Status and prospects of the NA62 experiment

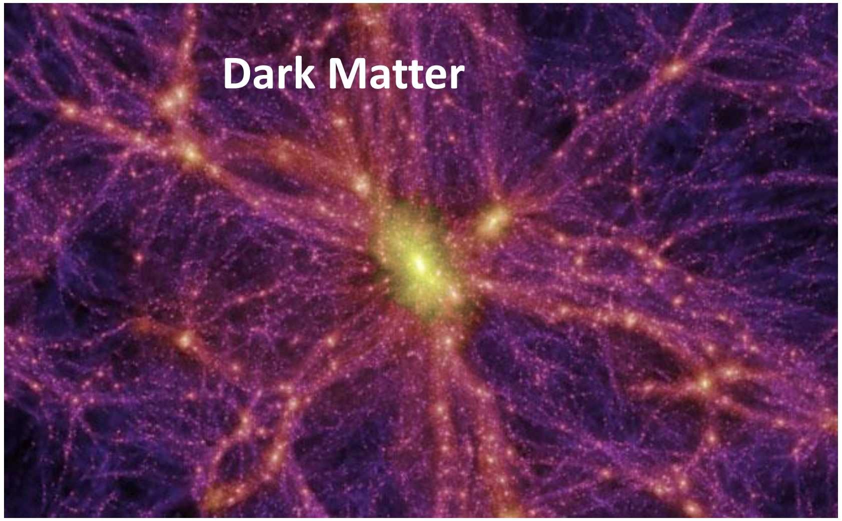
Chris Parkinson, University of Birmingham

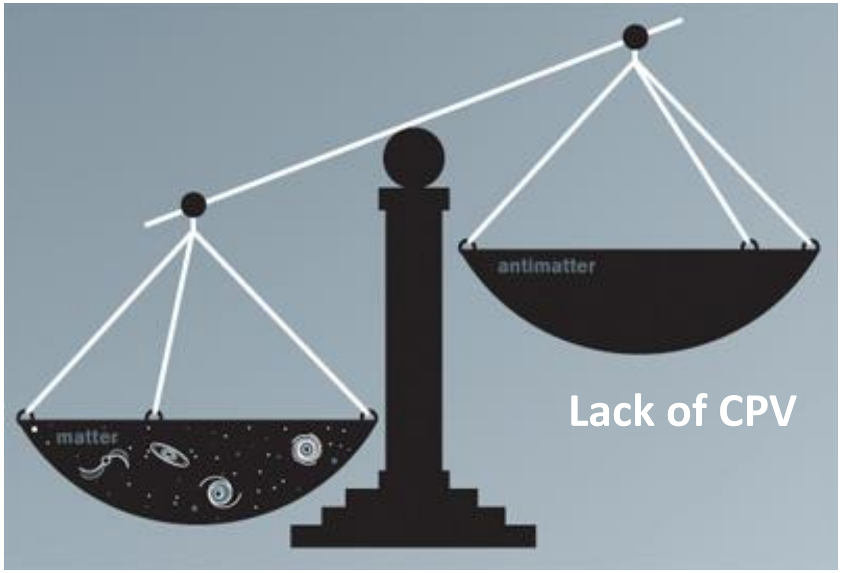
27th January 2016

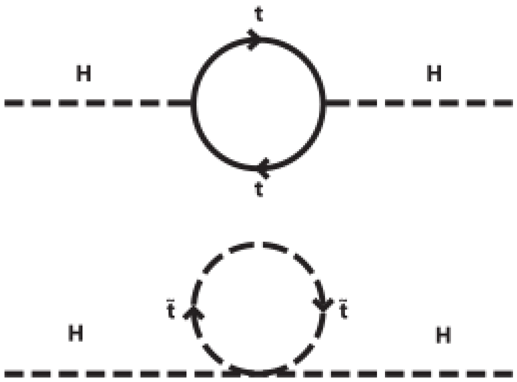
Outline

1. Flavour physics in the 21st century and the NA62 experiment
2. The NA62 experimental setup
3. Detector commissioning and data-taking in 2014 and 2015
4. The NA62 physics programme and proposed trigger strategy

Plenty of unanswered questions





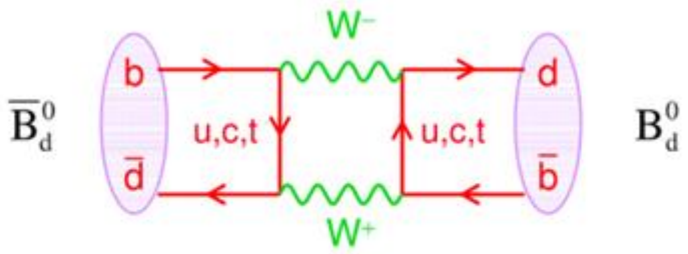


New particles at the TeV scale

Searching for new particles

- New particles can contribute to loop-mediated processes
- In the Standard Model, FCNC decays are forbidden at tree level → loop diagrams

- Example: B^0 mixing



$$M(B_d - \bar{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2}$$

- FCNC decays are highly suppressed:
  - Because they are forbidden at tree level
  - Because the off-diagonal CKM elements are small
  - Because of the GIM mechanism

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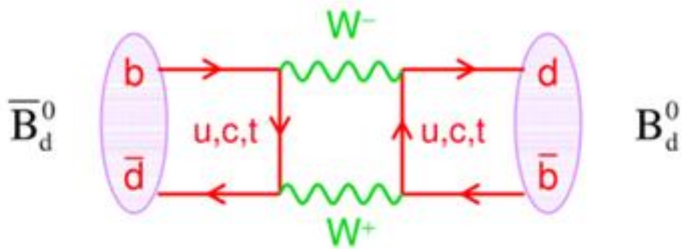

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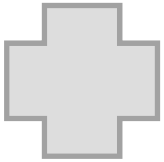

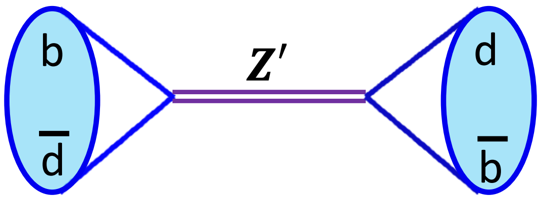

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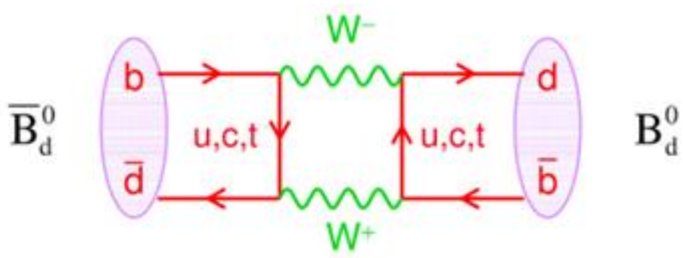

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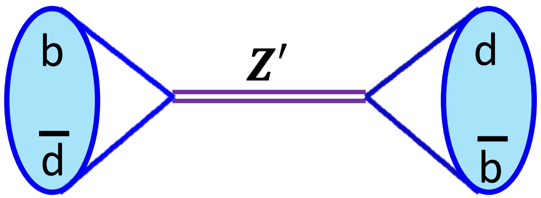

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- ~~FCNC decays are highly suppressed:~~
  - ~~Because they are forbidden at tree level~~
  - ~~Because the off-diagonal CKM elements are small~~
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$C_{NP} \sim O(1)$

The flavour problem

- But we don't see huge NP contributions to FCNC decays?

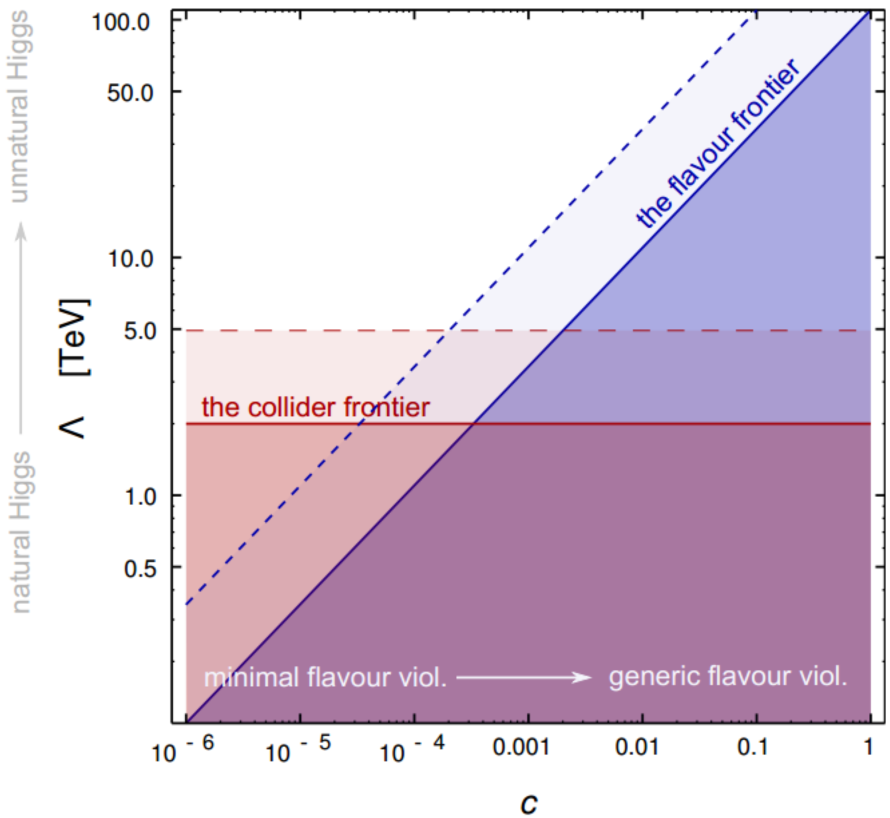
$$C_{NP}\frac{1}{\Lambda^2} \ll \text{SM term}$$

- Either:
  - New particles are extremely massive ($\Lambda \rightarrow \infty$).
  - The couplings of the new particle are suppressed too ($C_{NP} \ll 1$).

Complementarity

- The fact that $C_{NP}\frac{1}{\Lambda^2} \ll \textbf{SM term}$ sets C_{NP}-dependent limits on Λ
- This provides great complementarity with direct searches for new particles

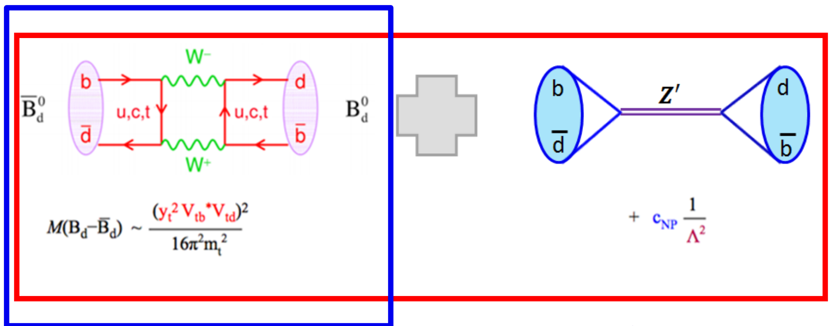
[Straub, IPPP 2014]



Searching for new particles

- **Experimentally** we measure ~ **the sum of both terms**

experimental measurement ~



SM prediction

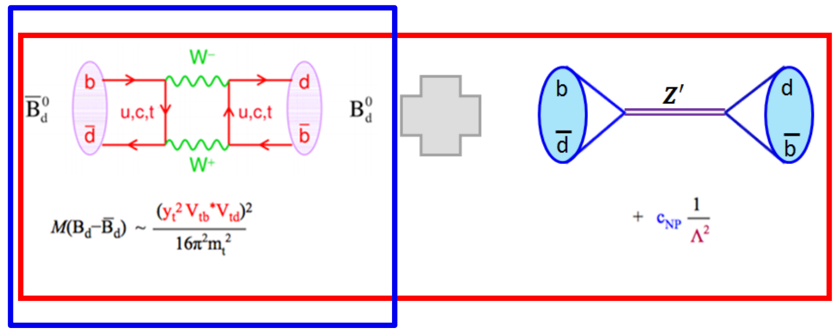
- But we can **predict the SM-only value**

- **Any difference is due to a NP contribution**
- If there is **no difference**, this sets **limits on the size of NP contributions**

Three criteria for searches

- Searching for new particles in this way

experimental measurement ~



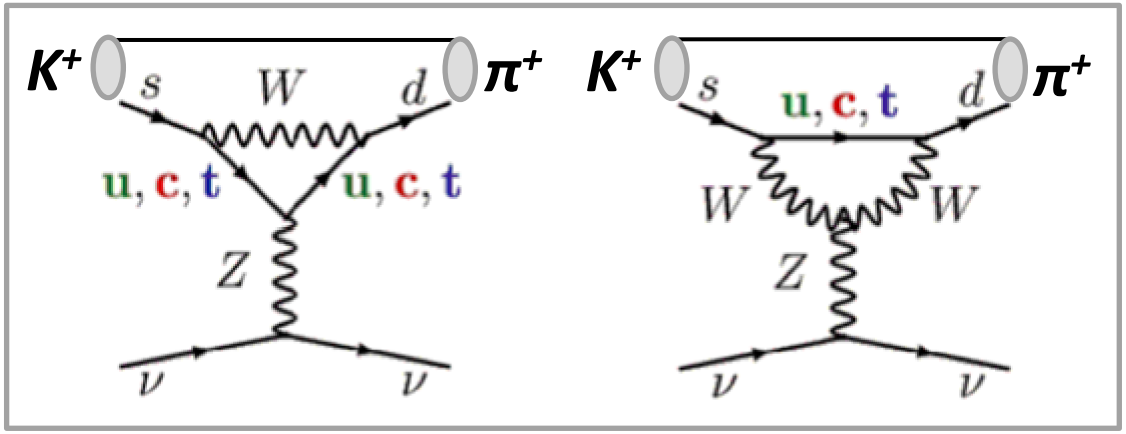
SM prediction

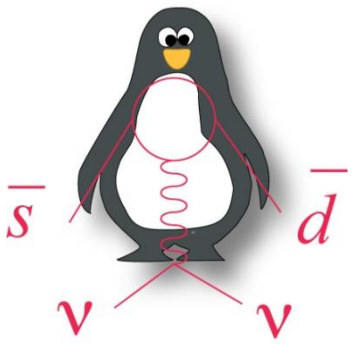
needs **three criteria** to be satisfied:

1. SM contribution must be small
2. Precise calculation of SM contribution
3. Experimentally accessible observable

- These criteria are satisfied by the FCNC decay ***$K^+ \rightarrow \pi^+ \nu\nu$***

The $K^+ \to \pi^+ \nu\nu$ decay





- **Small and precisely determined SM contribution**

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$ [Buras et. al.]

