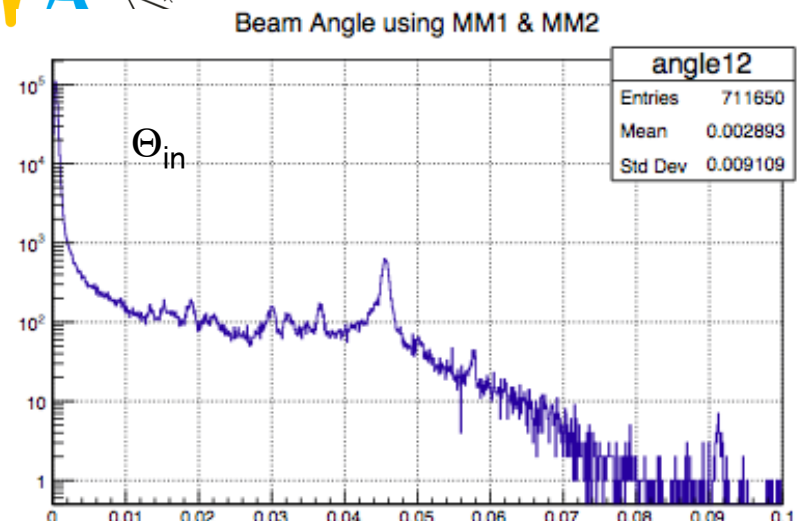
H4 beam line, 100 GeV e-

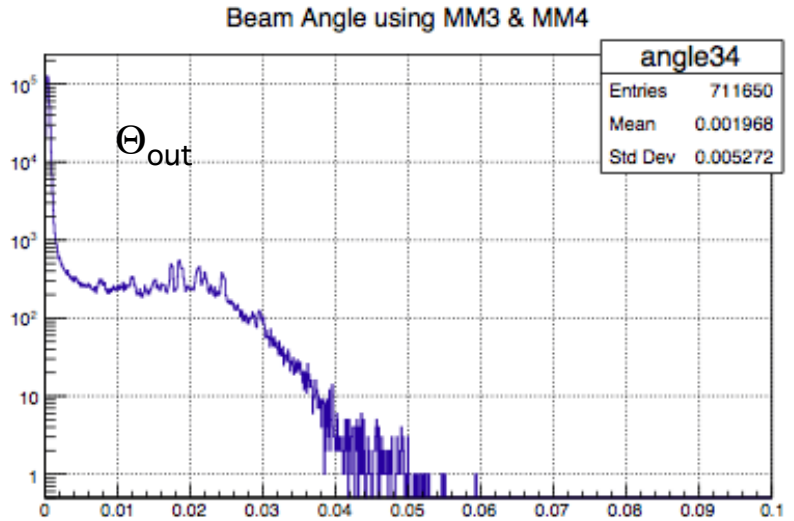
Beam parameters:
Intensity – up to 5x10⁶
Hallo - less than 5%
Beam size upstream of MBPL: s_x *= 3.0mm;* s_y *= 2.5mm; Beam size downstream of MBPL:* s_x *= 5.5mm;* s_y *= 5.5mm;*
Hadron contamination in electron beam ~ 1%;
Muon contamination in electron beam ~ 0.2%;

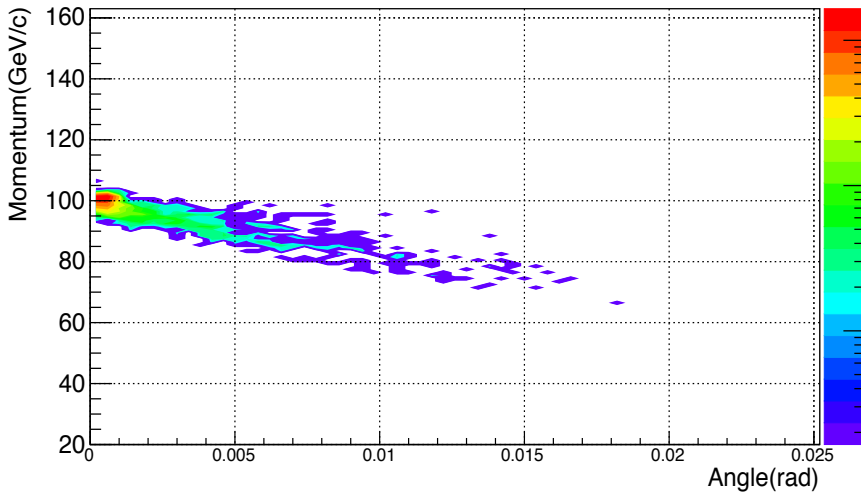


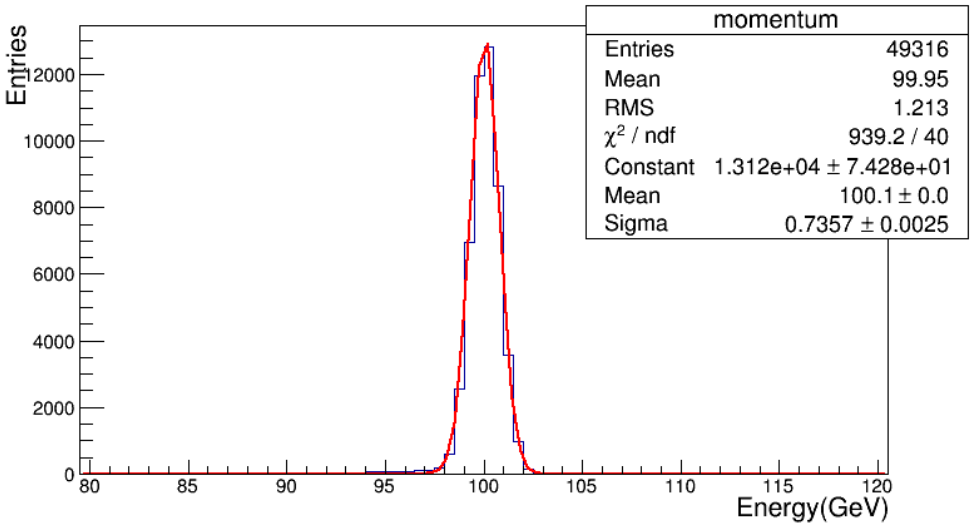
Very nice electron beam

H4 beam line, 100 GeV e-



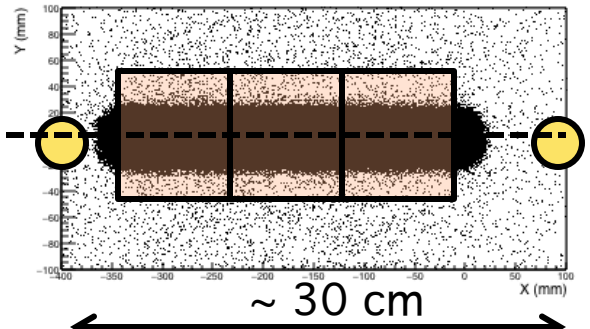




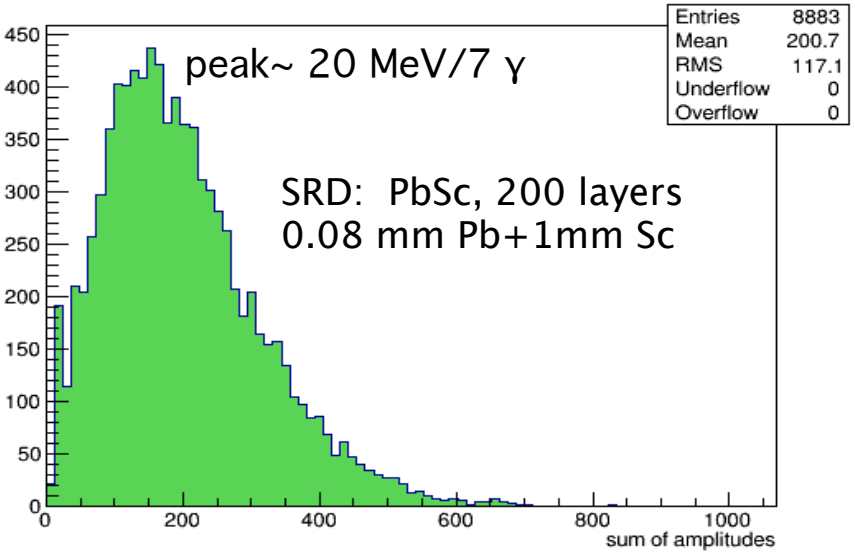


Typical pre-selection cuts used: Θ_{in} Θ_{out} < 0.005–0.01

Electron tagging with synchrotron radiation (SR)



Deflected
Beam position

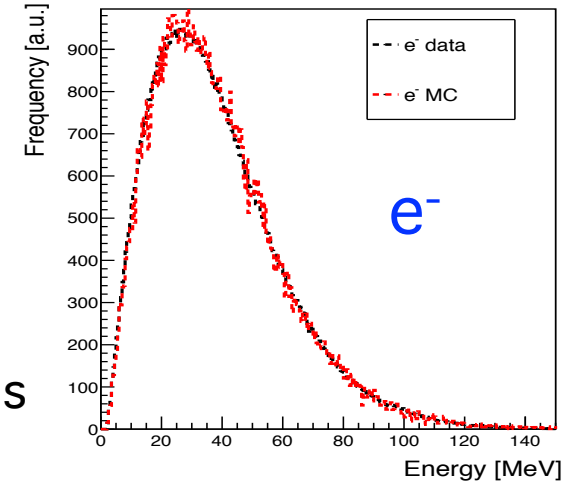


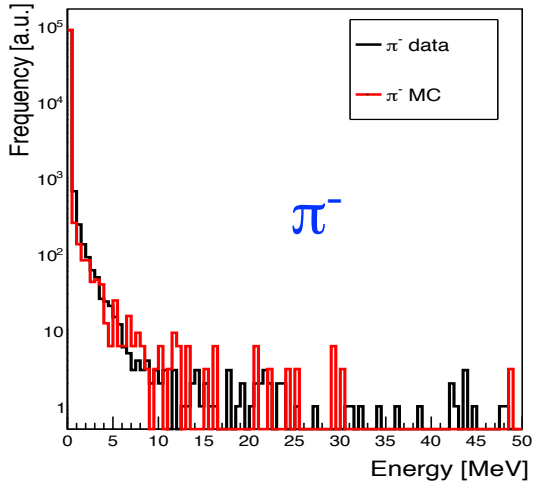
Amount of detected SR energy, γ's:

$\Delta E \sim E_0^3/m^4$, $\langle E\gamma \rangle \sim 2$ MeV, $\langle N\gamma \rangle \sim 30$

July run: BGO SRD – good ΔE/E, afterglow.
Replaced with a fine segmentation
Pb-Sc SRD – fast, poor ΔE/E

October run: Pb-Sc with transv. segmentation. Tuning halo.



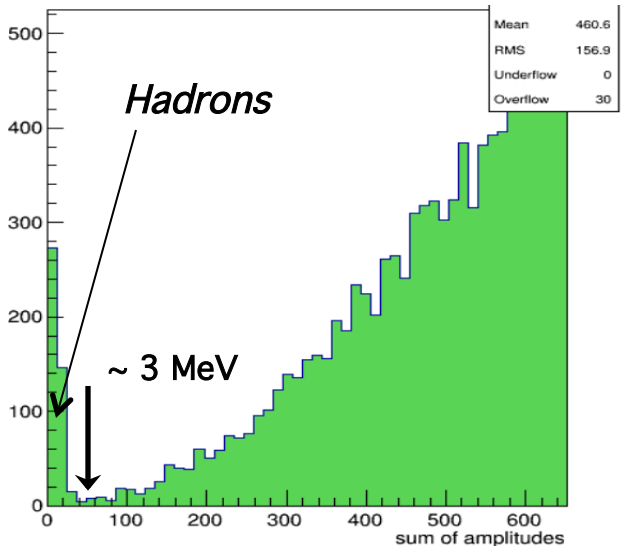


SRD selection cuts:

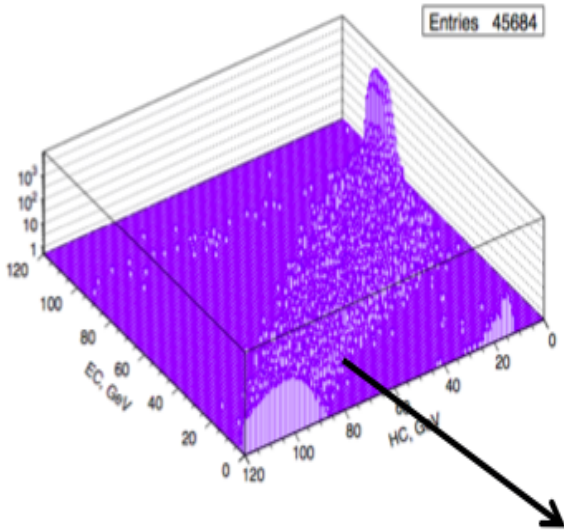
- $1 < SRD_i < 80$ MeV
- All SRD_i in time within ±2 ns
- Efficiency $\varepsilon_{SRD} > 0.95$

H4 e⁻ beam purity (to appear in NIM)

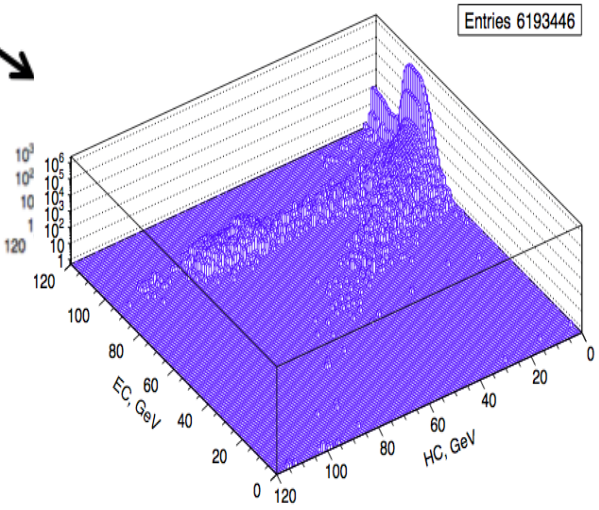
SRD sum (zoom)



Hadron rejection



SR tagging :
π rejection > 10^4



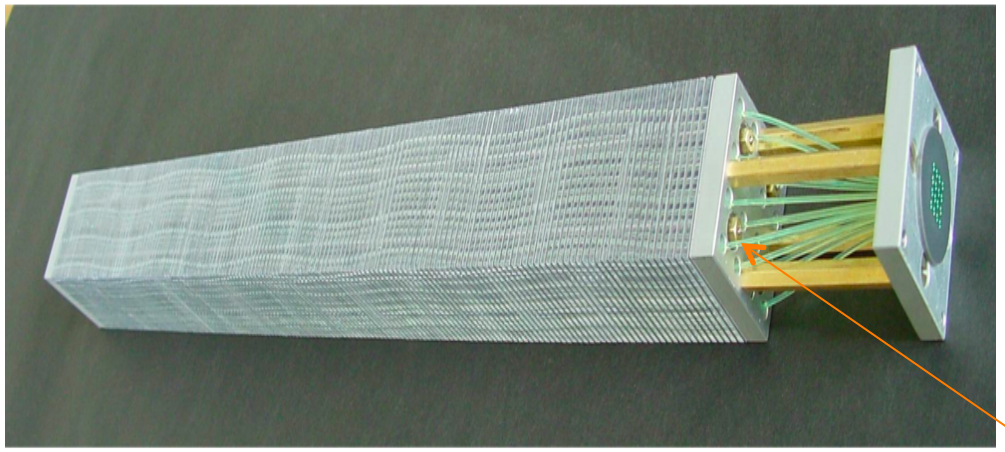
SRD selection cuts:

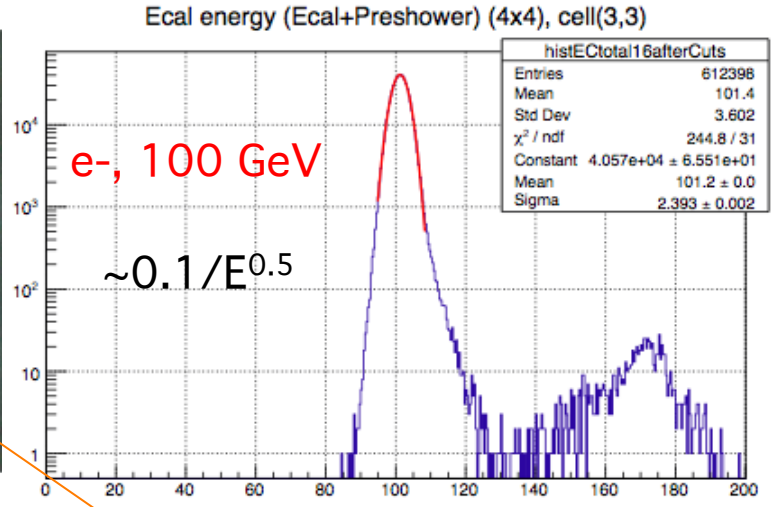
- $1 < SRD_i < 80$ MeV
- 3 SRD_i in time within ±1 ns
- $\Sigma\, SRD_i < \sim 120$ MeV
- additional factor ~5 from PS+ECAL
- $\varepsilon_{SRD} > 0.95$, $\pi/e < \sim 10^{-6}$

Hadronic background < 10^{-13} per EOT

Shashlik ECAL: hermeticity scan

ECAL cell

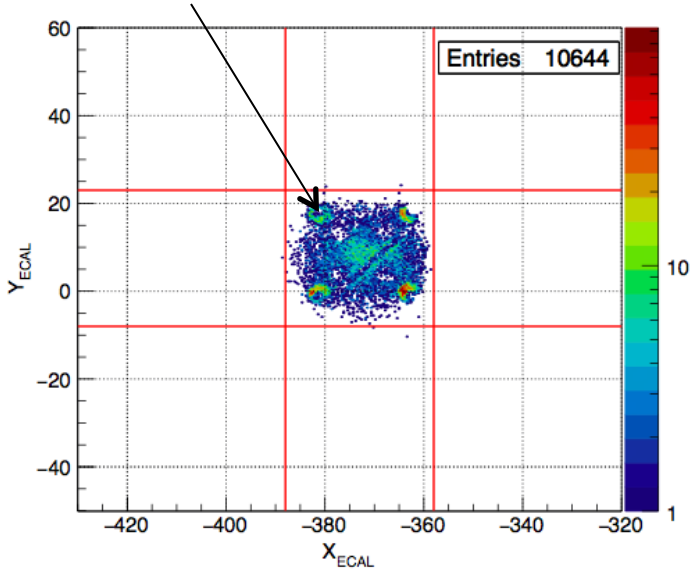




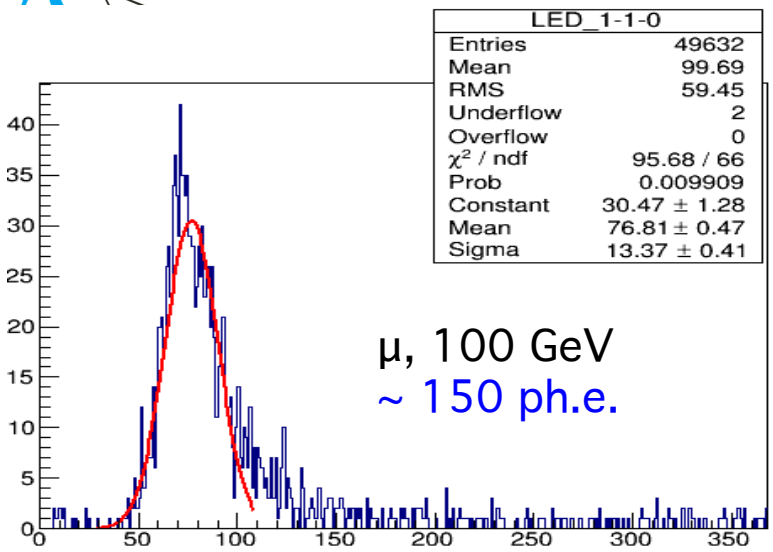
- WLS fibers go in a spiral to avoid E-leak
- Transverse X-Y scan showed no significant non-uniformity in vicinity of fibers $\delta E/E < 2\ \%$
- Variation of ECAL energy in vicinity of rods $\delta E/E < 10\ \%$

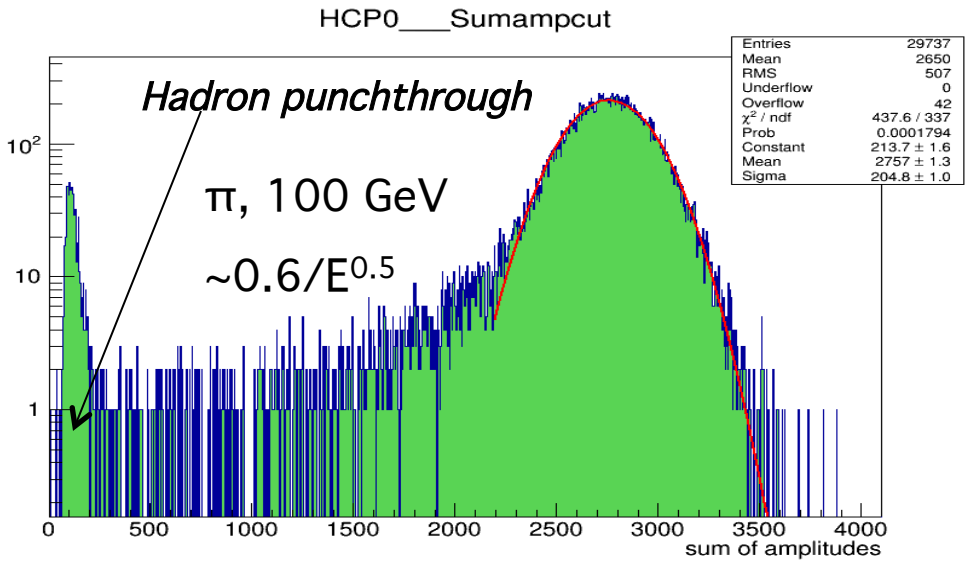
No potential source of background is found

e,γ punchthroughs



Fe-Sc HCAL hermeticity



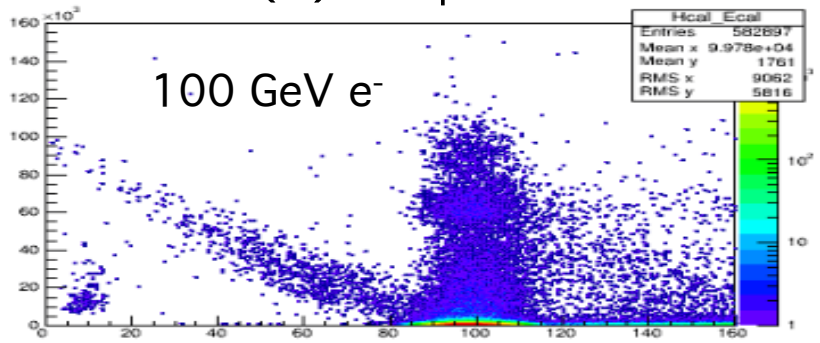


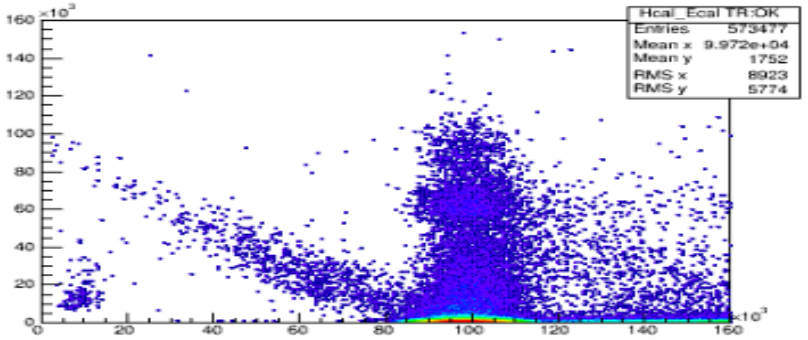
- Crucial number $\langle N_{ph.e.} \rangle$/MIP ~ 150–200 ph.e. (target~100 ph.e.)
- $\sigma/E \approx 0.56/E^{0.5} + 0.02$, negligible background from the leak to signal box
- HCAL module hermeticity. π–punchthrough level ~ 3×10^{-3}
  in agreement with MC. Neutrals are estimated from MC.
- Large transverse h-shower fluctuations (NOMAD)

No source of a significant background is identified

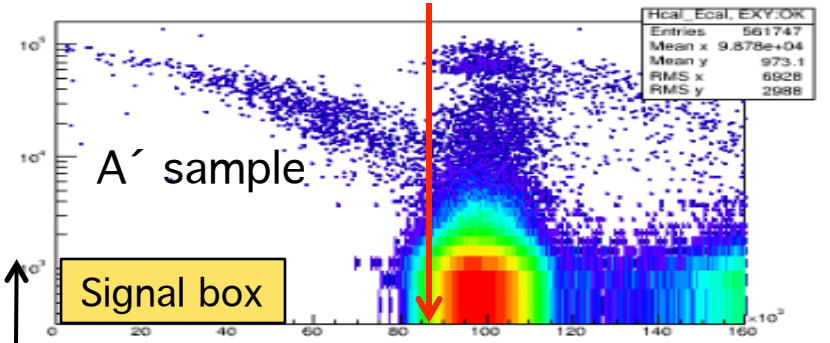
100 GeV e⁻ calibration and physical events