  – Highly suppressed due to 'hard-GIM' suppression

- **Experimentally accessible?**
  – Actually this is quite difficult. Require a specialised experiment → **NA62**

Current experimental status of $K^+ \to \pi^+ \nu\nu$

- Combined data from E787 and E949 experiments @ BNL
- Use 'stopped Kaon' approach to detect K^+ decays at rest
- Based on 9.4×10^{12} K^+ decays – collected **seven** signal candidates

- Prediction [Buras et. al.]:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$

- Measured $\mathcal{B}(K^+ \to \pi^+ \nu\nu)$ to be

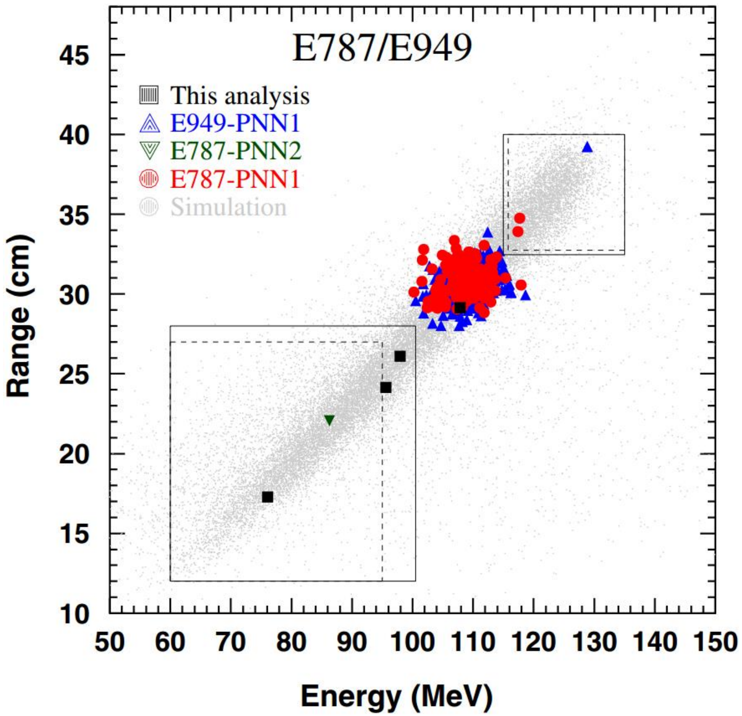
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73\ ^{+1.15}_{-1.05}) \times 10^{-10}$$

BNL E787/E949: PRL101 (2008) 191802

- The 'excess' could be evidence of contributions from Z'

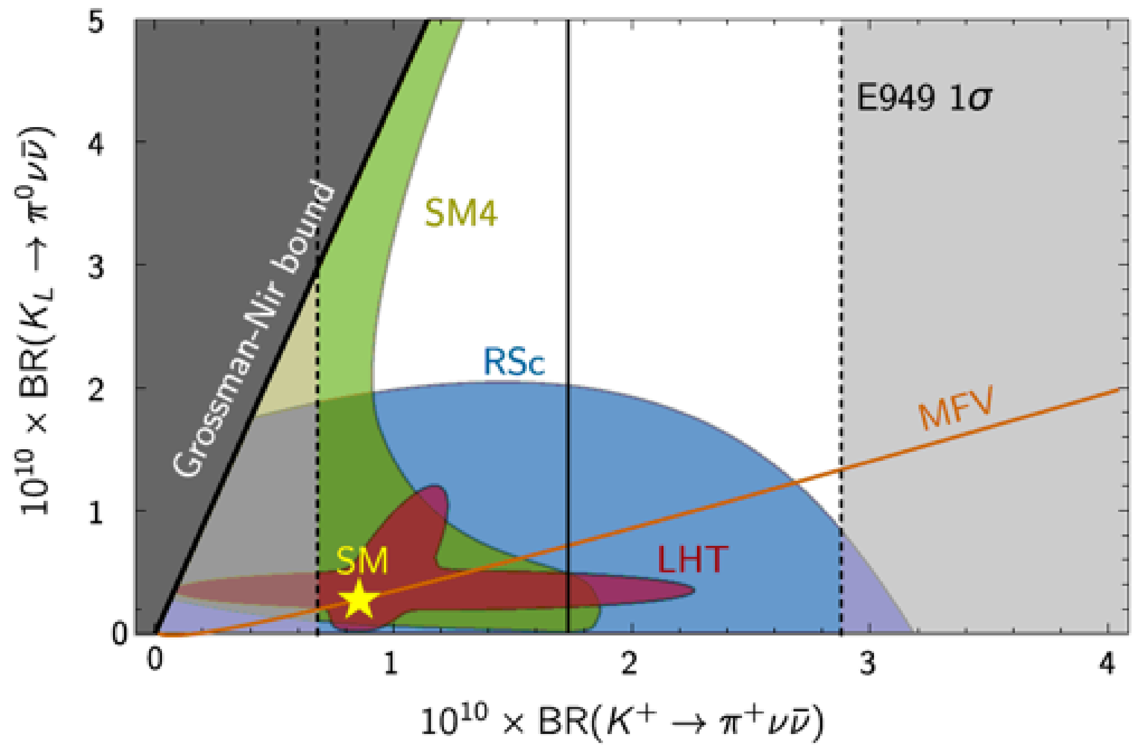
  Buras et al, JHEP 1302 (2013) 116

  – Similar interpretation to recent LHCb results



The impact of $K^+ \rightarrow \pi^+ \nu\nu$

[Straub, CKM2010]



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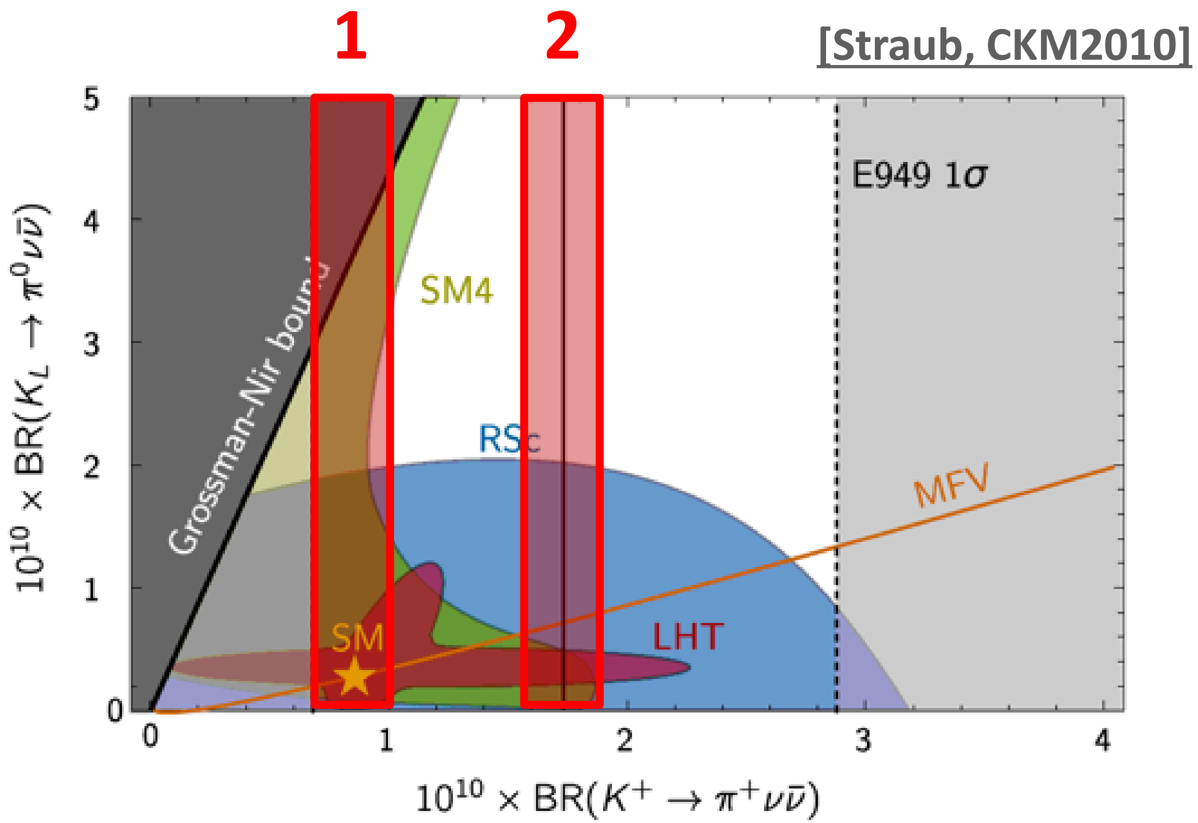

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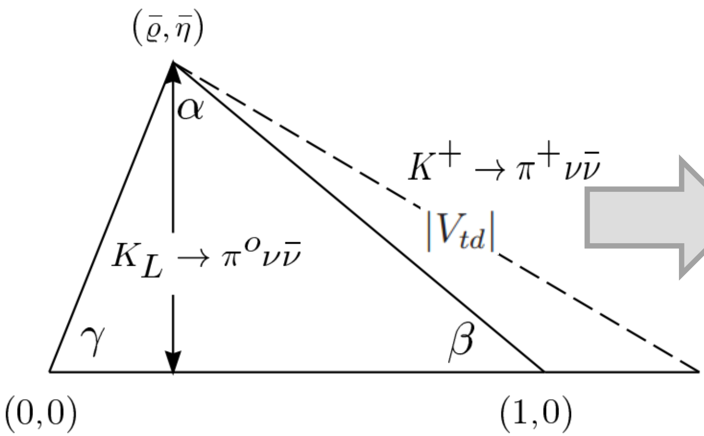

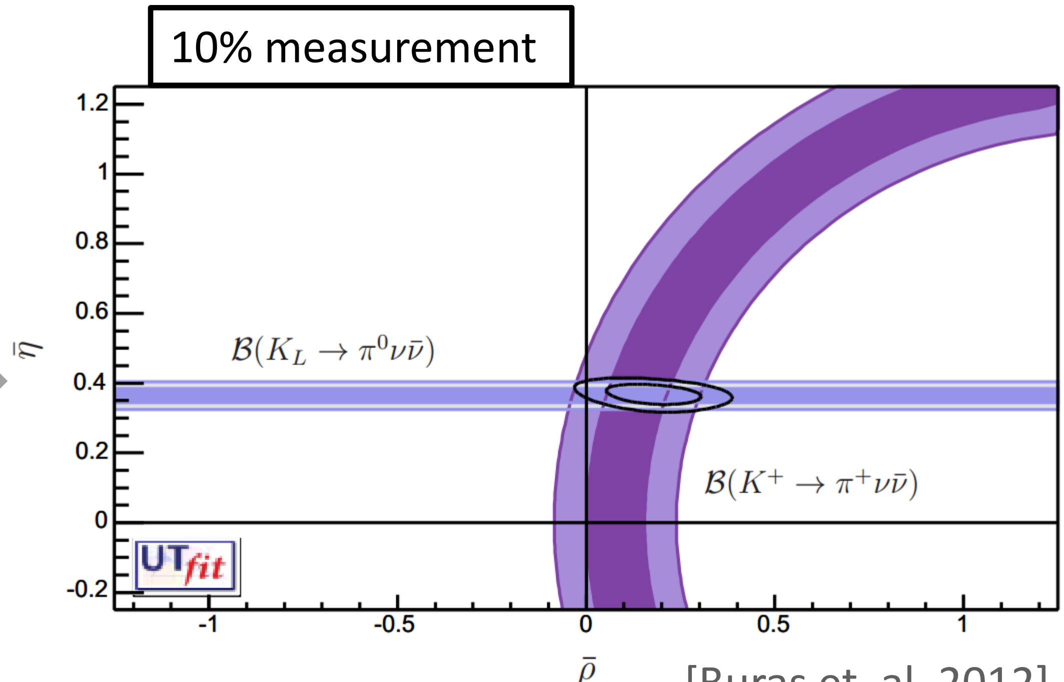

[Buras et. al. 2012]

The NA62 experiment

The NA62 collaboration

Kaon Physics at CERN

NA62: 233 collaborators of 29 institutes

Recent history of NA experiments		
1984 ↓ 1990	NA31 (K_S/K_L)	First evidence of direct CPV
1997 ↓ 2001	NA48 (K_S/K_L)	**Re ε'/ε** Discovery of direct CPV
2002	NA48/1 (K_S/hyperons)	Rare $\mathbf{K_S}$ and hyperon decays
2003 ↓ 2004	NA48/2 (K^+/K^-)	Direct CPV Rare $\mathbf{K^+}$ / $\mathbf{K^-}$ decays
2007 ↓ 2008	NA62 R_K phase (K^+/K^-)	$\mathbf{R_K = K^{\pm}_{e\nu}/K^{\pm}_{\mu\nu}}$
2009 ↓ 2017	NA62 (K^+)	$\mathbf{K^+ \to \pi^+ \nu\nu}$ Rare $\mathbf{K^+}$ and $\mathbf{\pi^0}$ decays

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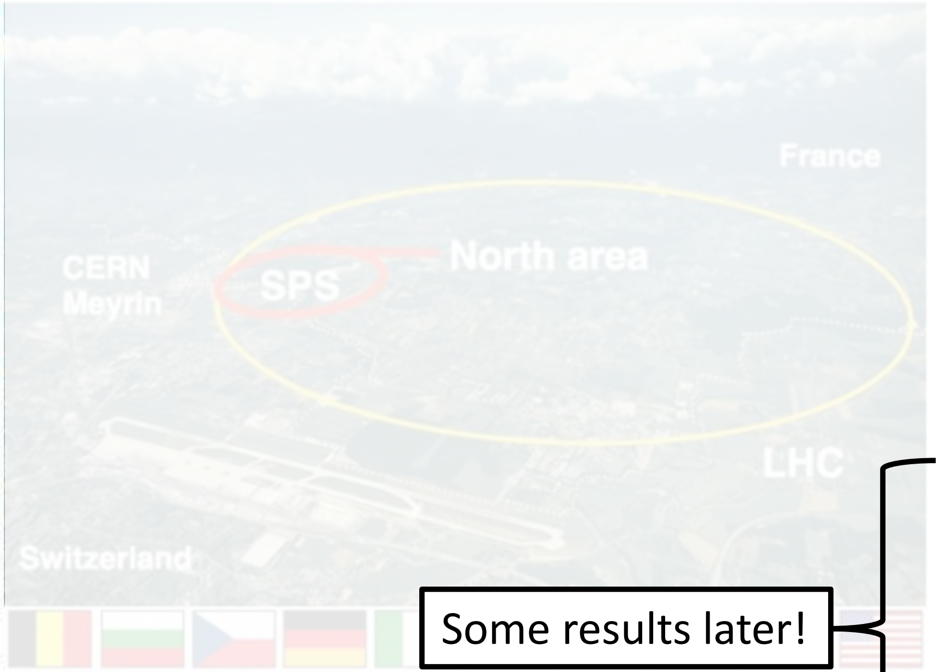

Some results later!

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Requirements of the NA62 experiment

- NA62 aims to make a 10% branching fraction measurement, to match the precision of the theory calculation
  - Must collect at least 100 signal events

- Assume SM branching fraction → 9.11×10^{-11} (lets say 10^{-10})
- Assume (realistic) 10% signal acceptance

- To collect 100 events:

  $100 / (0.1 * 10^{-10}) = 10^{13}$ K^+ decays in fiducial volume

- For every 100 signal events, must have less than 10 background events …

  Background rejection at the level of 10^{-12}

- **Measuring $K^+ \to \pi^+ \nu\nu$ needs a huge Kaon rate**

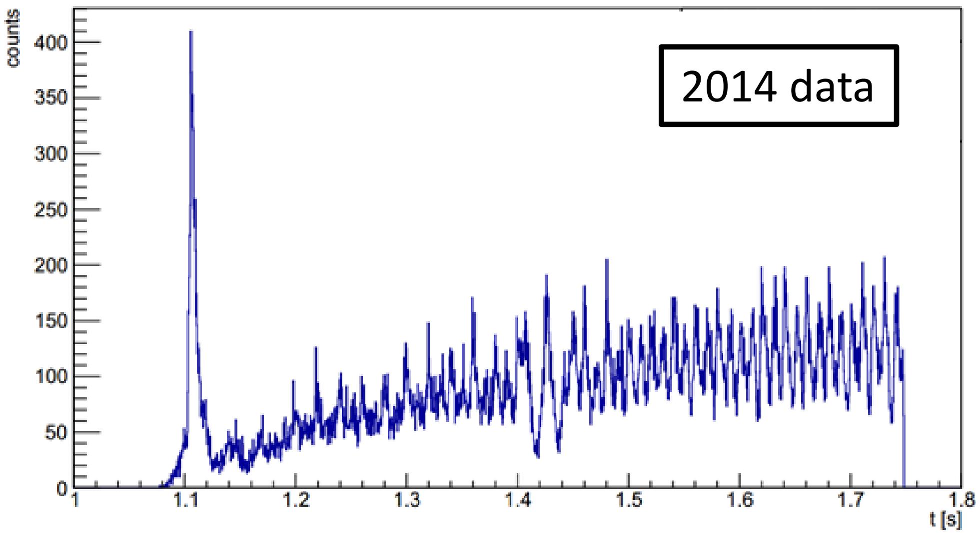
  with equally huge background rejection

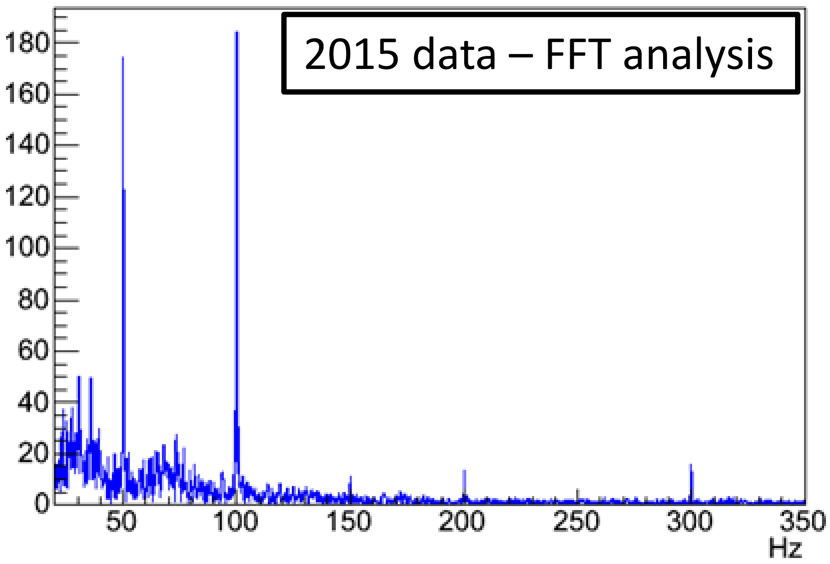
The NA62 beamline

- SPS Protons @ 400 GeV steered to Beryllium target (T10)
- Secondary hadron beam – 6% Kaons (70% pions, rest = protons, electrons)
- 750 million particles per second, each momentum selected @ 75 GeV

- SPS capable of delivering enough K^+ in two years to perform NA62 physics

- **50Hz and 100Hz beam oscillation discovered with first NA62 data**

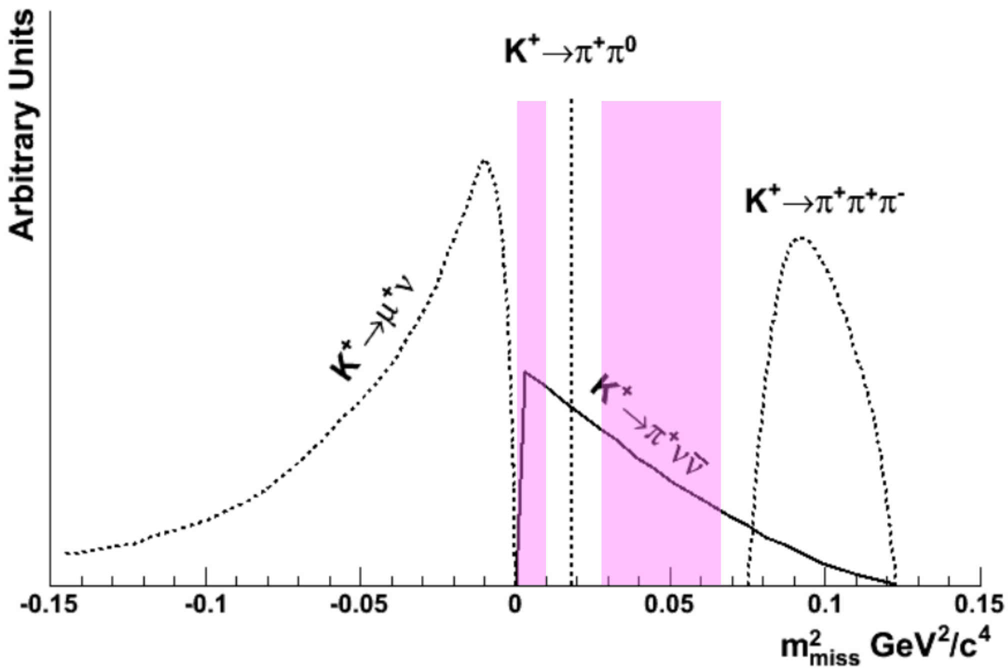




Kinematic rejection of background

- Before any selection is made, the single-track sample is dominated by the ***$K^+ \to \mu^+ \nu$, $K^+ \to \pi^+ \pi^0$** and **$K^+ \to \pi^+ \pi^- \pi^+$*** decays
- These decays can be removed using the squared missing mass:

$$m_{miss}^2 \approx m_K^2 \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m_\pi^2 \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta_{\pi K}^2$$



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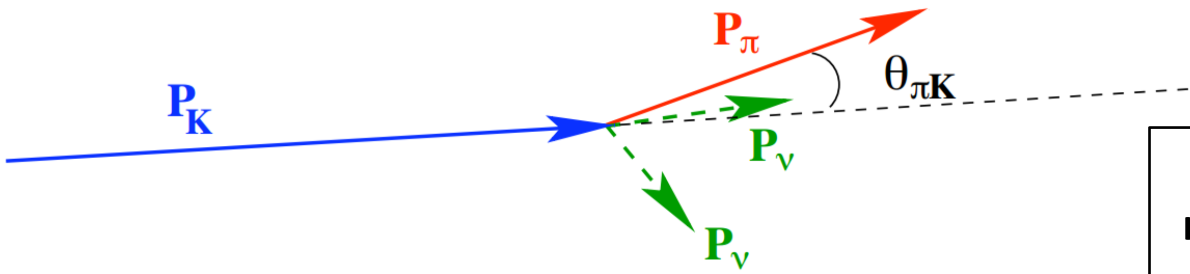
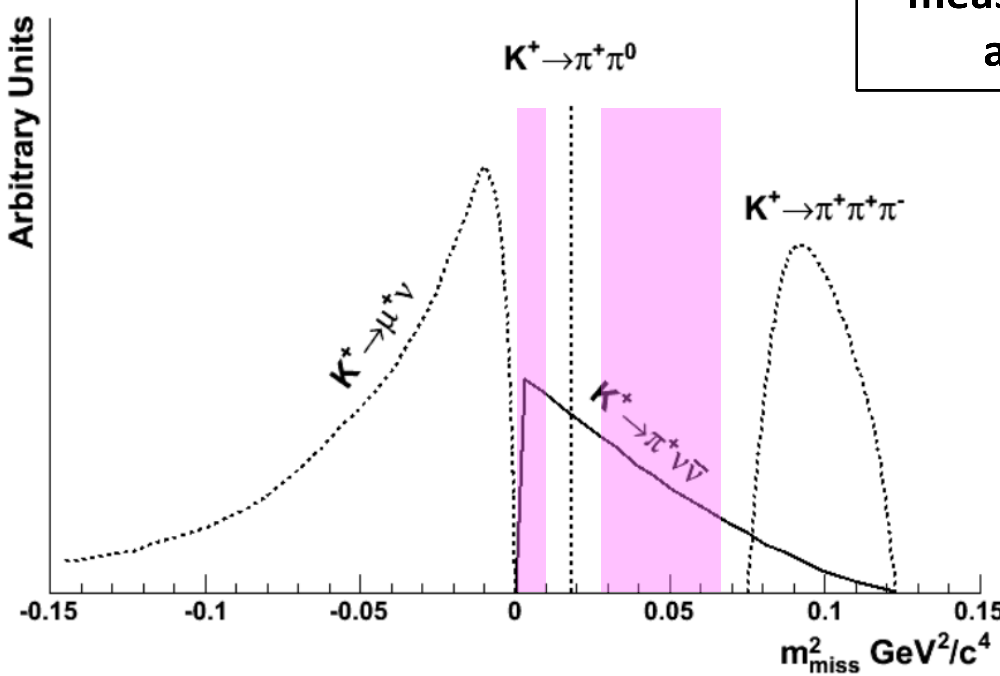
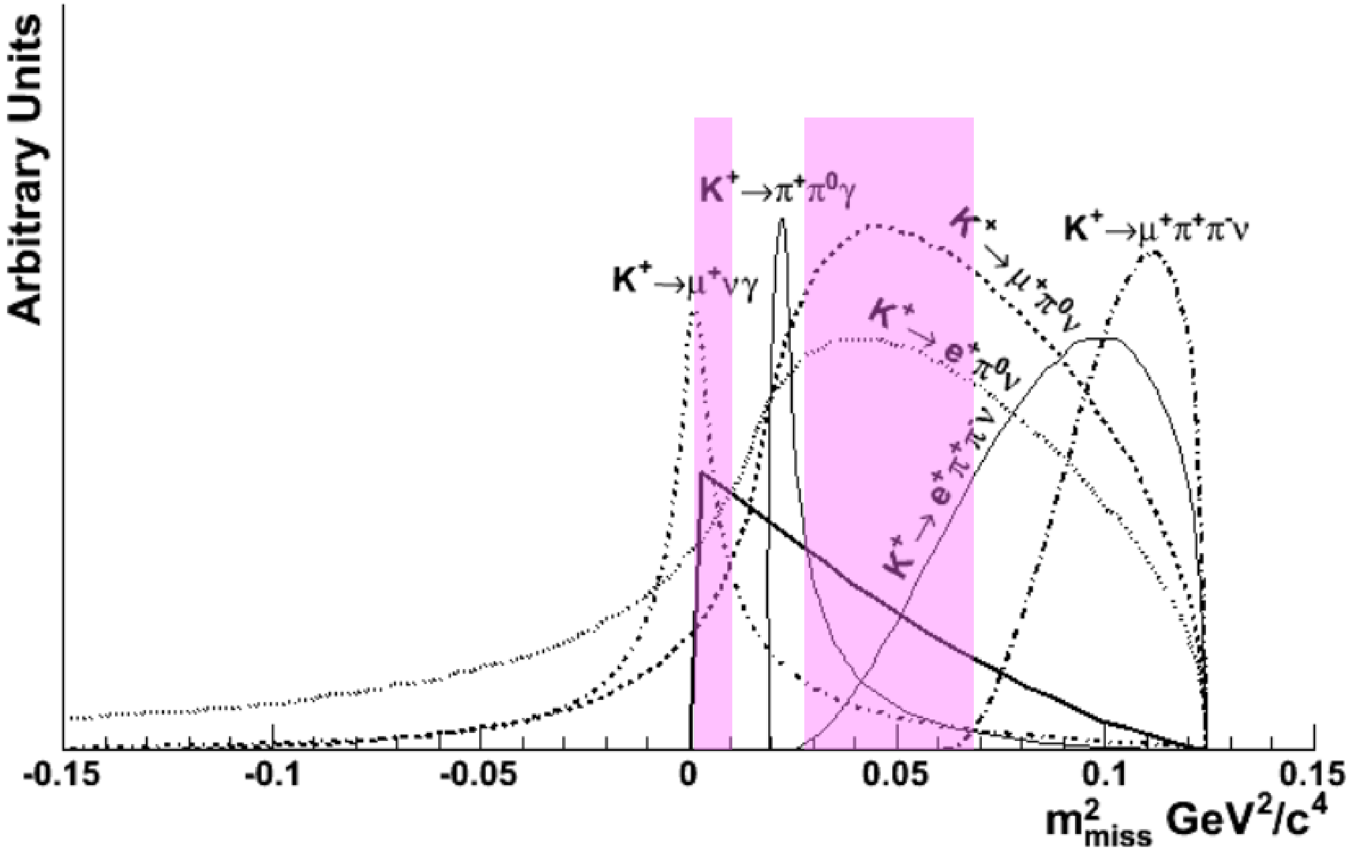


Need excellent momentum and position measurement of the K⁺ and π⁺ particles



Kinematic rejection of background

- Many processes contribute to the two signal regions!