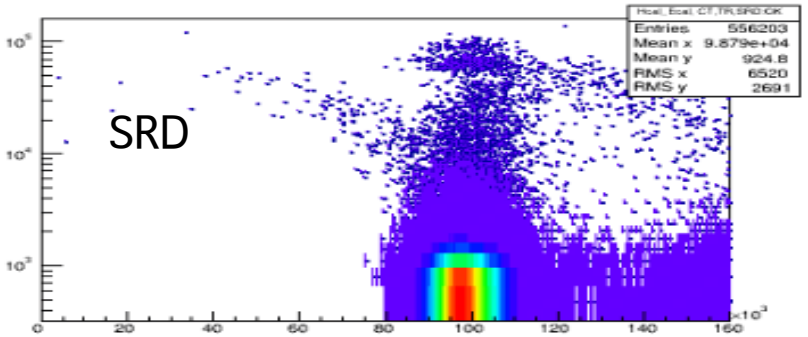
$Tr(e^-) = \Pi s_i \times V1$



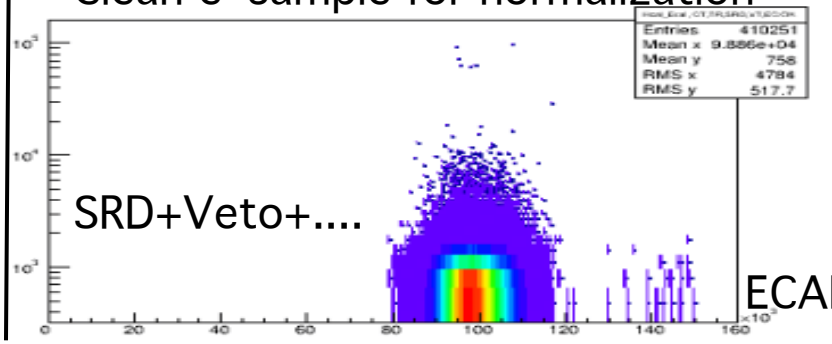


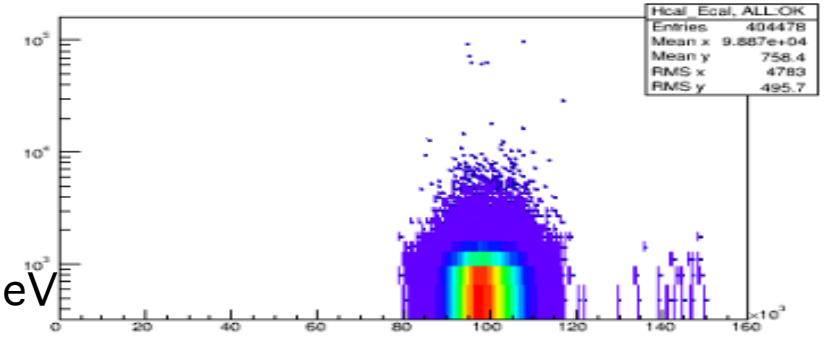
$Tr(A') = Tr_e \times PS(E>E_{PS}) \times ECAL(E<E_{EC})$; $Tr(A')/Tr(e^-) \sim 1:100$





Clean e⁻ sample for normalization





HCAL, GeV

ECAL, GeV

July run: A´ signal event selection

A´ selection criteria optimization:
– maximal A´ efficiency,
– minimal level of background

A´ selection efficiencies cross-checked with the data from e^- beams and MC.
The overall A´detection efficiency is $\varepsilon_{A'}$~0.54–0.62 depending on $m_{A'}$

Signal box

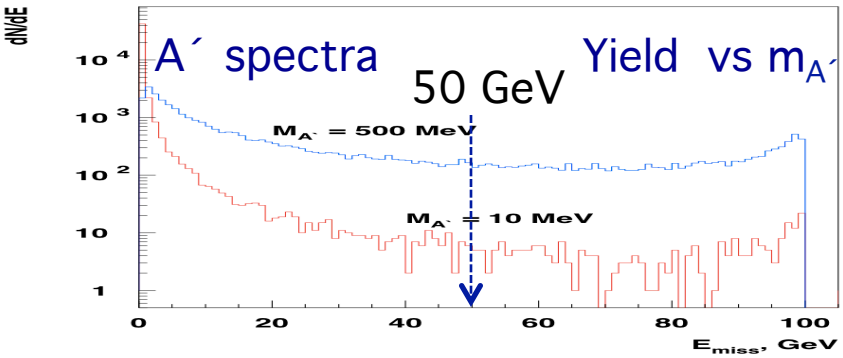
E_{EC} < 50 GeV, HCAL<1 GeV

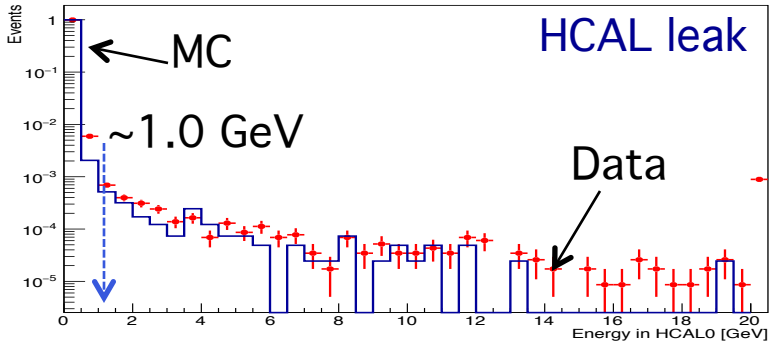
Summary of e^- and A´ efficiencies

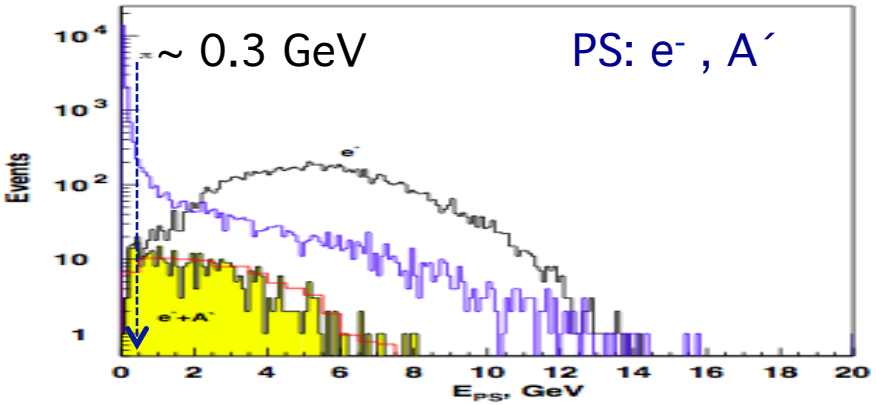
selection criteria	efficiency
incoming e- selection	
S_i – tracker hits in time	0.98
SRD_i in-time, SR range	0.98
no large Θ_{in} angle tracks	0.95
p momentum in range	0.80
A´ signal	
Yield ε_{EC}, ECAL < 50 GeV	$m_{A'}$ dependent
ε_{PS} , PS > 0.3 G	0.94
ε_{SH}, ECAL in time	
+ shower shape	0.96
ε_V ,Veto < MIP	0.97
ε_{HC}, HCAL<1 GeV	0.96

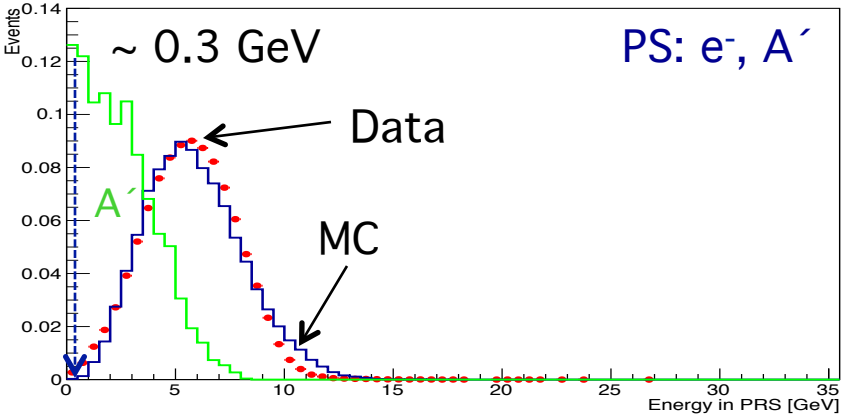
MC vs Data: A´ yield and selection cuts

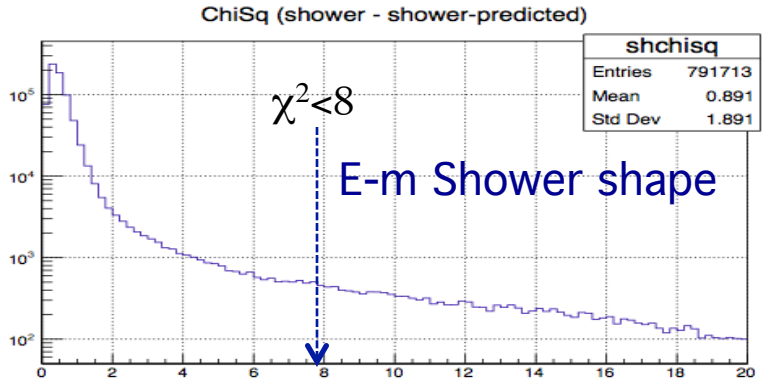
Geant4+WW approximation for σ(eZ->eZA´)