Remaining backgrounds

- After kinematic selection, remaining backgrounds include:

Decay backgrounds

Mode	BR
$\mu^+\nu(\gamma)$	63.5%
$\pi^+\pi^0(\gamma)$	20.7%
~~$\pi^+\pi^+\pi^-$~~	~~5.6%~~
$\pi^0 e^+\nu$	5.1%
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$\pi^+\pi^- e^+\nu$	4.1×10^{-5}
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Muon veto, π and μ identification

Photon veto

Electron identification

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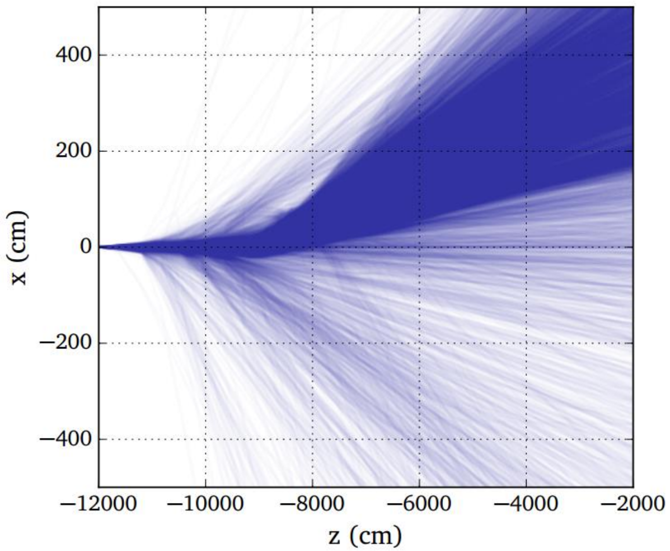
The Muon Halo

- There is a further background contribution from

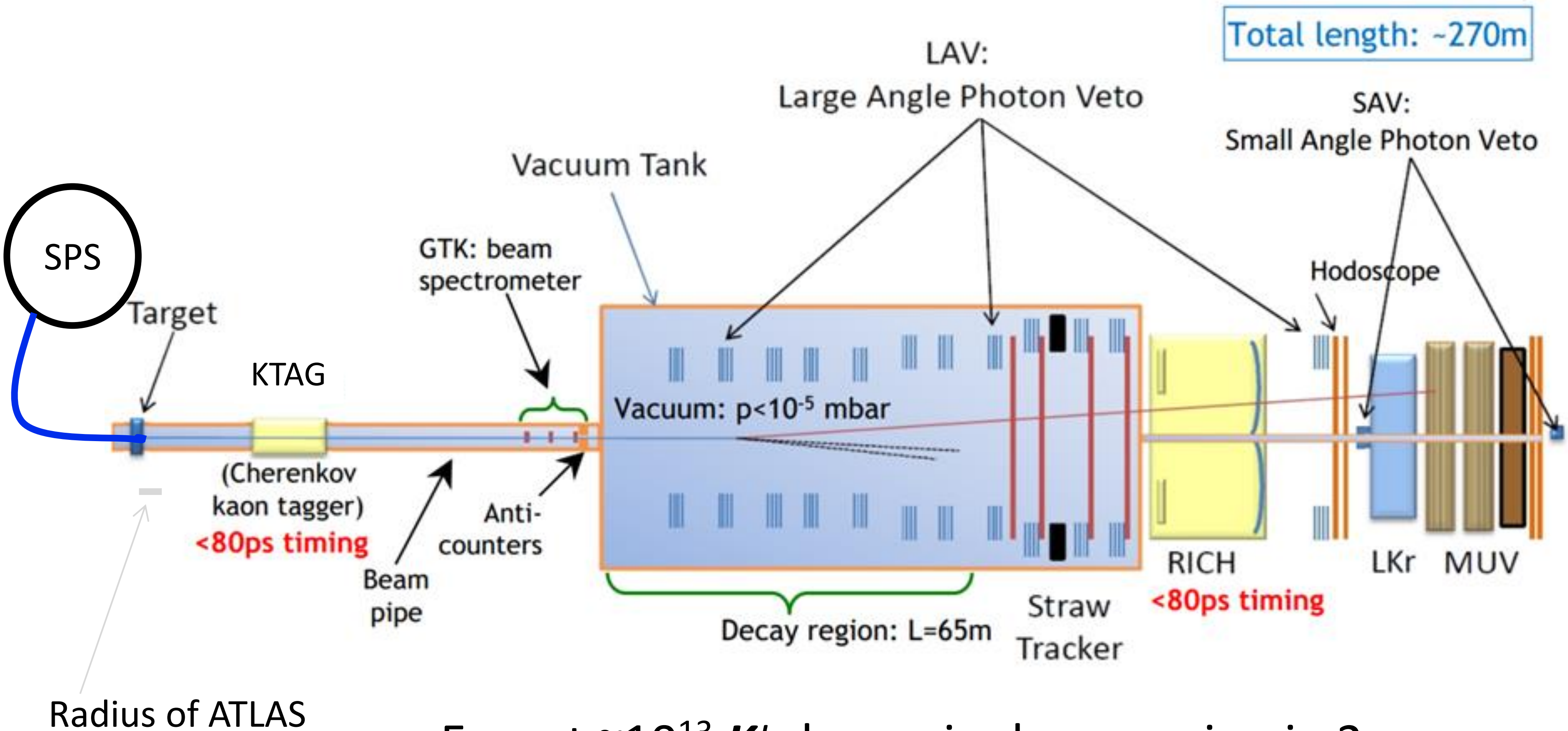
1. Muons generated at the target
2. Muons generated by beam interactions with material,
3. Muons from decays of beam particles ($\pi^{\pm} \rightarrow \mu^{\pm}\nu$),

- Creates a high-rate 'halo' of muons



- The 'halo muons' are **not** correlated with Kaon decays in the fiducial volume.
- Rejection based on **Tagging Kaons,** plus muon veto and π - μ identification

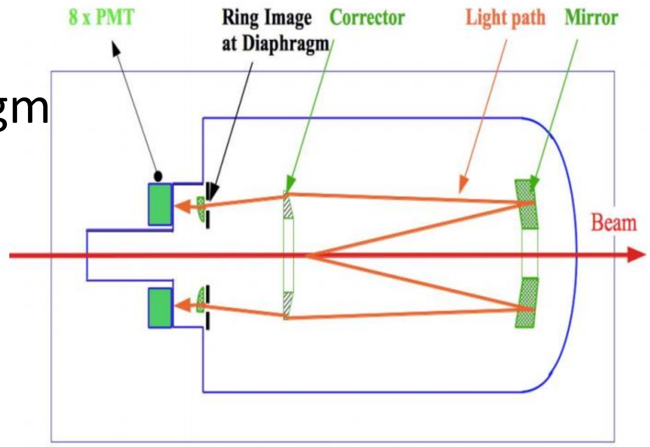
The NA62 Detector

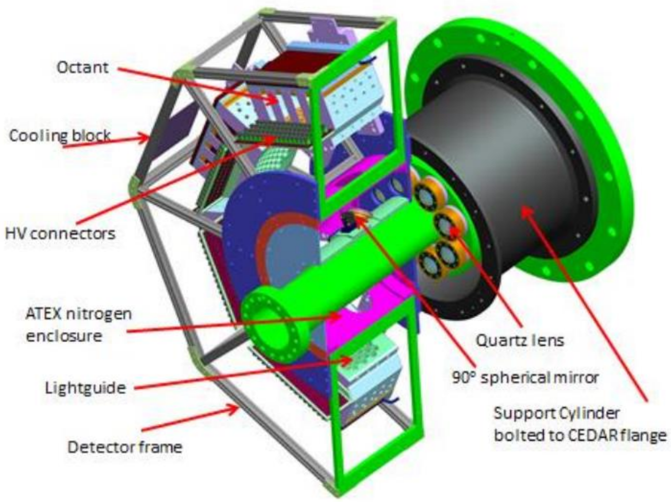


Expect ~10^{13} K^+ decays in decay region in 2 years

K^+ tagging – CEDAR/KTAG

- Kaons are tagged with the **CEDAR/KTAG** system
- **CEDAR** – collects Cherenkov light with fixed diaphragm
- **KTAG** – 8-fold PMT array with $\sigma_t \approx 80$ ps
- Kaon rate ≈ 45 MHz
- Rate of detected photons ≈ 4 MHz per PMT





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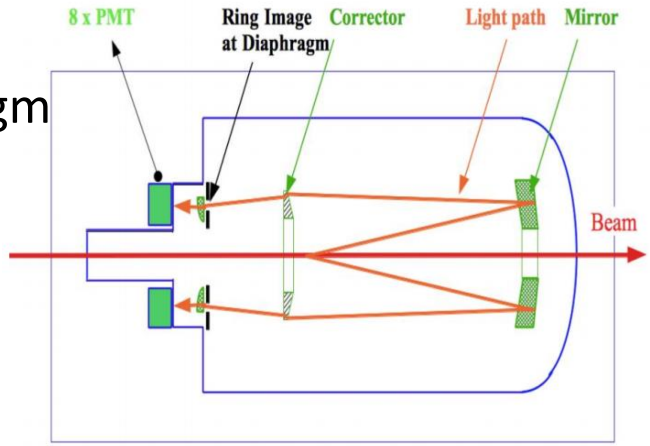
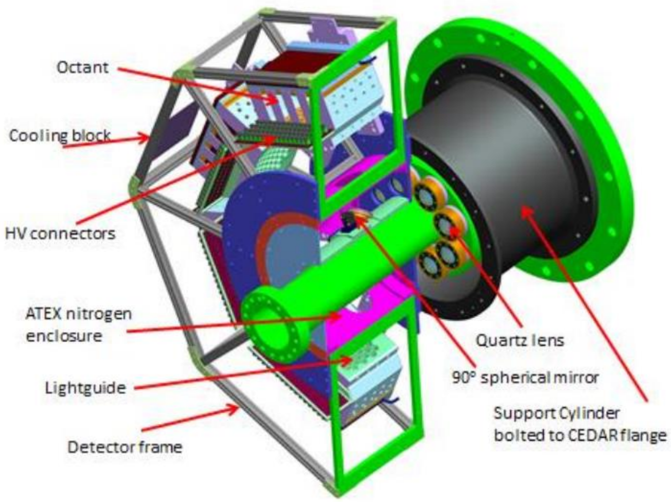
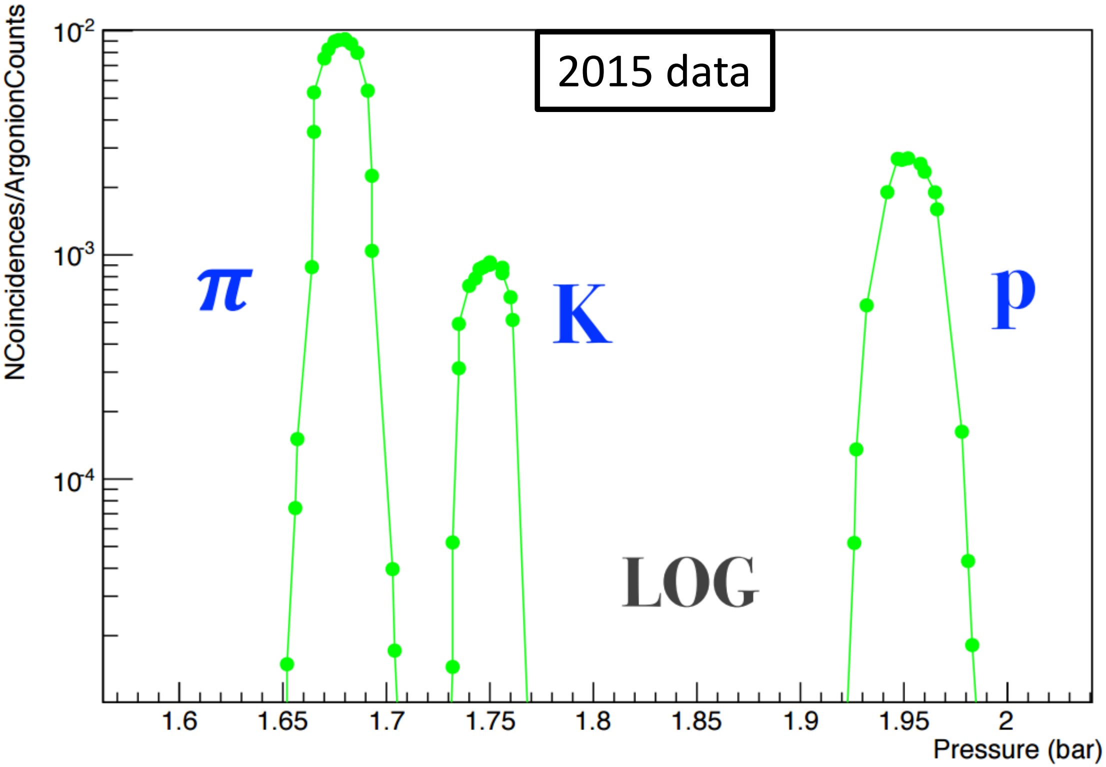
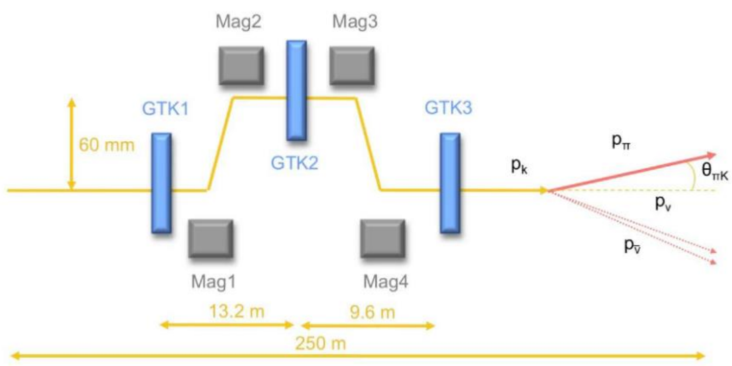