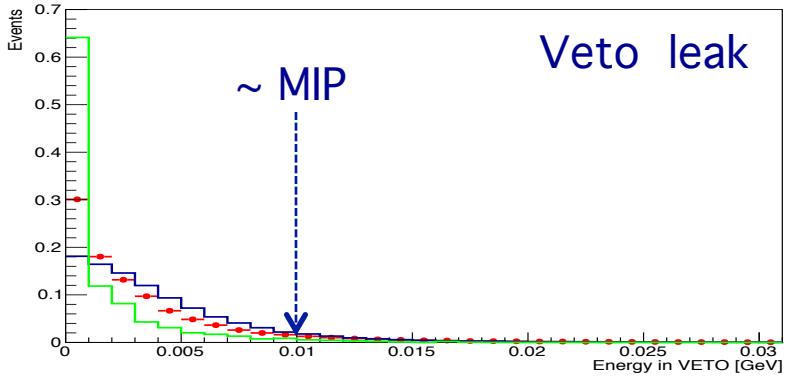












Results from July run, 2.75x10^9 EOT

~10^6 e-/spill

A´ signal box: E_{EC} < 50; E_{HC} < ~1 GeV

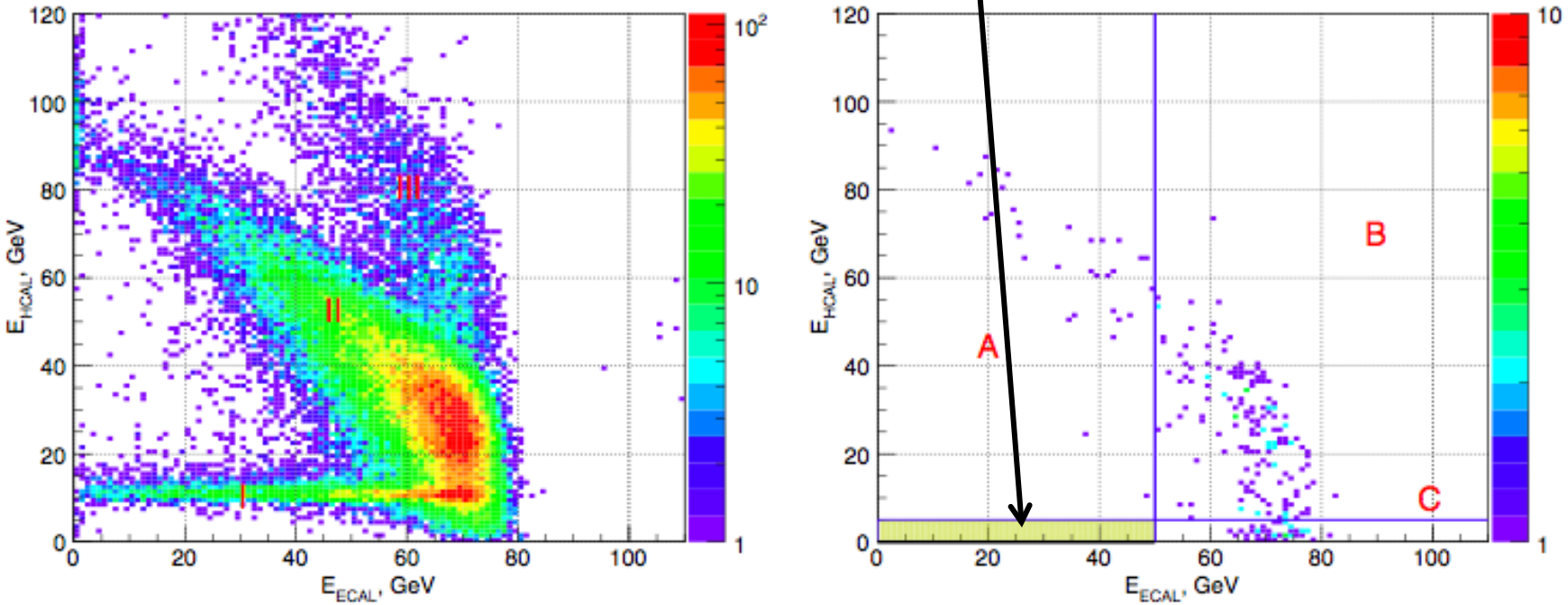
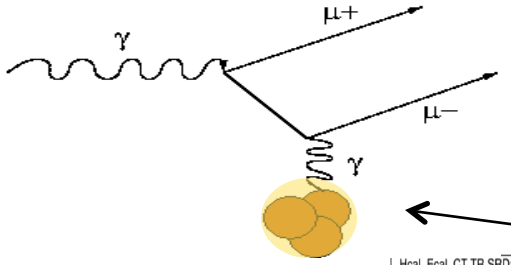
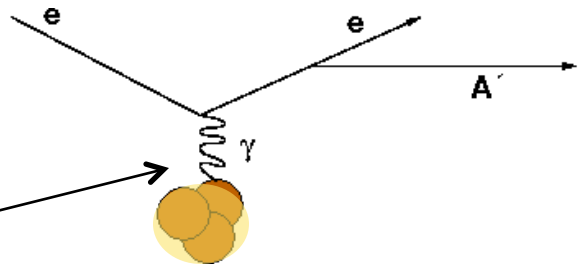


FIG. 2. The left panel shows the measured distribution of events in the (E_{ECAL}; E_{HCAL}) plane from the combined BGO and PbSc run data at the earlier phase of the analysis. Another plot shows the same distribution after applying all selection criteria. The dashed area is the signal box region which is open. The side bands *A* and *C* are the ones used for the background estimate inside the signal box. For illustration purposes the size of the signal box along the E_{HCAL} axis is increased by a factor of 5.

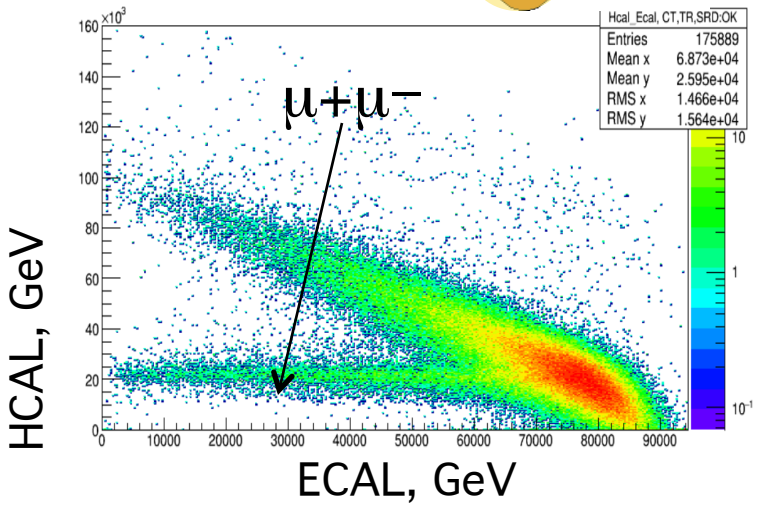
Systematics errors are dominated by the uncertainties in the A´ yield ~20%. Cross checked with dimuon production.

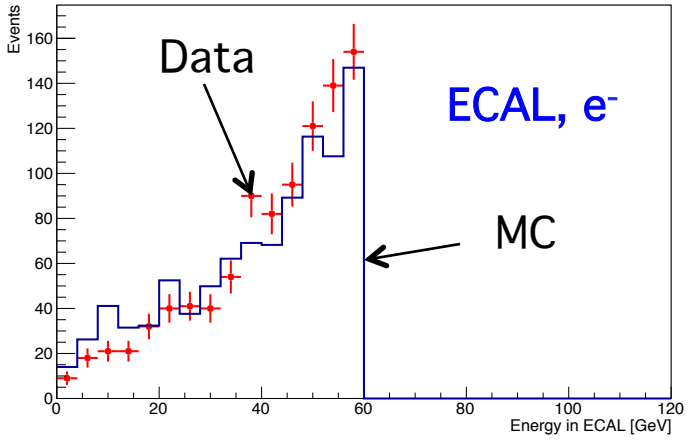
Gauge: dimuon production in eZ->eZγ, γ->μ⁺μ⁻





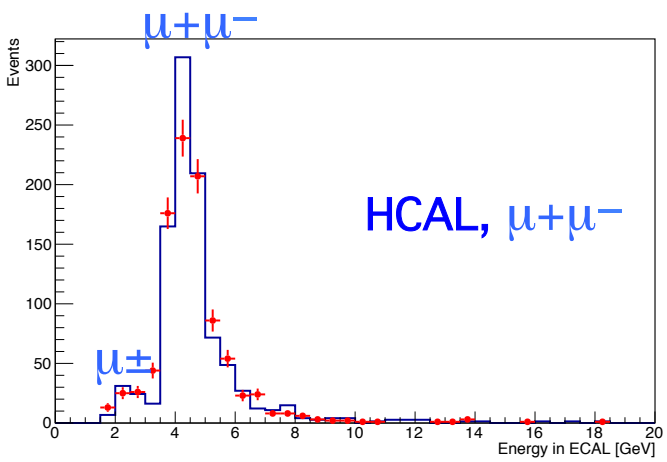
$F(q^2)$





Rare QED reference process ~10^{-5}/EOT:

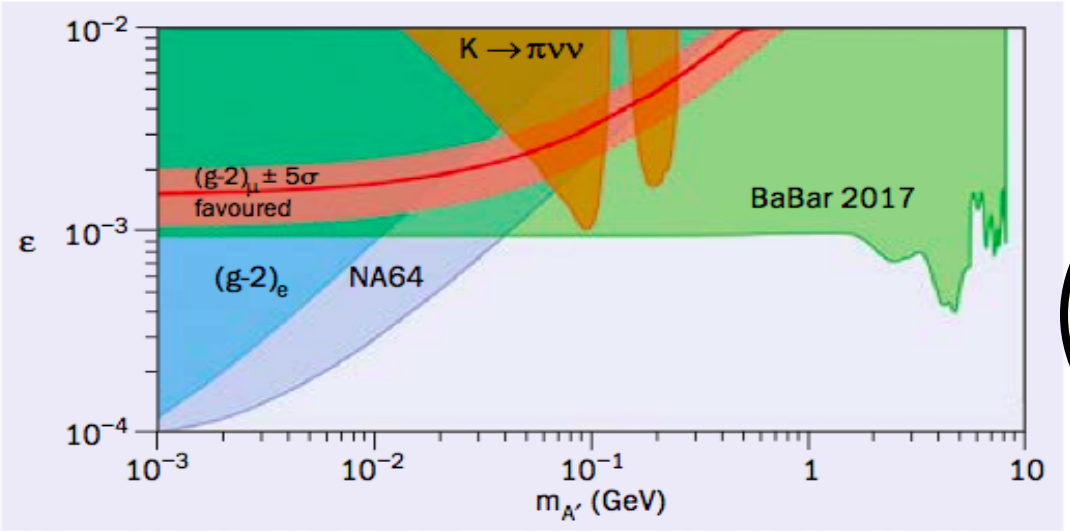
- similar to the A´ production
- same region of $q^2 \sim m^2_{A'}/E \sim m^2_{\mu\mu}/E$
- cross check of A´ yield, systematic errors
- background prediction from data
- cross check of overall efficiency



A´explanation of $(g-2)_\mu$ anomaly is ruled out

CERN Courier April 2017

News



Regions of the dark-photon parameter space (mixing strength versus mass) excluded by BaBar (green) compared with the previous constraints. The new analysis rules out dark-photon coupling as the explanation for the muon (g-2) anomaly and places stringent constraints on dark-sector models.

of Caltech, who has worked on dark-photon models. "In contrast to massless dark photons, which are analogous to ordinary photons, this experiment constrains a slightly different idea of dark force-carrying particles that are associated with a broken symmetry, which therefore get a mass and then can decay. They are more like 'dark Z bosons' than dark photons."

Further reading

BaBar Collaboration 2017 arXiv:1702.03327.
NA64 Collaboration 2017 *Phys. Rev. Lett.* **118** 011802.

Results from July run

PRL 118, 011802 (2017) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2017

Search for Invisible Decays of Sub-GeV Dark Photons in Missing-Energy Events at the CERN SPS

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(NA64 Collaboration)

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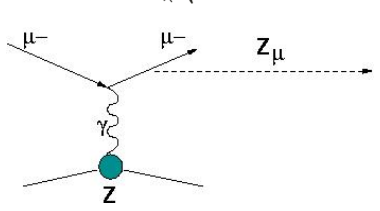
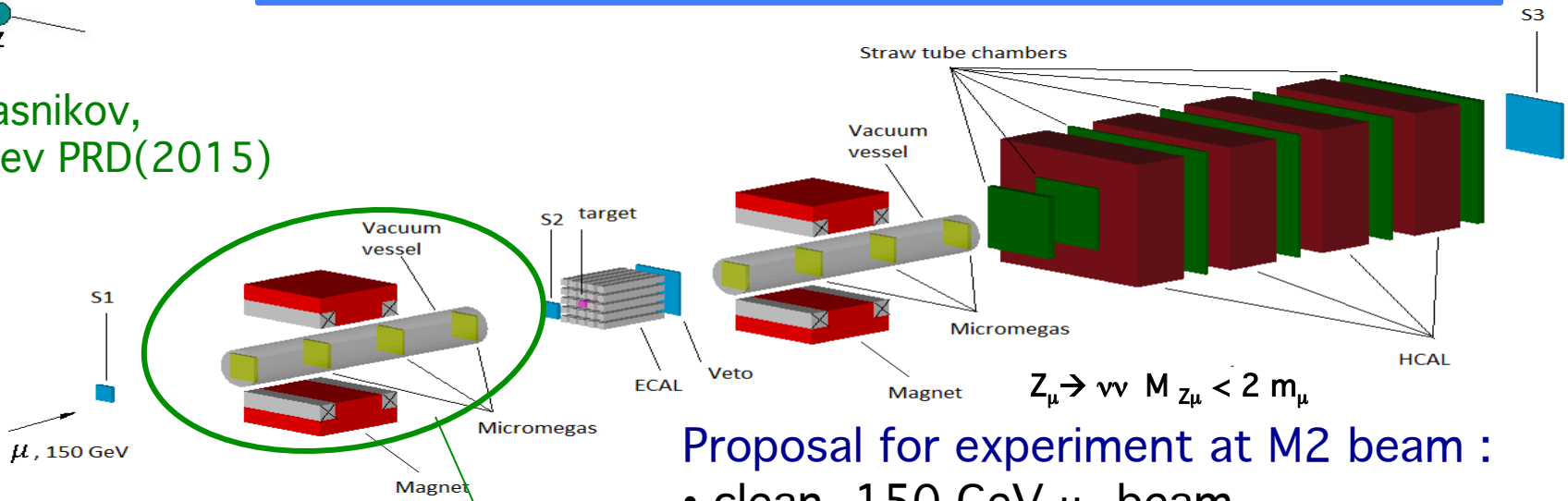
(Received 17 October 2016; published 5 January 2017)

Search for $L_\mu - L_\tau$ Z_μ in a muon NA64-like experiment



Remaining explanation of $(g-2)_\mu$ anomaly:
new massive Z_μ from the broken $U(1)_{L\mu - L\tau}$ symmetry
that coupled predominantly to μ and τ (PBC'16/17)

SG, Krasnikov, Matveev PRD(2015)



M2 BMS

Signature:

- in: 150 GeV μ-
- out: < 100 GeV μ- ; $Z_\mu \to \nu\nu$
- E≈0 in the hermetic ECAL+ HCAL
- Sensitivity ~ g_μ^2

Proposal for experiment at M2 beam :

- clean 150 GeV μ- beam
- initial μ state can be tagged with BMS.