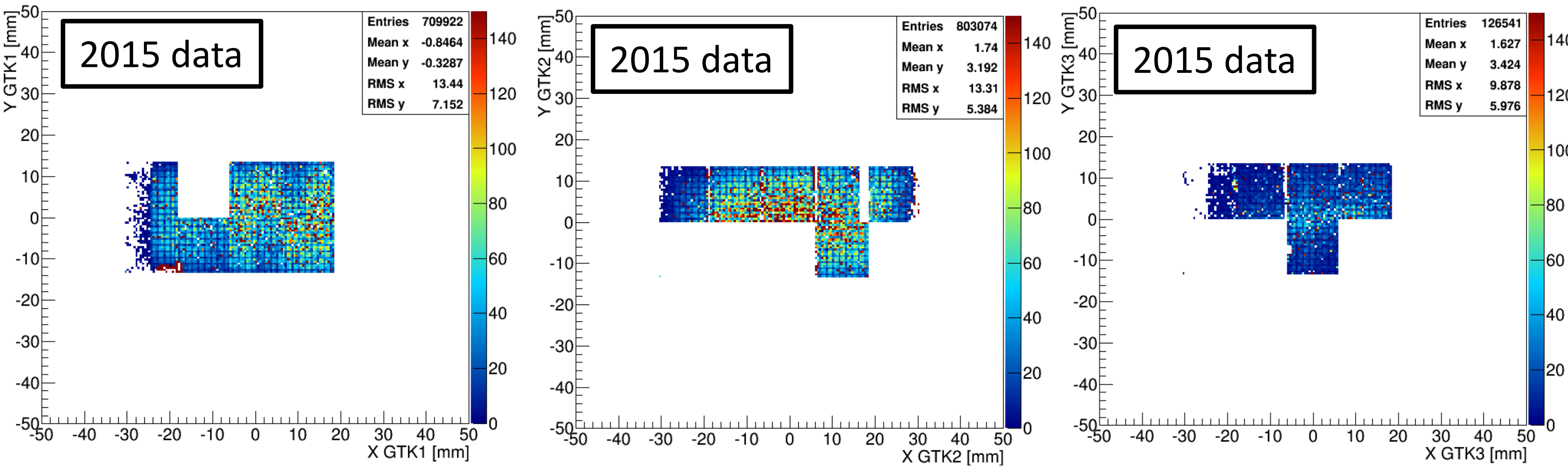




K^+ measurement – GigaTracker

- Position and momentum of K^+ measured with **GTK**
- **GTK** – beam spectrometer based on silicon pixel sensors
- Rate at **GTK3** ≈ 750 MHz, measures $\sigma_p/p \approx 0.2\%$, $\sigma_\theta \approx 16$ μrad, $\sigma_t \approx 200$ps





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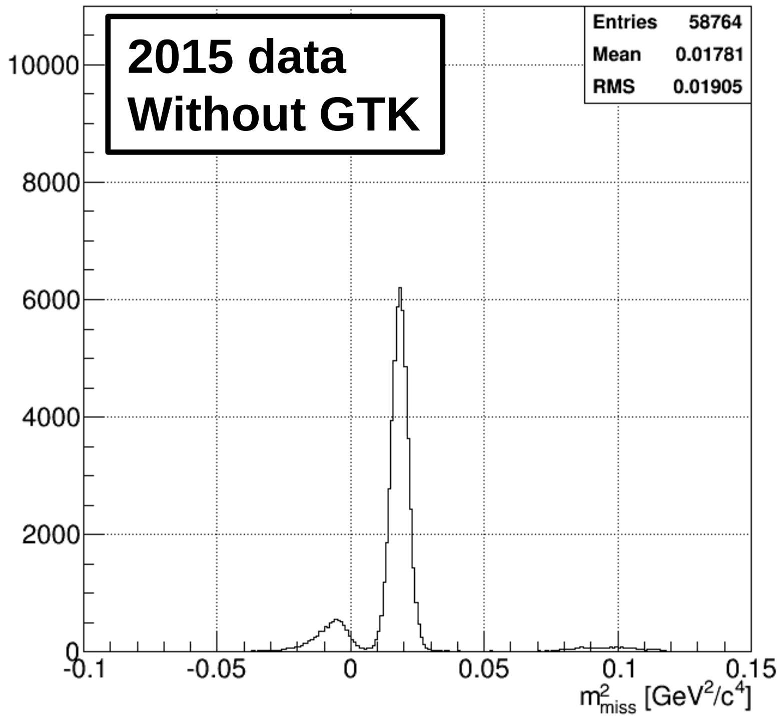

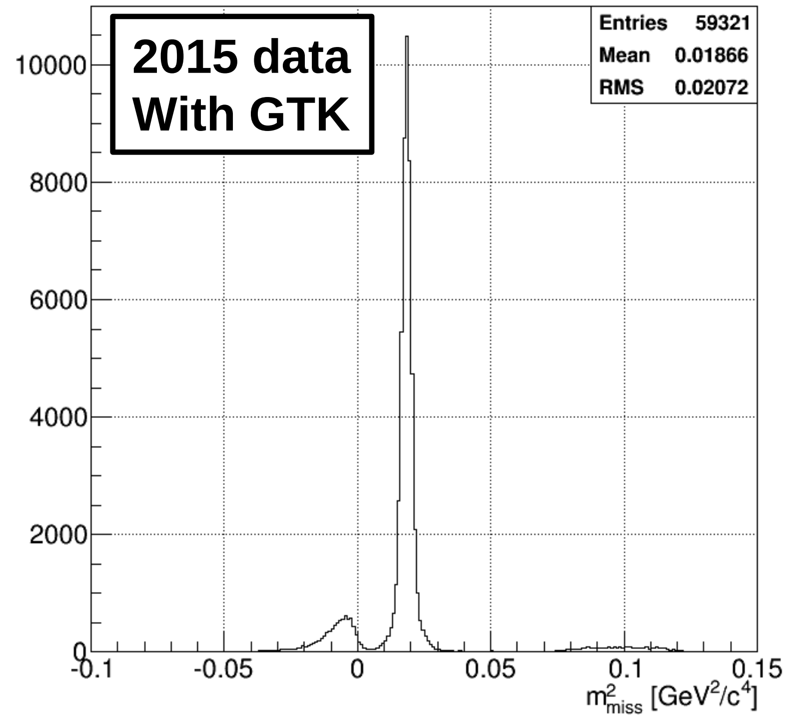

- Further improvements expected…

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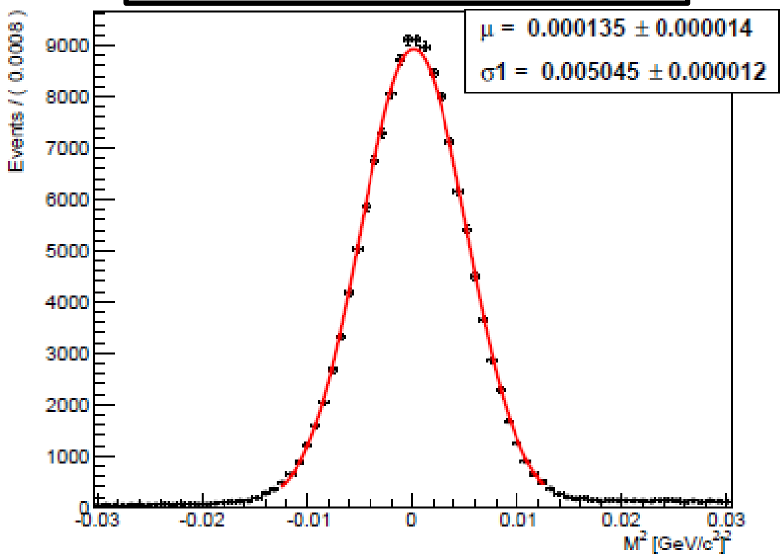
2015 data without GTK



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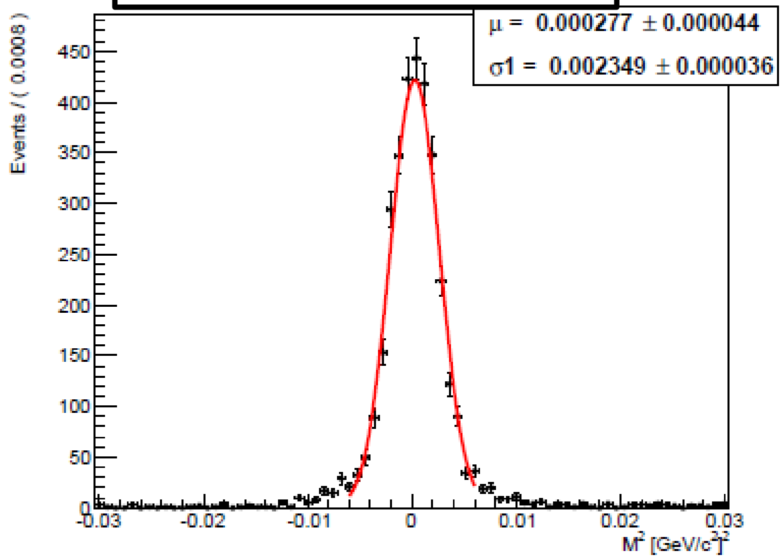

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π^+ measurement – STRAWS

- Position and momentum of π^+ measured by the **STRAW** spectrometer
- Straw tubes operated in vacuum – very low material budget!
- 4 chambers * 4 views (uv,xy) * 4 layers
- 112 straws per layer = 7168 total

- **$\sigma_{x,y} \leq 80\mu m$ per chamber**

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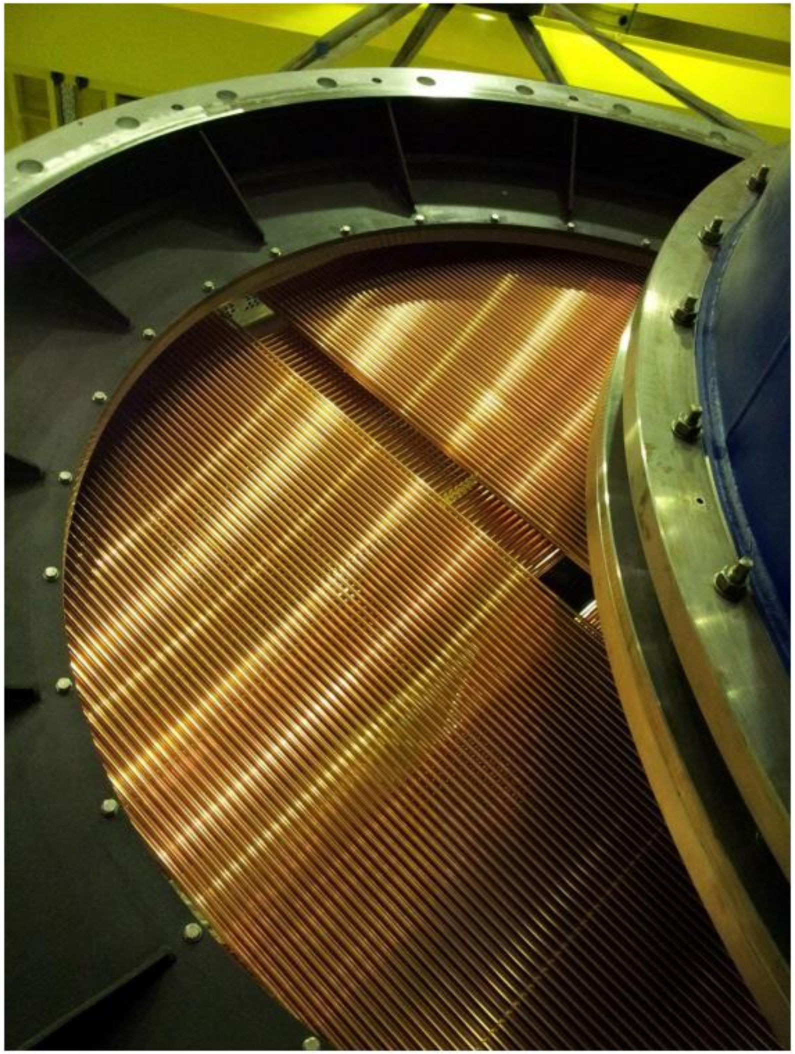
  ATLAS pixel resolution > 6 μm^2
  LHCB VELO hit resolution > 5 μm^2