Study is needed:

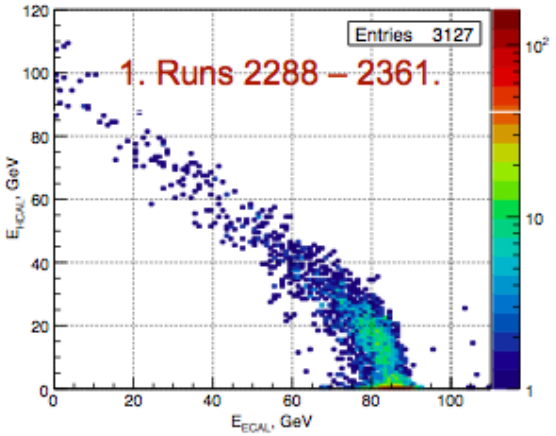
- $\pi/\mu < 10^{-(5-6)}$ purity?
- initial, final μ state tagging purity?
- trigger rate?
- calorimeter hermeticity?

NA64-COMPASS: Beam tests are planed and partly performed

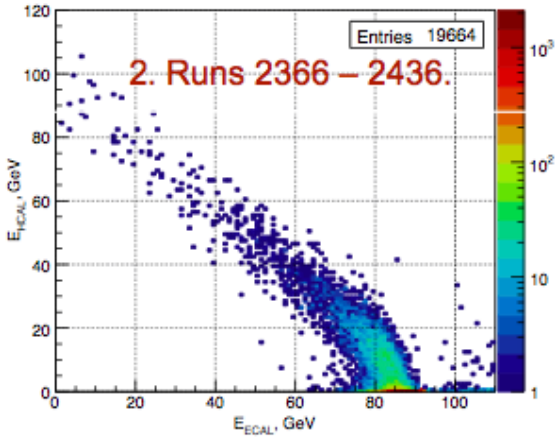
Preliminary results from October run

Data analysis in progress.

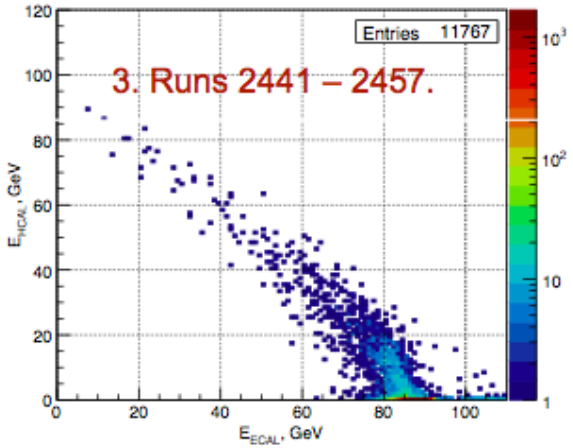
~2x10⁶ e-/spill



~3x10⁶ e-/spill

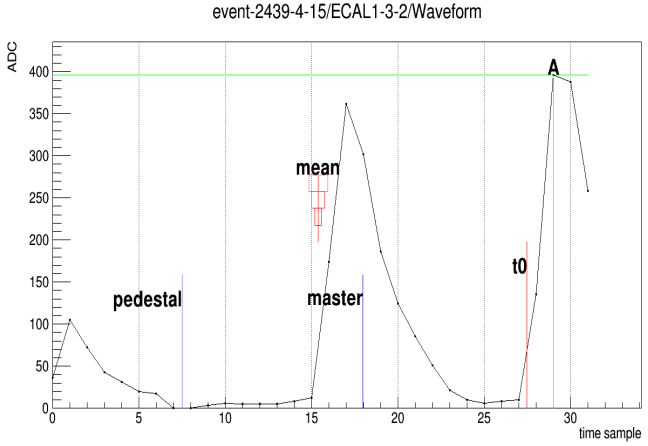


~5x10⁶ e-/spill



Pileup removal algorithm efficiency

Intensity per spill	~2x10⁶	~3x10⁶	~5x10⁶
no pileup algorithm	0.53	0.45	0.32
pileup algorithm	0.72	0.65	0.55

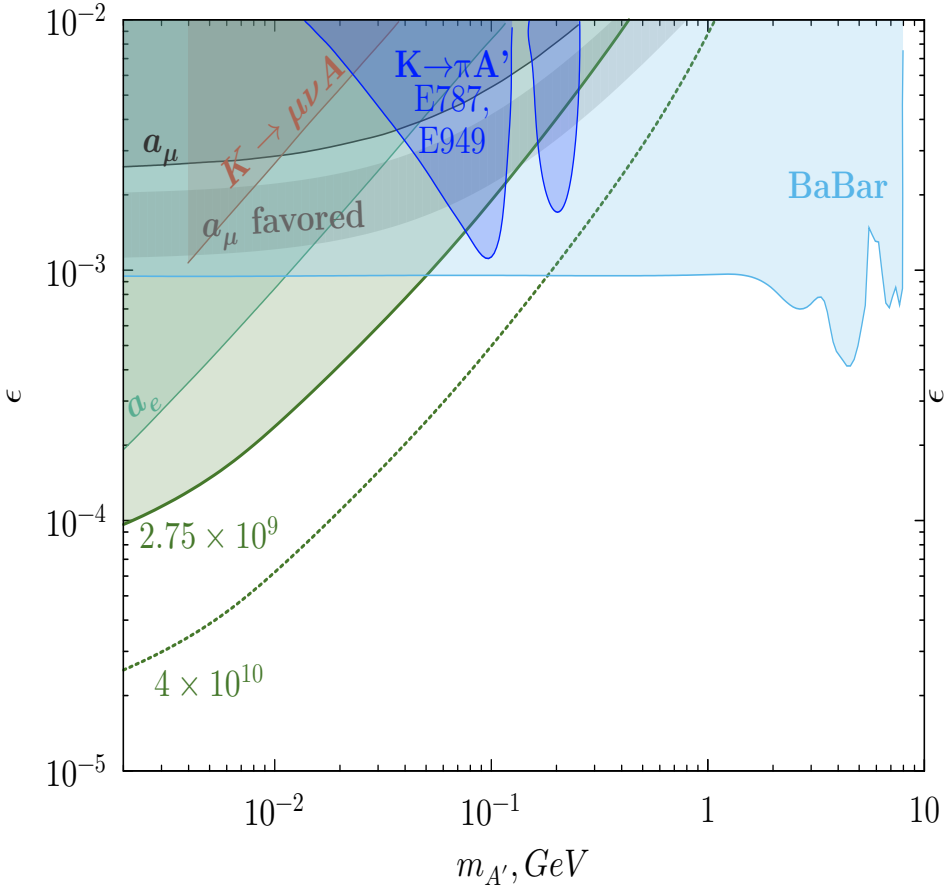


Summary of background

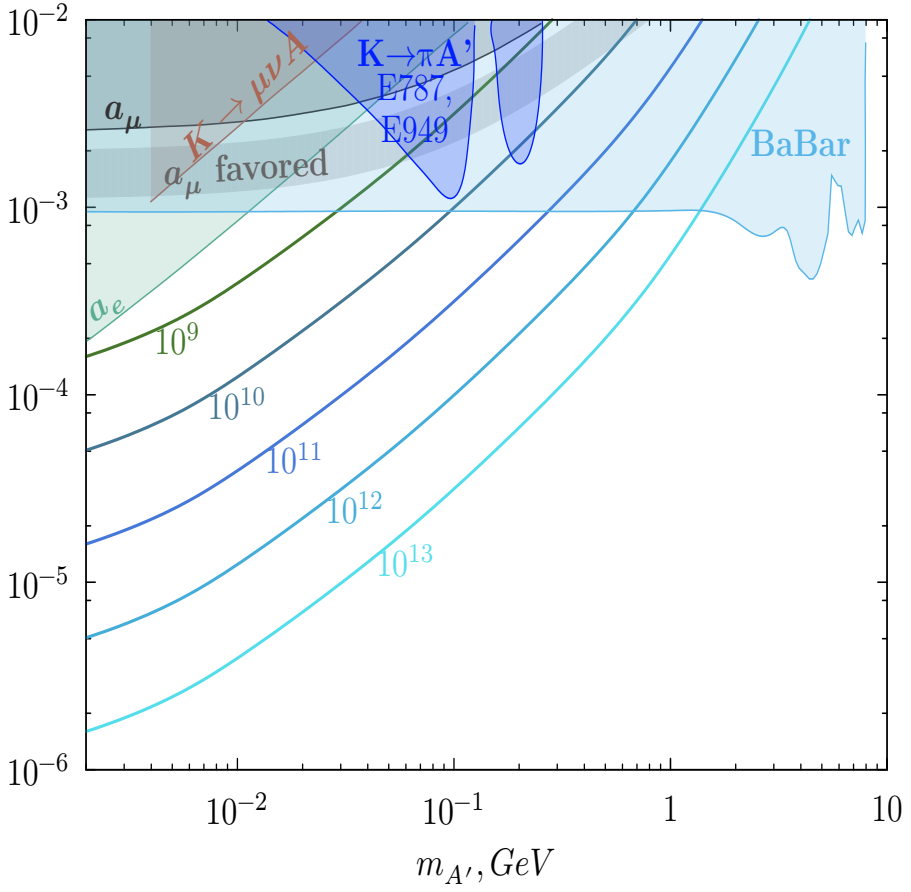
Source	Expected level	Comment
Beam contamination		
- π, p, μ reactions and punchthroughs,... - π, μ -decays in flight... - e^- below ~50 GeV + wide secondaries from upstream interactions	$< 10^{-13}$-10^{-12} $< 10^{-13}$ $< 10^{-12}$	Impurity < 1% high precision MM tracker + e^- SR tag Full downstream V coverage required
Detector		
ECAL+HCAL energy resolution, holes, dead material, cracks...	$<10^{-13}$	Full upstream coverage
Physical		
- hadron electroproduction, e.g. $e^-A \to e^-A^* + n,\pi,\rho,J/\psi-$ - n punchthrough, μ inefficiency - WI process: $e^- Z \to e^- Z\nu\nu$	$< 10^{-13}$ $< 10^{-13}$	HERA ep-data (H1 Collaboration) WI σ estimated.
Total	$< 10^{-12}$	

Expected limits for kinetic mixing ε

2016



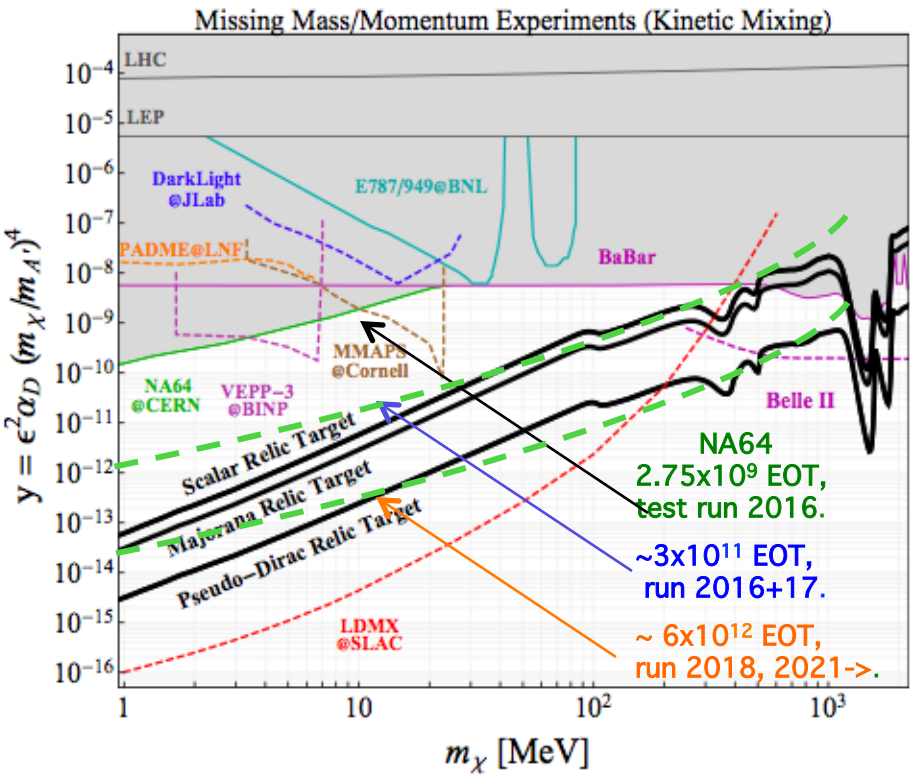
2017->



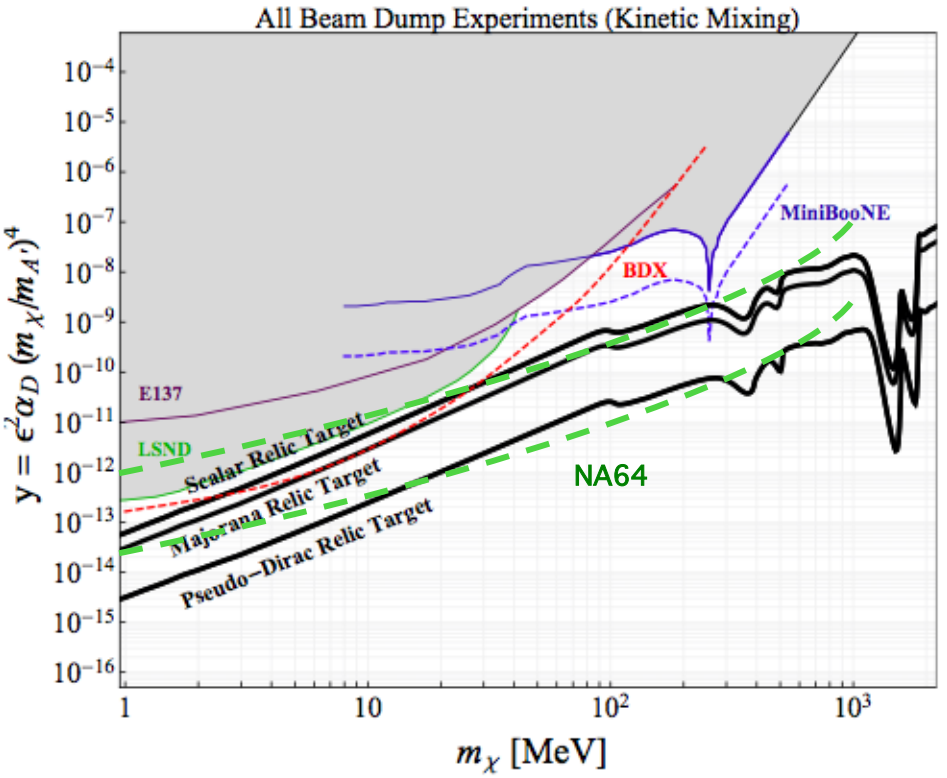
(background free case)

Existing and projected limits on light TDM

Missing mass / momentum / energy



Beam dump



Lessons from 2016: ~10^7 e^-/spill, n_{EOT}~ $6x10^{12}$/6 m are feasible

NA64 has a good potential to cover region sub-GeV thermal DM targets.
LDMX@SLAC ~ 2021/22->

Plots from US Cosmic Visions Workshop, March 2017

The ^{8}Be excess

A new light X from $^8Be^*$ transition ?

PRL 116, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
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(Received 7 April 2015; published 26 January 2016)

^{7}Li(p, γ)^{8}Be, M $_X$ =16.7 MeV

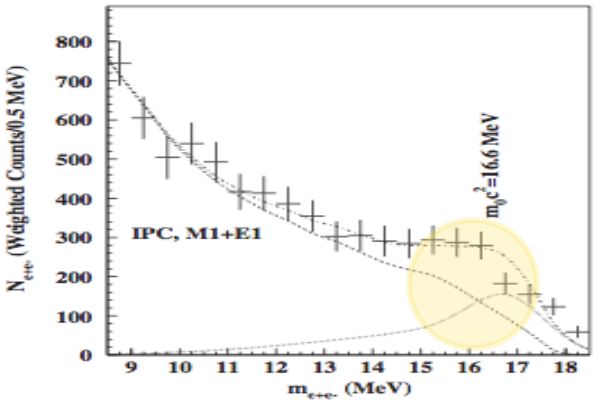
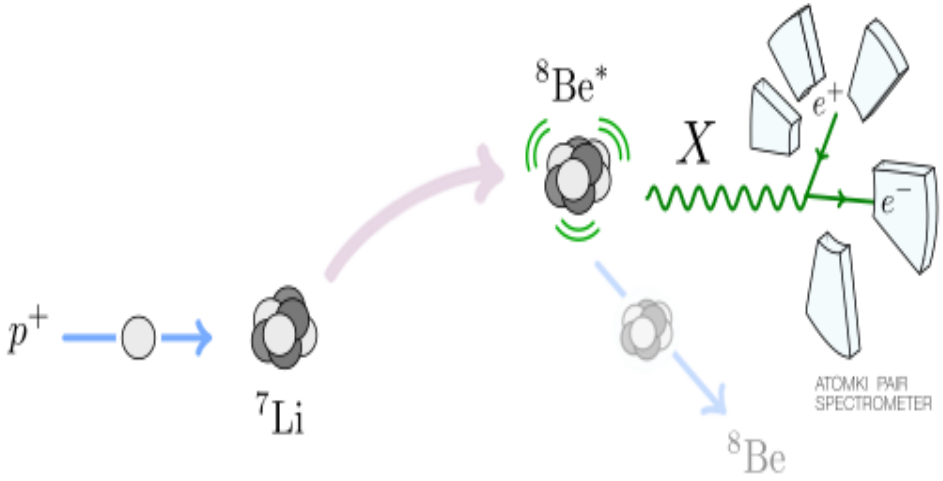


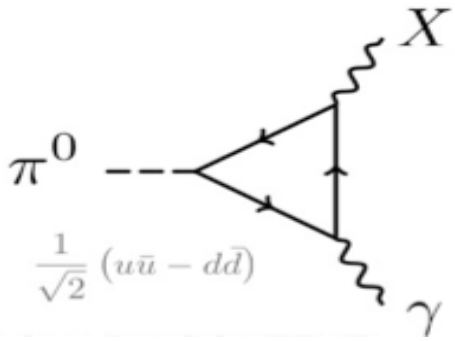
FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.



Feng et al, 2016

$2\times10^{-4} < \varepsilon_e < 1.4\times10^{-3}$

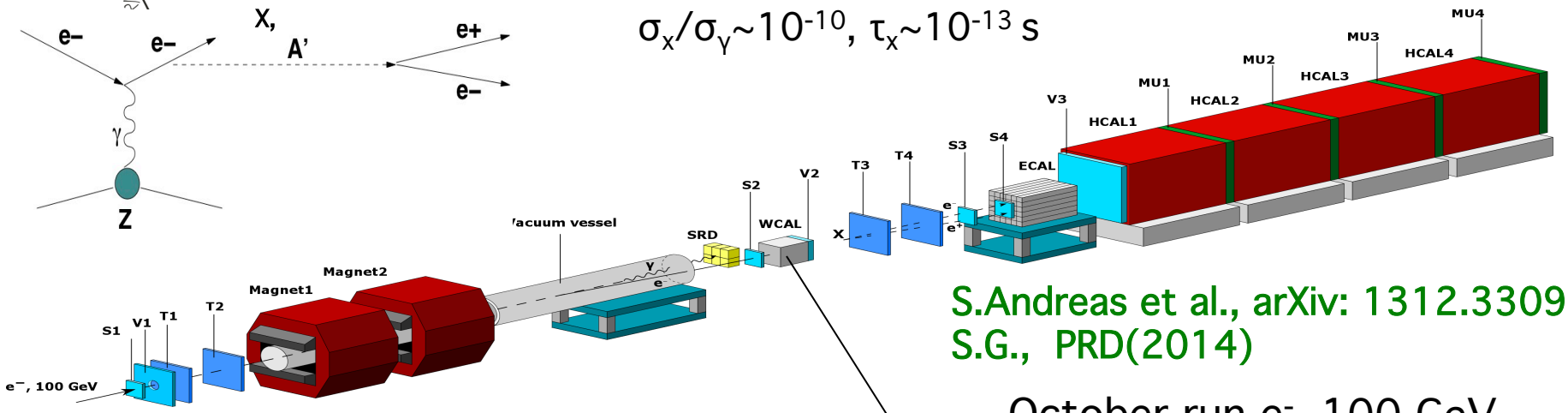
X cannot be A´due to constraints from π^0->Xγ decay:



$\Gamma(\pi^0\text{->}X\gamma)\sim(\varepsilon_u q_u-\varepsilon_d q_d)^2 \sim 0$

if $2\varepsilon_u=-\varepsilon_d$ -> protophobic X

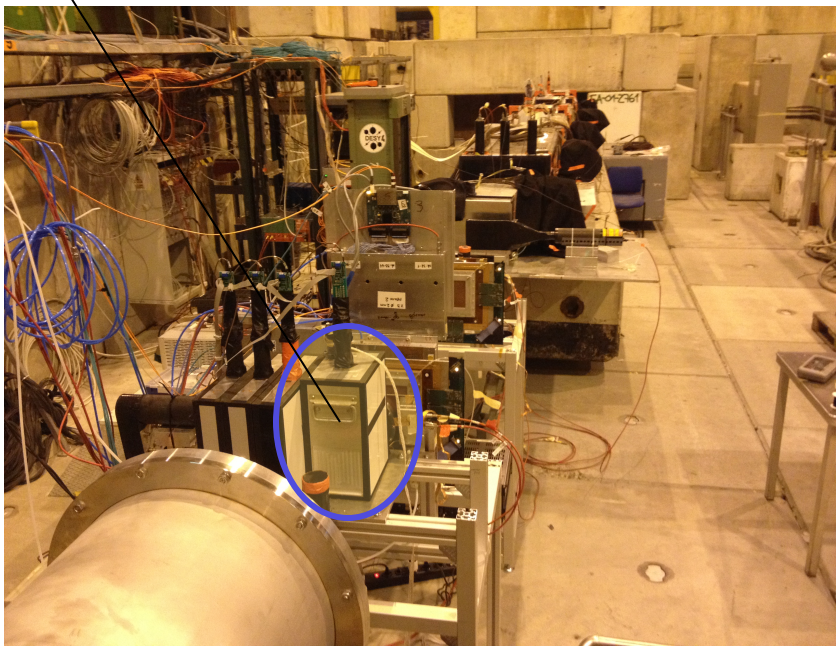
Feasibility test for the X(A´)->e^+e^- decay



S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

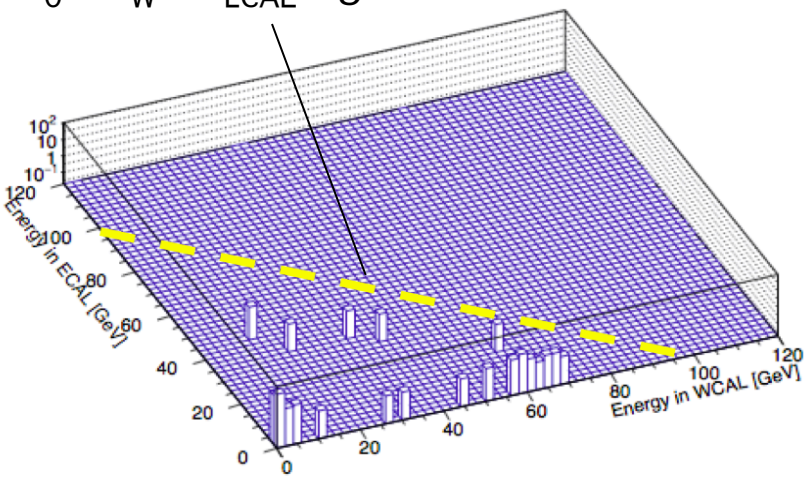
October run e^-, 100 GeV

- X's decay mostly outside WCAL
- Signature: two separated showers from a single e-
- $E_{WC} < E_0$, and $E_0 = E_{WC} + E_{EC}$
- θ_{e+e-} too small to be resolved
- background mainly from
  - bremss γ punchthrough
  - beam and secondary hadrons

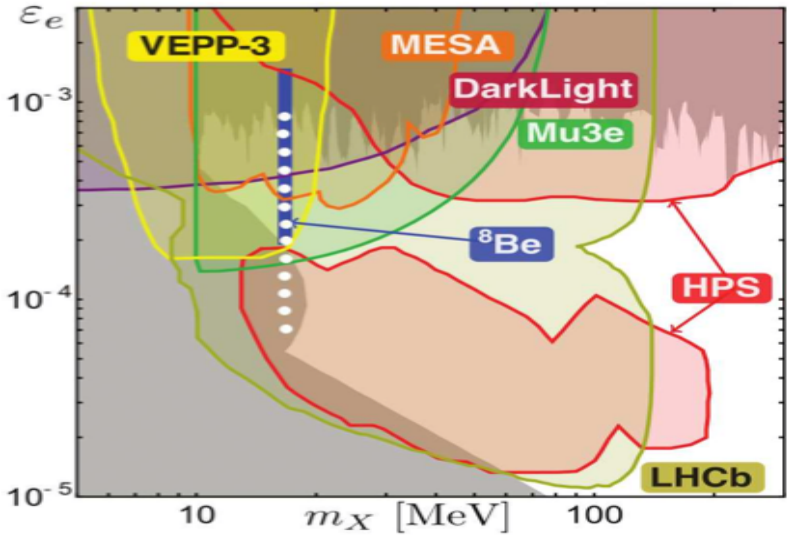


Results from October run, ~0.5x10[10] EOT (preliminary)