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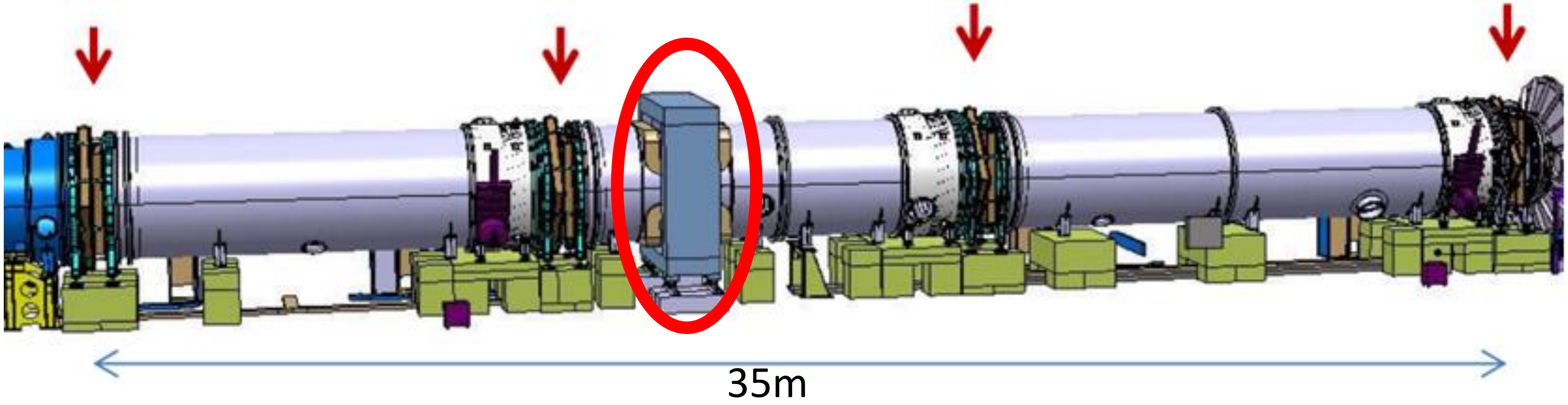
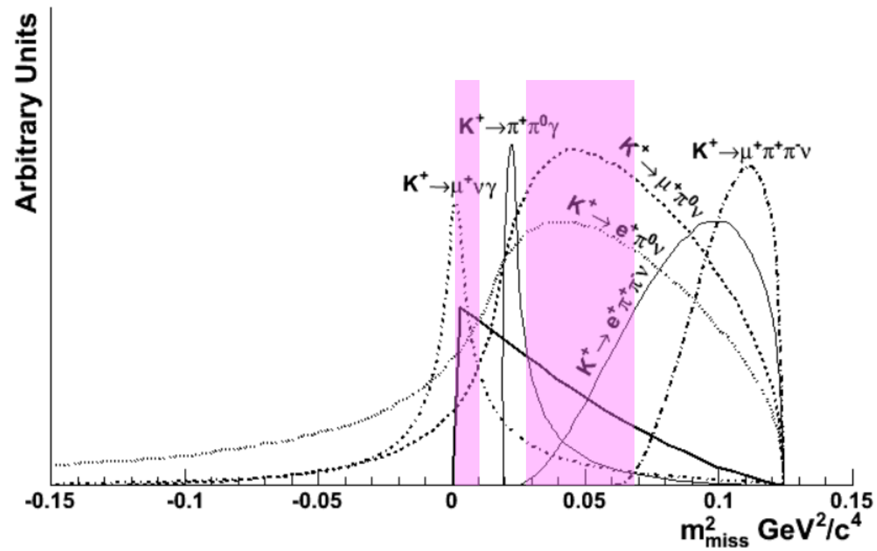


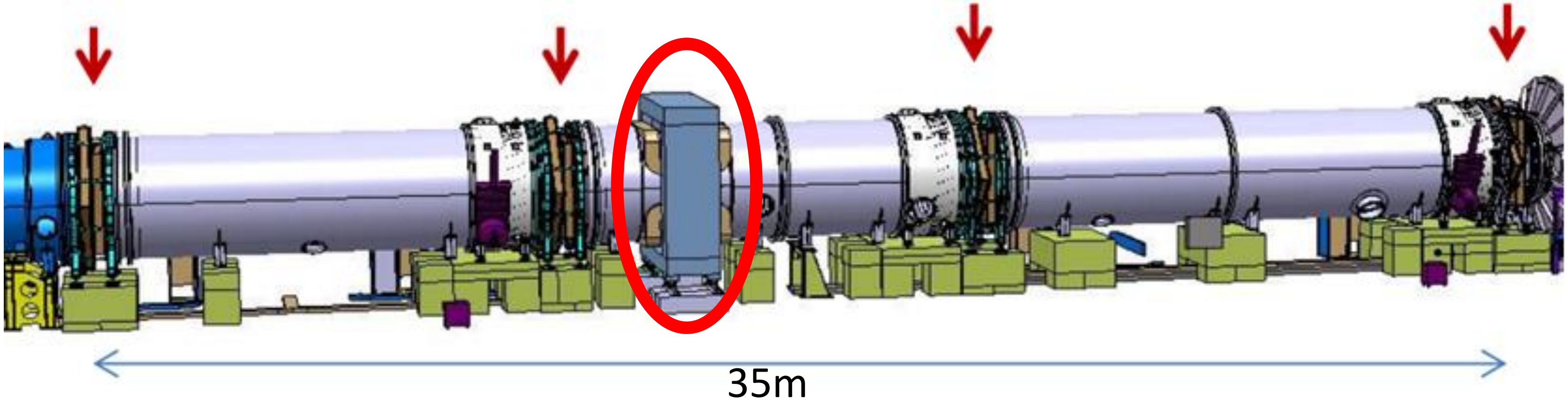
- Magnet system causes $\mathbf{\Delta p_x \approx 270}$ **MeV**
- $\sigma_p/p \approx 0.32\% \oplus 0.008\%\, p$ **[GeV/c]**
- $\sigma_{\theta(K\pi)} \approx 20\text{-}50$ **μrad**

- m^2_{miss} **resolution ≈ 0.001 GeV^2/c^4**

$\sigma_{pT}/pT \approx$ 2-10% ATLAS muons 2010
$\sigma_p/p \approx$ 0.5% LHCb muons 2015



π^+ measurement – STRAWS



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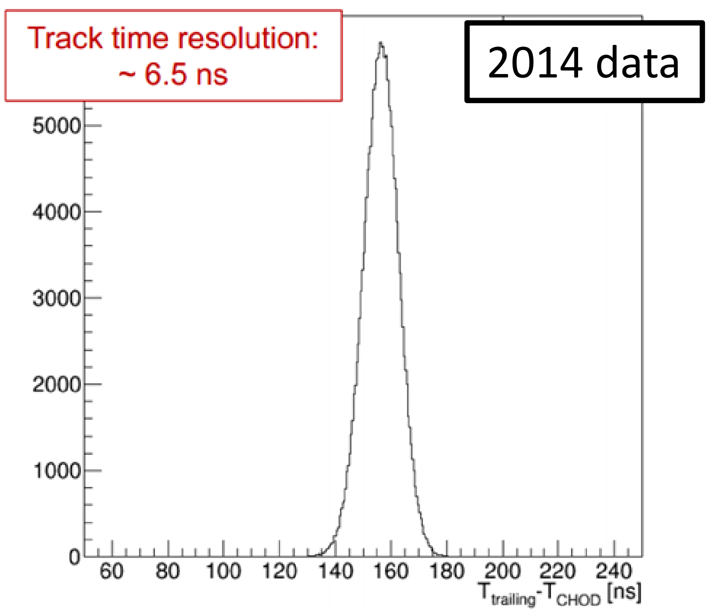
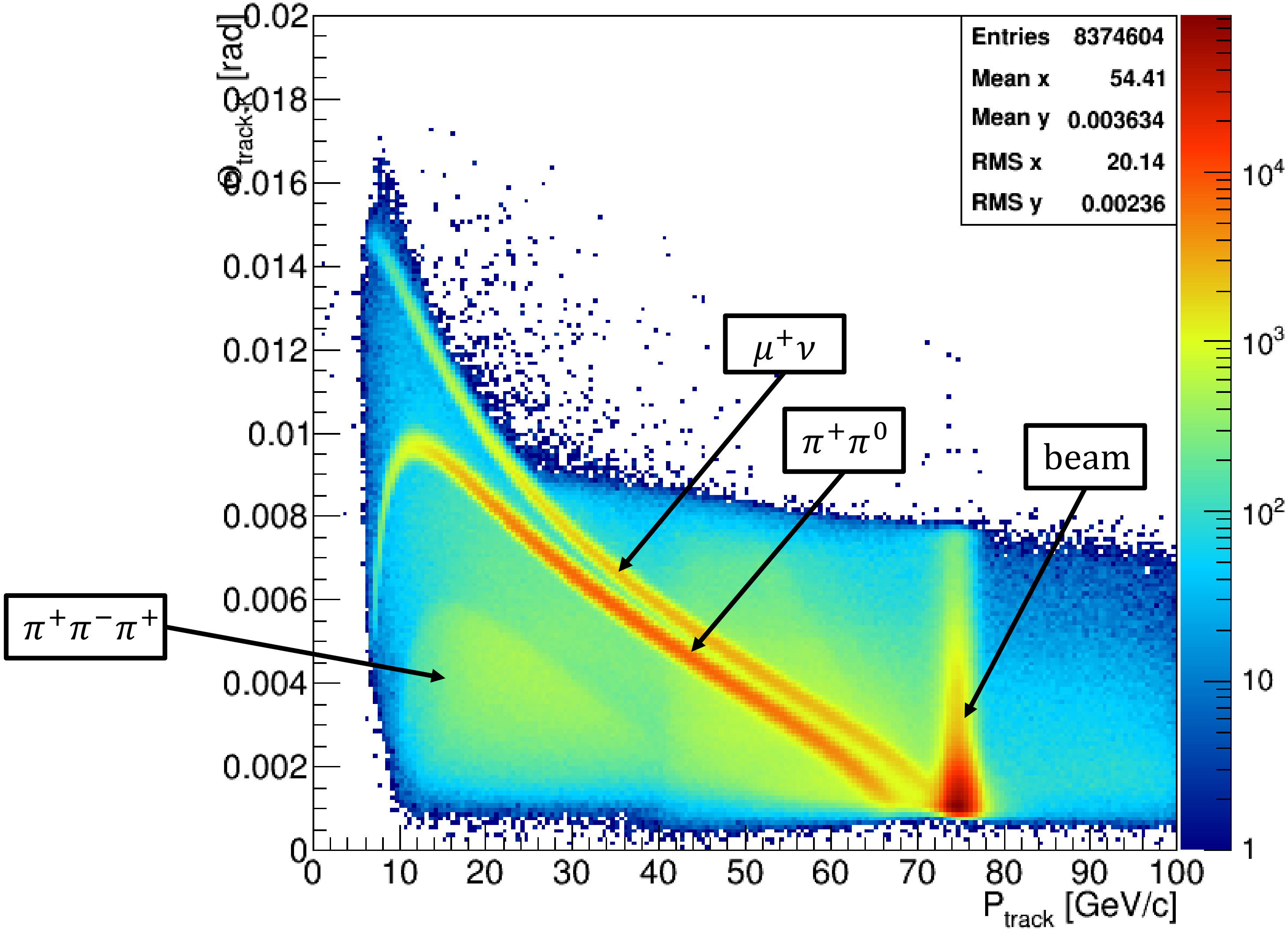
$\sigma_{pT}/pT \approx$ 2-10% ATLAS muons 2010
$\sigma_p/p \approx$ 0.5% LHCb muons 2015

- **$\sigma_t \approx$ 80ns hit resolution**
- Cannot be used in low-level trigger

- **$\sigma_t \approx$ 6.5ns track resolution**
- Not sufficient for *K^+* matching

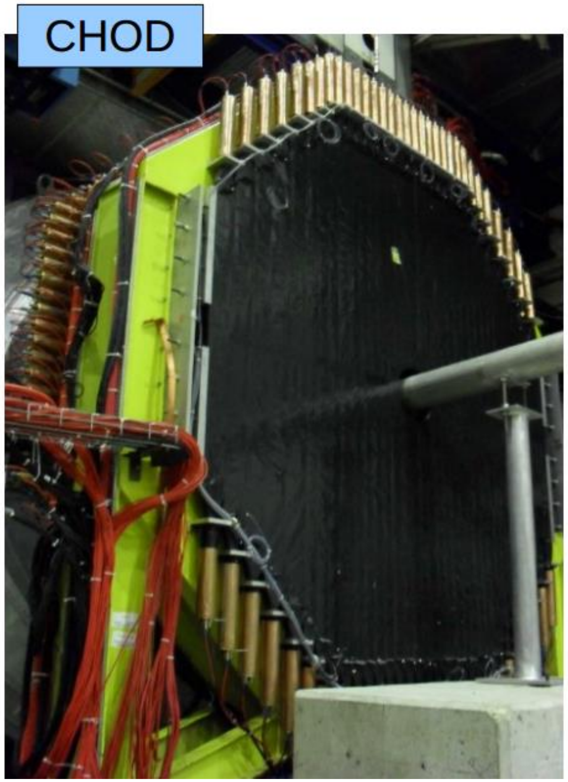


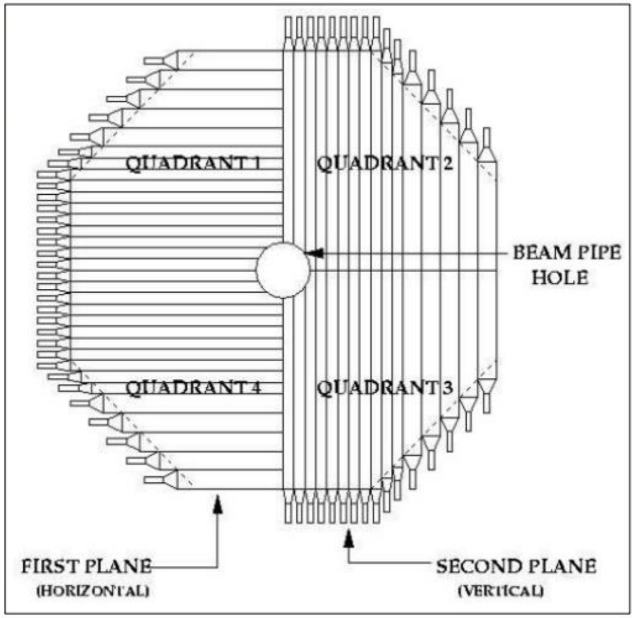
STRAW tracker – 2015 data



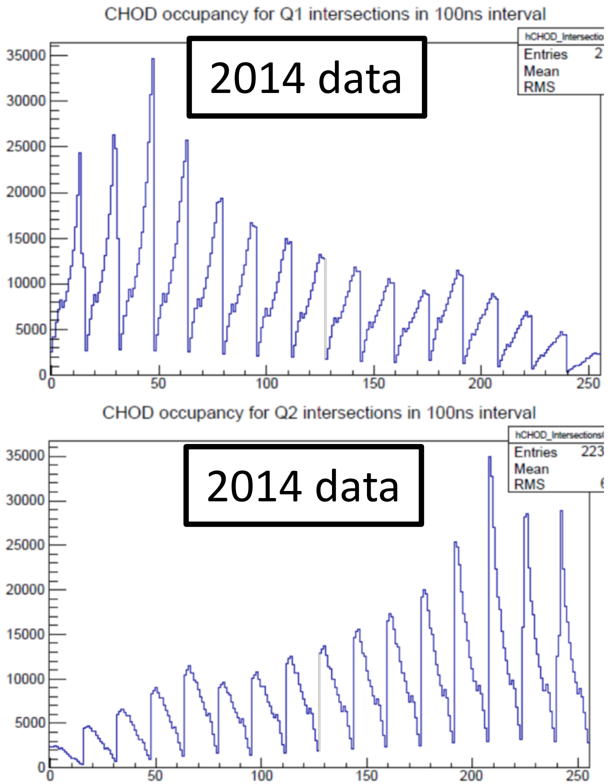
Charged particle triggering – CHOD

- Charged Hodoscope (CHOD)
- Fast detector for triggering on charged particle(s)
- Time resolution $\sigma_t \approx$ **300ps**
- Each quadrant has 16 scintillating slabs. $16_X * 16_Y = 256$ intersections/quad



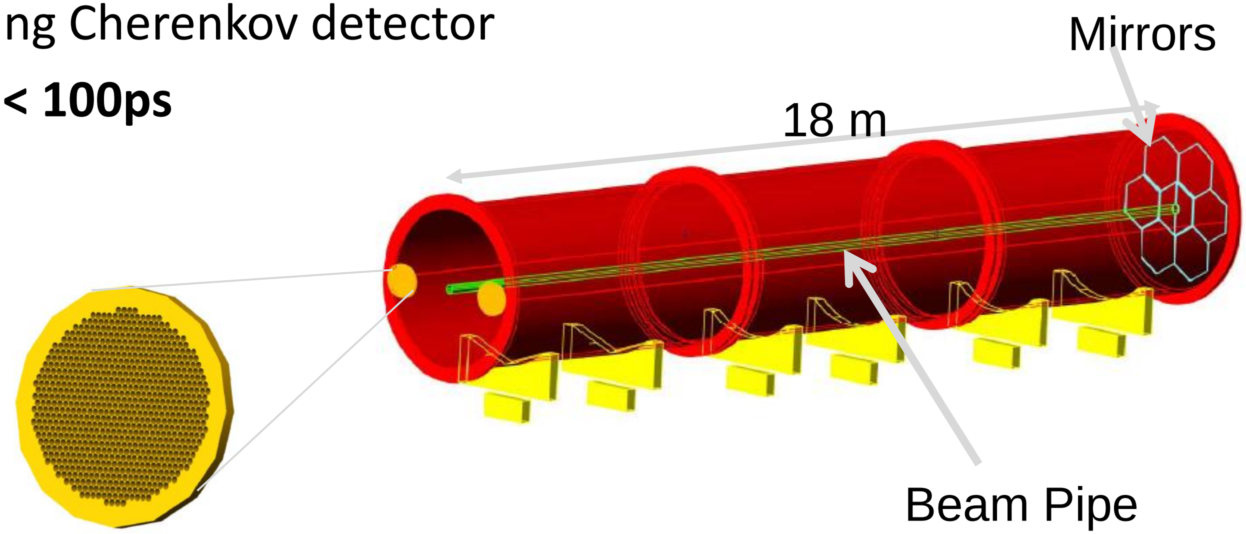


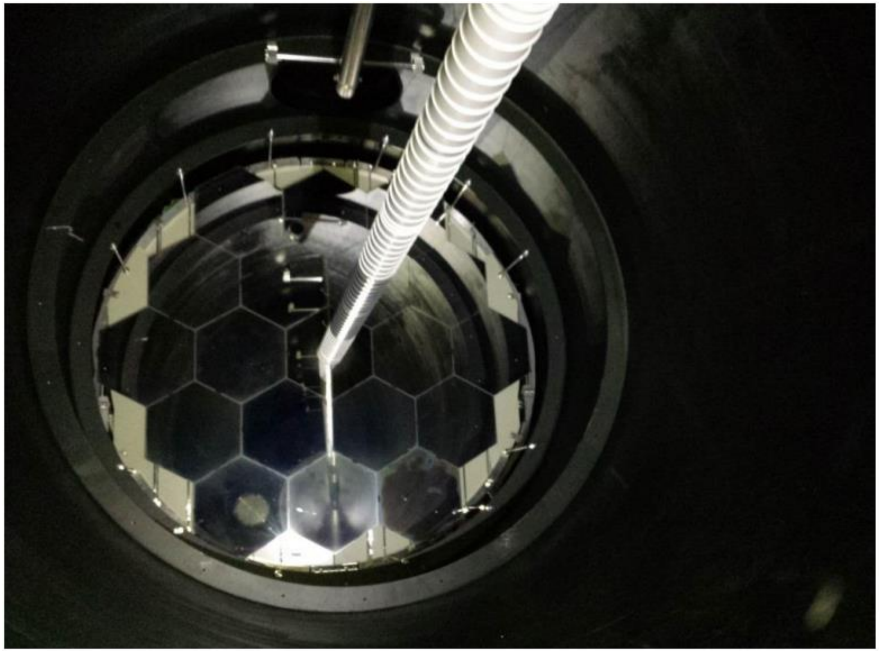
2 planes (horizontal + vertical) of 64 plastic scintillator strips each



Particle identification – RICH

- RICH – Ring Imaging Cherenkov detector
- **Precise timing at < 100ps**
- Over 2000 PMTs!





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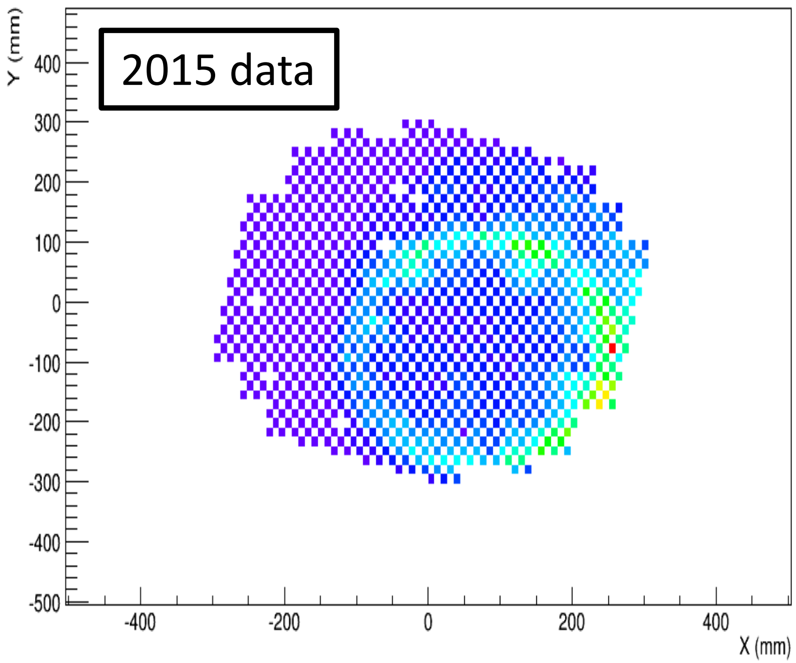

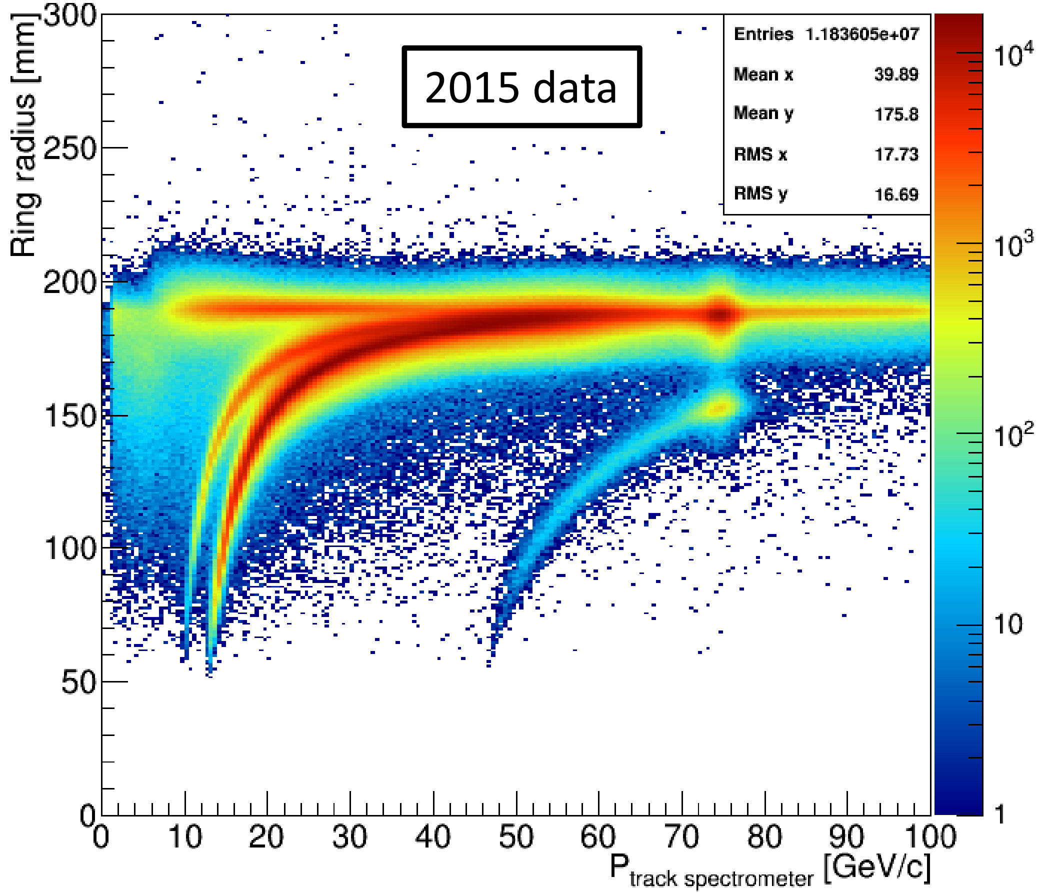

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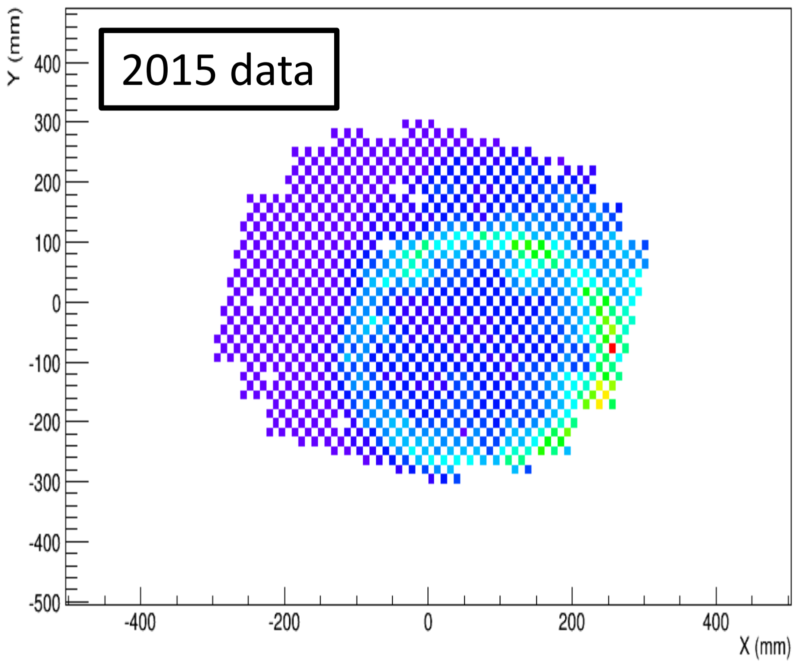
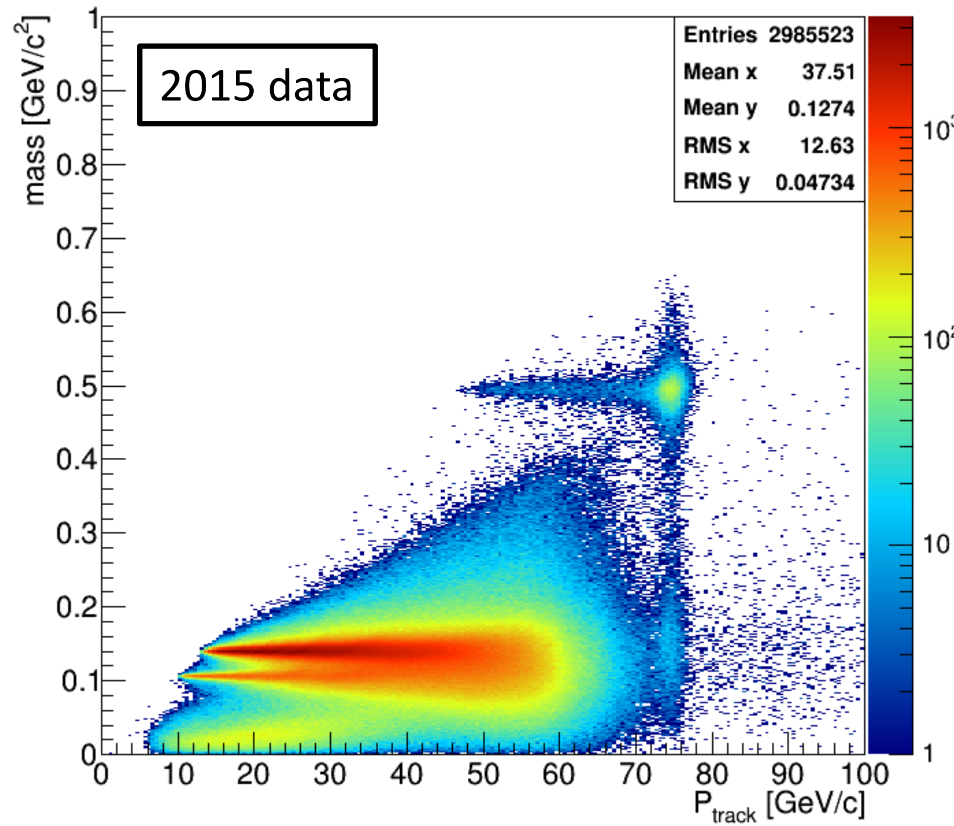
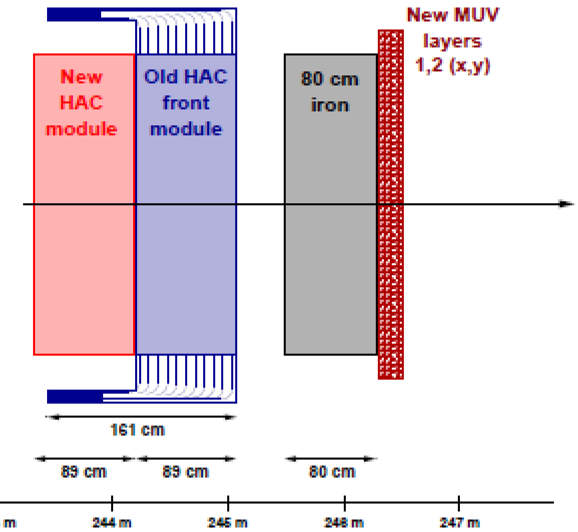