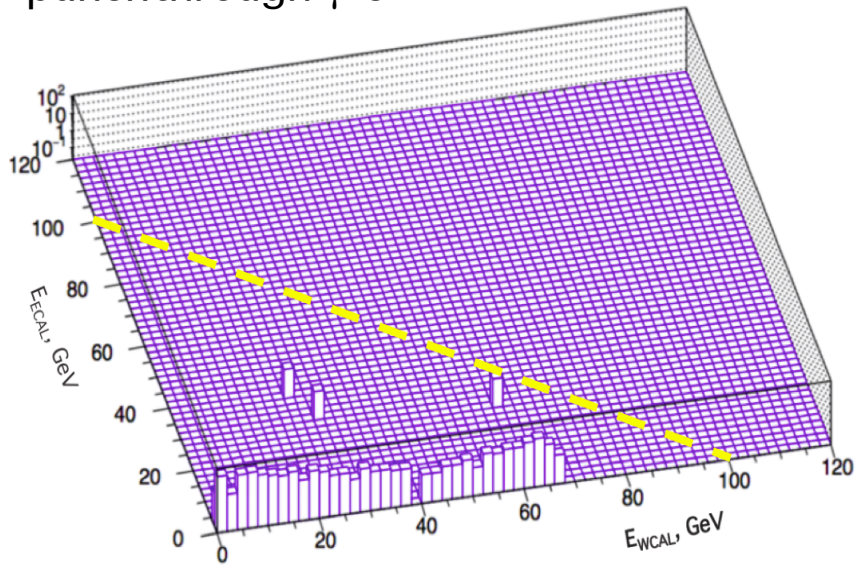
$E_0 = E_W + E_{ECAL}$ signature



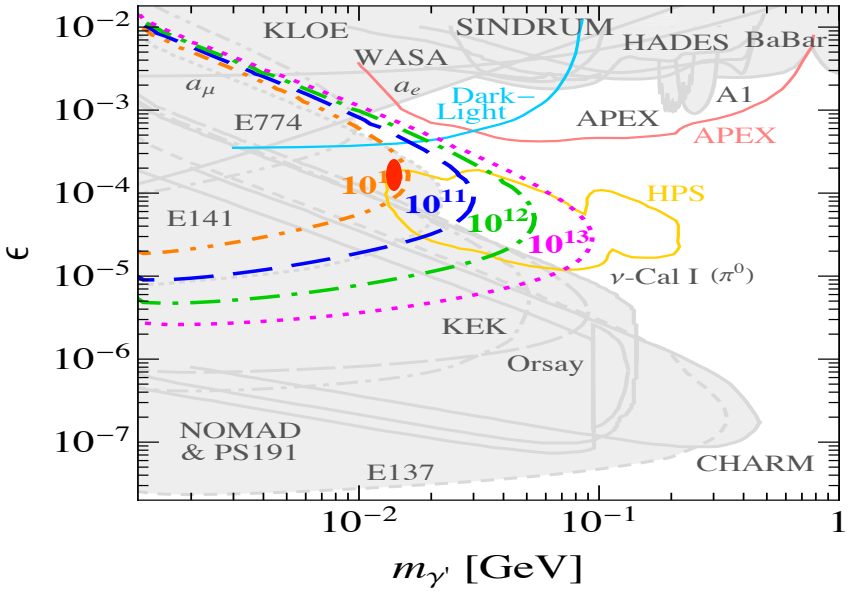
Expected exclusion area, 5x10[10] EOT



Estimate of background from punchthrough γ's



Exclusion area for A´→ e^+e^- vs EOT



Conclusions

2016 runs:

Detector is fully operational and working

Good quality data data from July (2.75×10^9 EOT) and October (4.05×10^{10} EOT) runs.

July run: The results rule out the invisible A´ as the explanation for the muon g-2 anomaly (PRL paper)

October run: Analysis of the data set in good progress.

Goal: to test A´ SES down to $\sim 10^{-11}$ per EOT

Preliminary results from the feasibility study of the X(A´)->e^+e^- decays look promissing

Searching for missing-energy events in an active beam dump is a sensitive probe of dark sector physics.

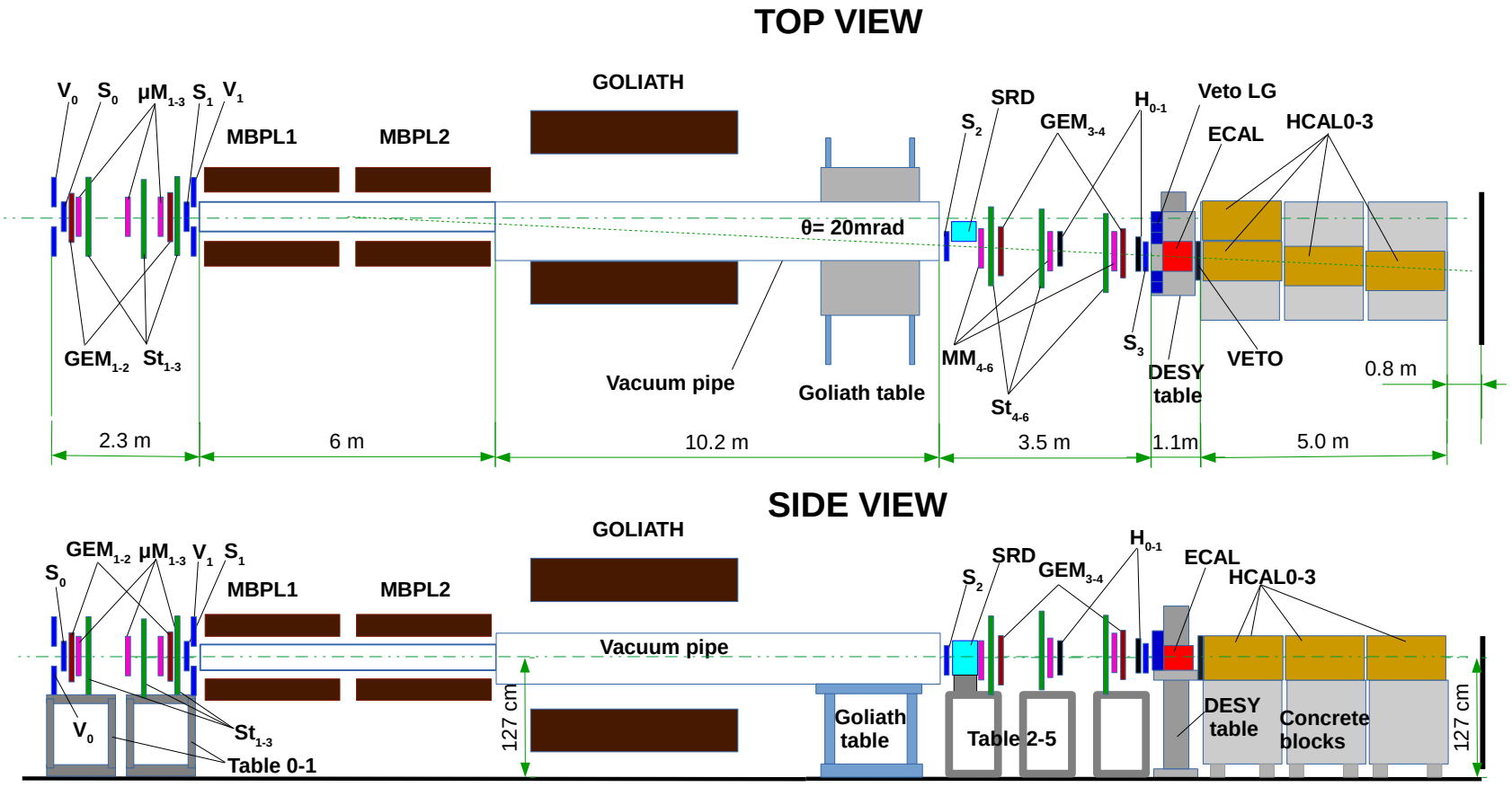
Excellent potential of a broad NA64 physics program.

Plans for 2017

- Data taking for: A´-> invisible, X (A´)->e^+e^-, muon test
- 2017 intensity: (5–8) x10^6 e^-/spill, ~ 3x10^3 spills/day
- 2017 runs expectations:
  ~ 10^{11} EOT for A´-> invisible
  ~ 10^{11} EOT for X (A´)->e^+e^-
- Upgrade:
  Increase the number of tracker stations up to 12 (MM, GEM,ST) + beam hodoscopes; SRD green-extended PMT, large downstream Veto, 0-angle HCAL.

2018 run: Permanent location at H4 is requested. Would be very useful to avoid assembly (disassembly) and tuning of the quite complicated detector and beam. Would save several weeks of beam time.

The NA64 detector in 2017

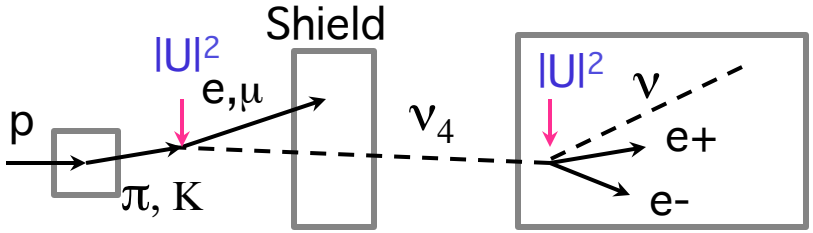


BACKUP

NA64 approach to search for new physics

The NA64 is a new fixed-target experiment aiming to search for dark photon A´->invisible decays at the CERN SPS with a new approach: the active beam dump combined with missing energy technique.

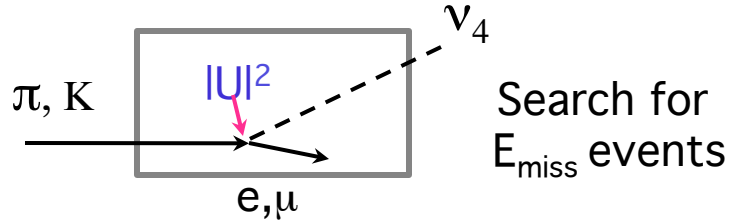
Beam dump: ⟷ Complementary to each other ⟷ NA64 approach:



Sensitivity ~$|U|^4$

e.g. SHIP, A. Golutvin talk

active beam dump + E_{miss}



Sensitivity~$|U|^2$

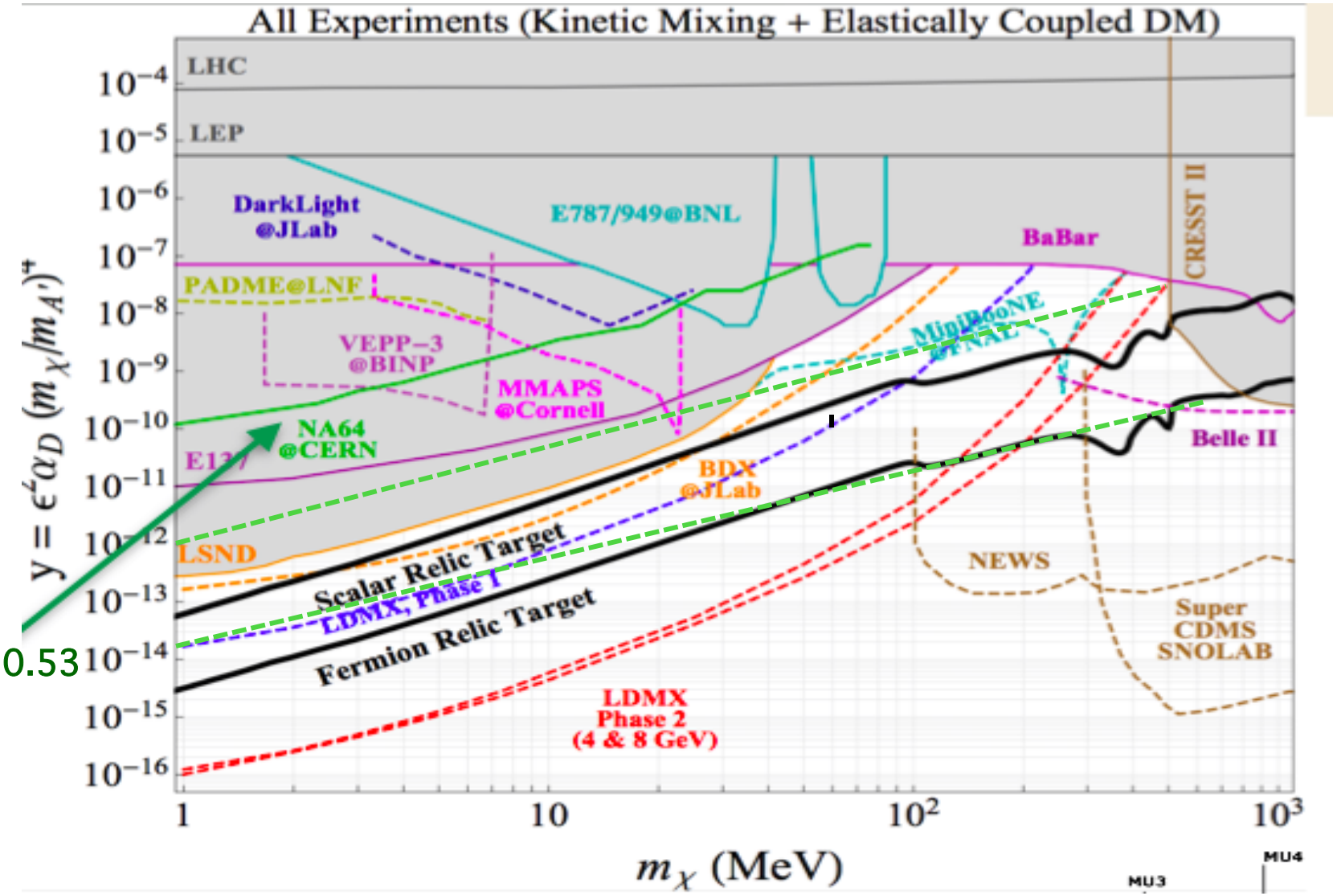
Goal of the talk: to show that this approach allows a sensitive probe of "light new physics" (dark sector physics, new symmetries, new WI sub-GeV particles coupled to e, μ, q's) by using e, μ, π, K, and p beams from existing facilities at CERN.

Cuts and efficiencies

№	1	2	3	4	5	6
Run	2363	2365	2406	2410	2438	2439
Trigger	SV	SVPs	SVPs	SV	SV	SVPs
Intensity	2.0×10^6	2.4×10^6	3.1×10^6	3.2×10^6	4.6×10^6	5.1×10^6
S1 time cut, %	1.10	1.12	1.25	1.28	1.61	1.62
ECxy cut, %	1.15	0.60	0.62	1.37	1.62	0.85
SRD cut, %	1.23	1.12	1.26	1.78	2.33	1.99
VETO cut, %	8.50	8.76	9.66	13.0	24.8	23.6
EcalBadEnergy, %	2.31	2.05	2.22	3.04	3.01	2.46
Efficiency, %	85.7	86.3	85.0	79.5	66.7	69.5

№	1	2	3	4	5	6
Run	2363	2365	2406	2410	2438	2439
Trigger	SV	SVPs	SVPs	SV	SV	SVPs
Intensity	2.0×10^6	2.4×10^6	3.1×10^6	3.2×10^6	4.6×10^6	5.1×10^6
S1 time cut, %	1.10	1.12	1.25	1.28	1.61	1.62
ECxy cut, %	1.15	0.60	0.62	1.37	1.62	0.85
SRD cut, %	1.20	1.08	1.22	1.73	2.26	1.92
VETO cut, %	8.51	8.76	9.67	13.0	24.8	23.6
EcalBadEnergy, %	2.33	2.06	2.24	3.06	3.03	2.48
MMGoodTrack, %	3.81	3.78	5.43	5.76	7.67	5.06
ShowerChisq, %	6.71	6.76	7.42	7.74	7.59	7.45
ECratio, %	0.0009	0.0008	0.0005	0.0005	0.0003	0.0003
HCpass1, %	2.74	2.78	2.46	2.32	1.61	1.79
HCpass2, %	0.31	0.33	0.28	0.27	0.22	0.27
Efficiency, %	72.1	72.7	69.4	63.4	49.6	54.9

Expectation for TDM

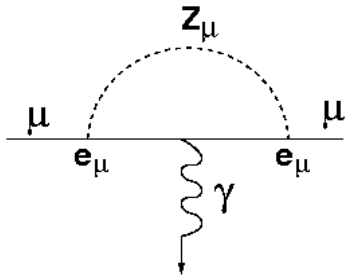


eff~ 0.53

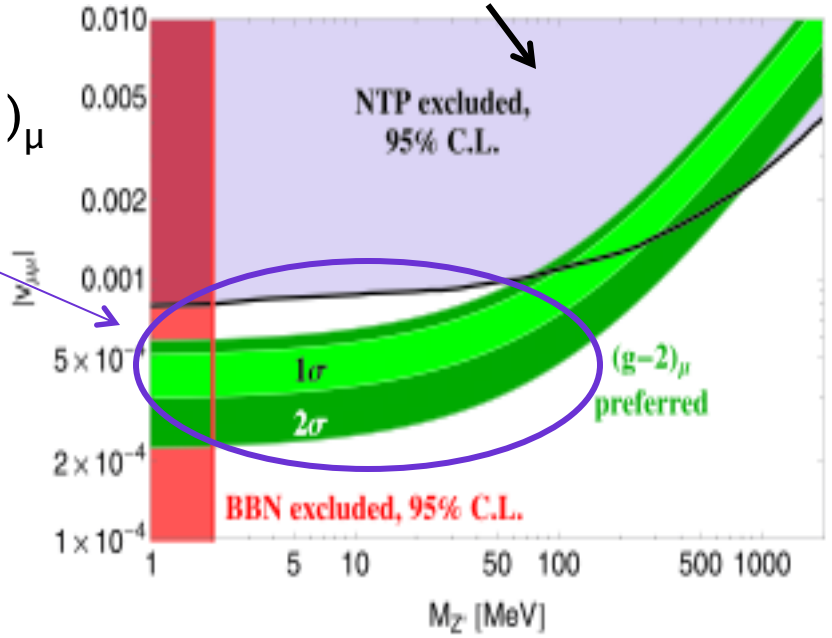
S.N. Gninenko – NA64 Status Report, SPSC Open Meeting, CERN, June 20–21, 2017

New leptonic Z´ (or Z_μ) from gauged $L_\mu - L_\tau$

- Class of U(1)´models: in SM it's possible to gauge one of L_e-L_μ, L_e-L_τ, $L_\mu-L_\tau$ LN differences. No anomaly.
- Extra (broken) U(1)´, new massive boson Z´ coupled predominantly to μ and τ through the $L_\mu - L_\tau$ current (leptonic dark photon)
- $M_{Z'}$ could be in sub-GeV range
  Z´→ $\mu^+\mu^-$ or Z´→ νν if $M_{Z'} < 2\, m_\mu$
- Impact on: ν-physics, explanation of $(g-2)_\mu$



Altmannshofer et al., arXiv:1406.2332



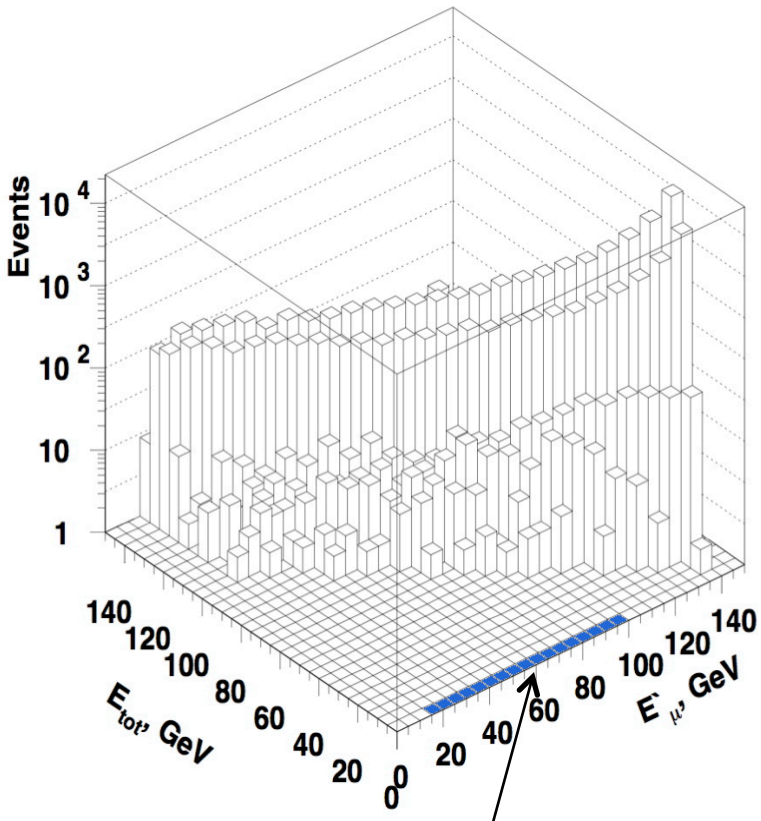
Strong motivation for a sensitive search for Z´->νν, $\mu^+\mu^-$ in a near future experiment by using (unique) high intensity muon beam at CERN.

The upgraded muon beam at the SPS

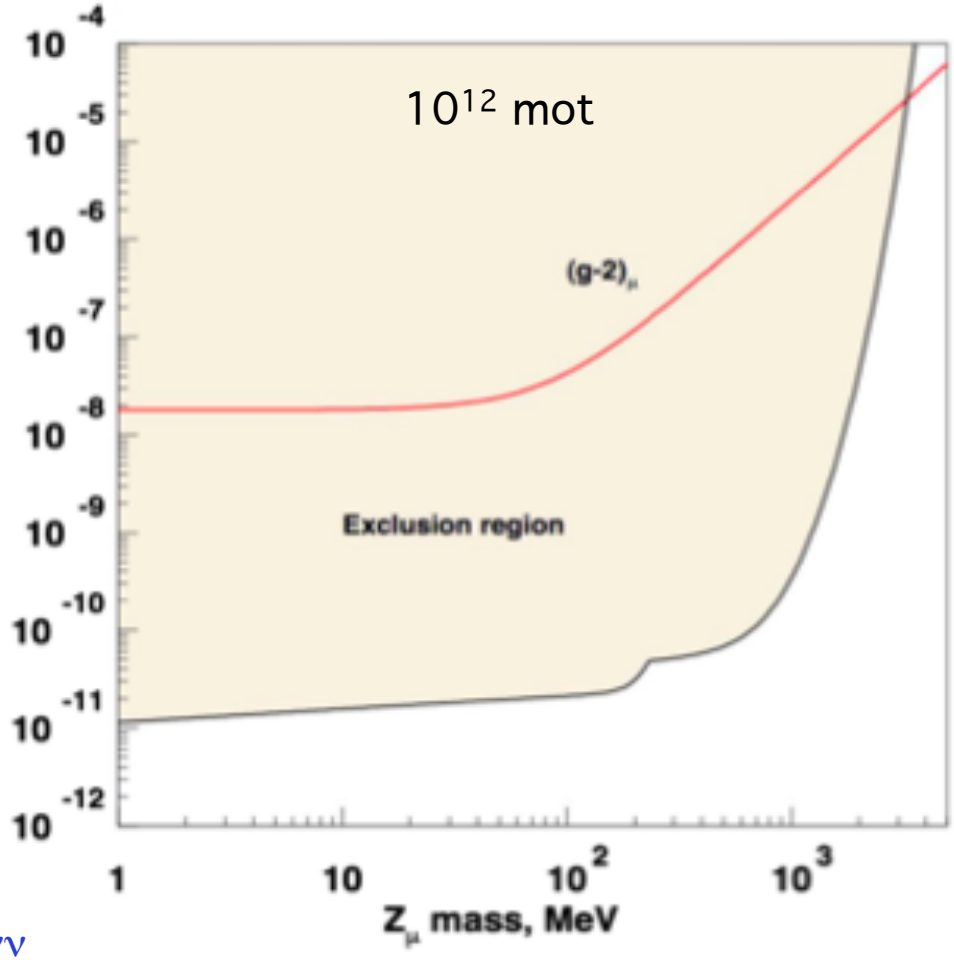
N. Doble, L. Gatignon *, G. von Holtey, F. Novoskoltsev [1]
CERN, SL Division, CH-1211 Geneva 23, Switzerland

From J.Heeck PLB'16

Expected exclusion area



Signature for $\mu Z \to \mu' Z\, Z'$; $Z' \to \nu\nu$ in $(E_{\mu'}; E_{tot})$ plane



Same signature for LFV $\mu \to \tau \to \mu\nu\nu$ conversion