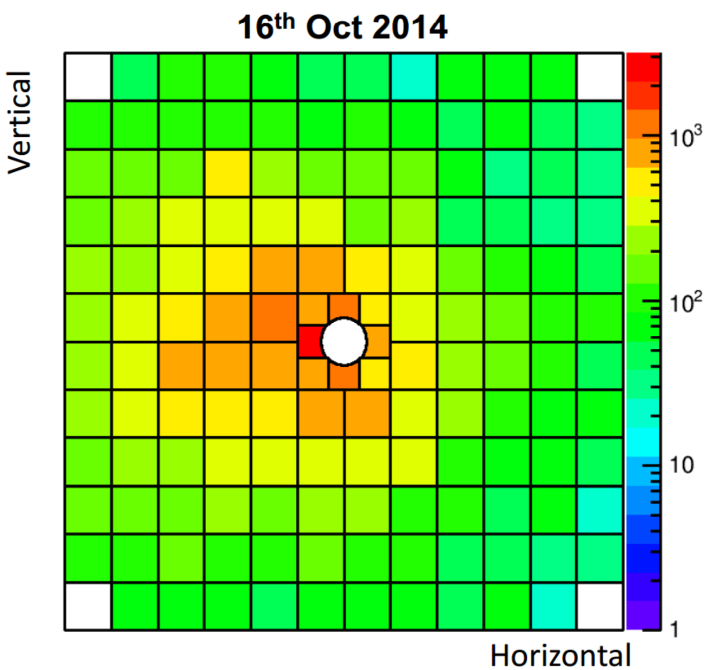


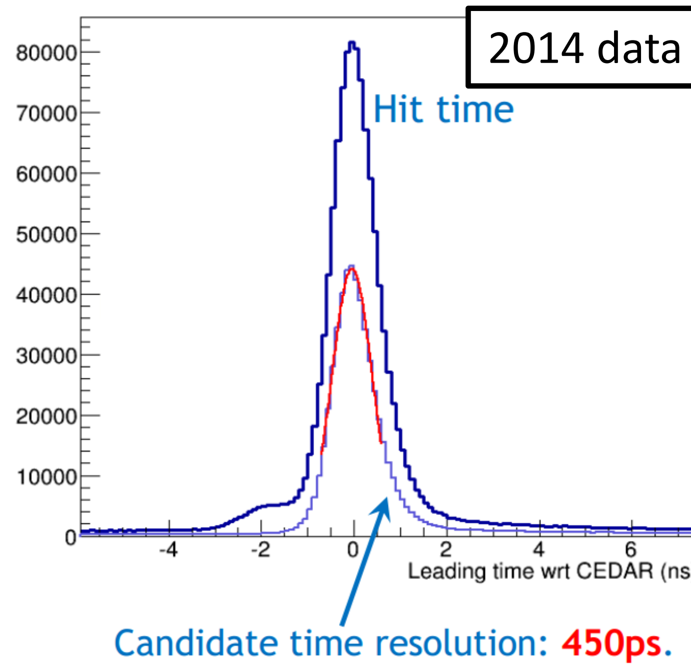
- Clear separation of **π** and **μ** at low momentum
- Support RICH at high momentum with dedicated **π** and **μ** particle identification

Muon veto – MUV

- MUV system formed of two calorimeters (MUV1, MUV2) plus a segmented layer of plastic scintillator (MUV3)
- MUV1&MUV2 provide **10^{-5}** muon rejection **offline**
- MUV3 provides muon rejection in the **trigger**
  MUV3 **$\sigma_t \approx$ 450 ps**, suitable for the low-level trigger







Photon veto – large angles

- The Large Angle Veto (LAV) – used lead glass blocks from **OPAL**
- Vetoes photons with $8.5 < \Theta < 50$ mrad, inefficiency $< 10^{-5}$
- **12 LAV stations** distributed along the experiment

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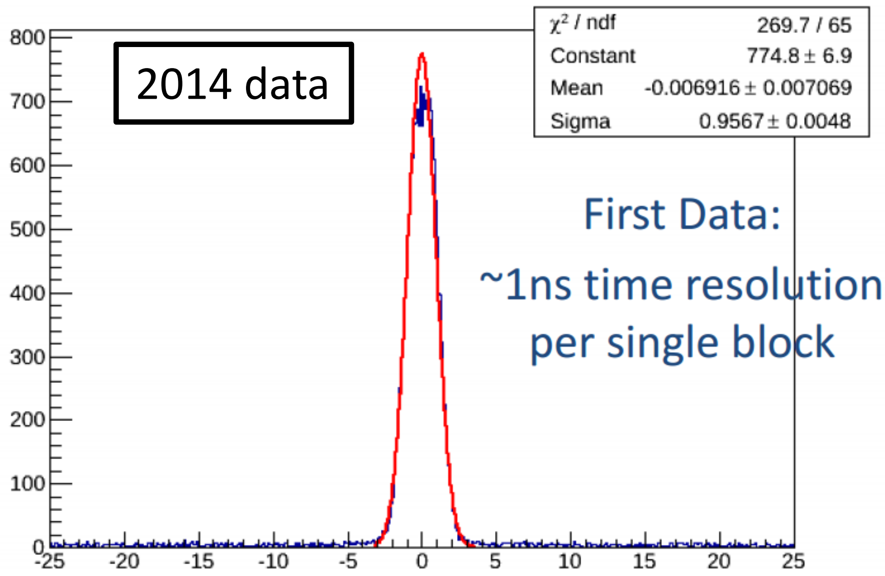
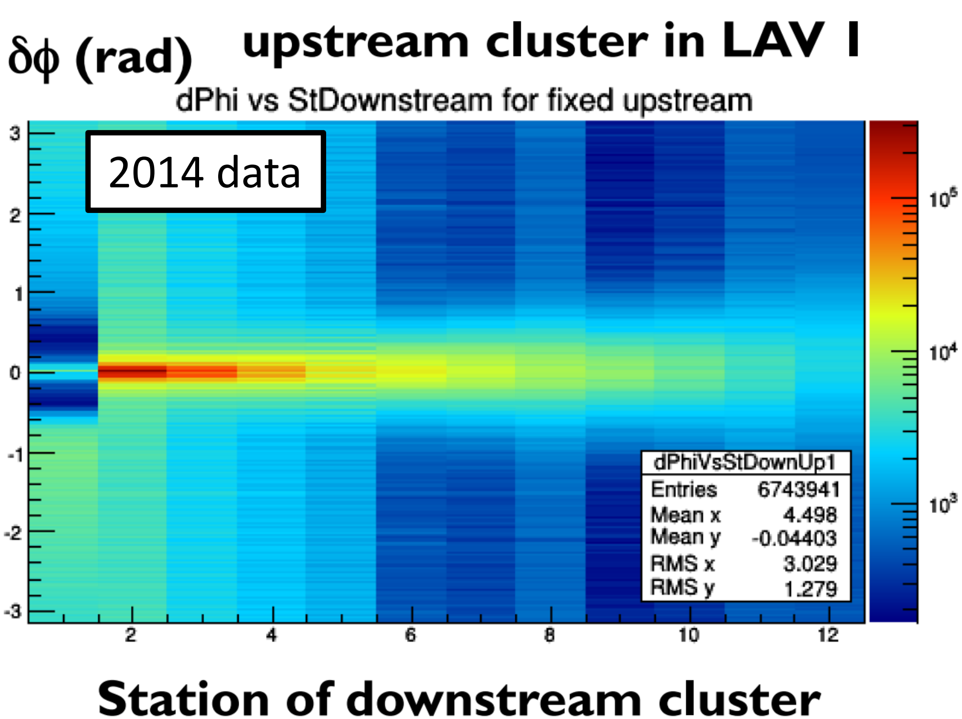
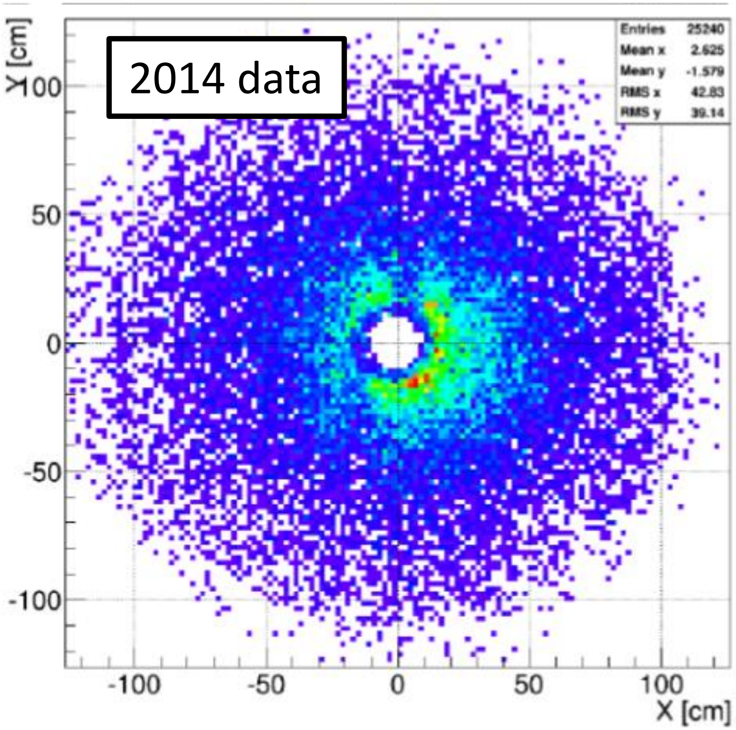




Photon veto – medium angles

- The **Liquid Krypton Calorimeter** (LKr, as used in NA48)
- Vetoes photons with **1 < ϴ < 8.5 mrad**
- Also provides electron identification, and photon – electron separation
- High granularity: more than 13k cells of $2x2cm^2$ area



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- Photon veto for photons with **1 < ϴ < 8.5 mrad**
- Also provides electron identification, and photon – electron separation
- High granularity (>13k channels)

Photon Inefficiency ($E\gamma$ > 10 GeV) < 8×10^{-6}

$$\frac{\sigma_E}{E} = \frac{3.2\,\%}{\sqrt{E(GeV)}} \oplus \frac{9\,\%}{E(GeV)} \oplus 0.42\,\%$$ [$\sigma_E/E \approx 1\%$ @ 10 GeV]

$$\sigma_{x,y} = \frac{4.2\text{mm}}{\sqrt{E(GeV)}} \oplus 0.6\text{mm}$$ [= 1.5 mm @ 10 GeV]

Comparable to CMS

ATLAS barrel	$\frac{\sigma_E}{E} = \frac{10.1\%}{\sqrt{E}} \oplus 0.17\,\%$

3% @ 10 GeV

Photon veto – medium angles

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- Photon veto for photons with $1 < \Theta < 8.5$ mrad, inefficiency $< 10^{-5}$
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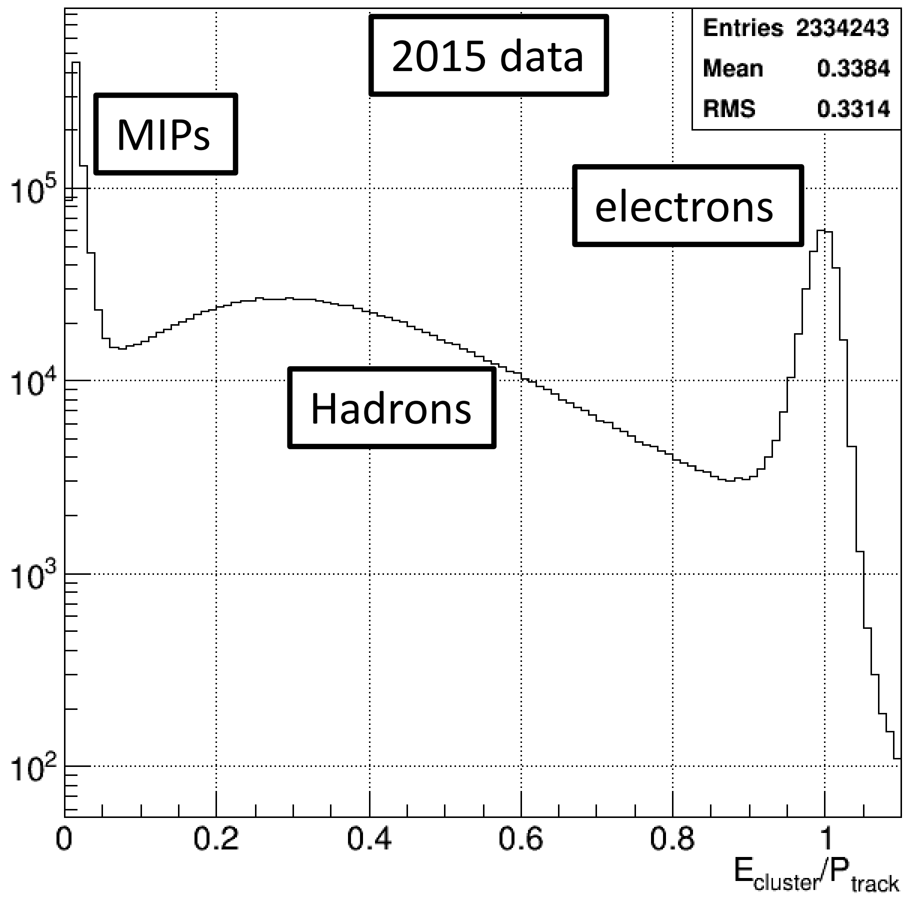
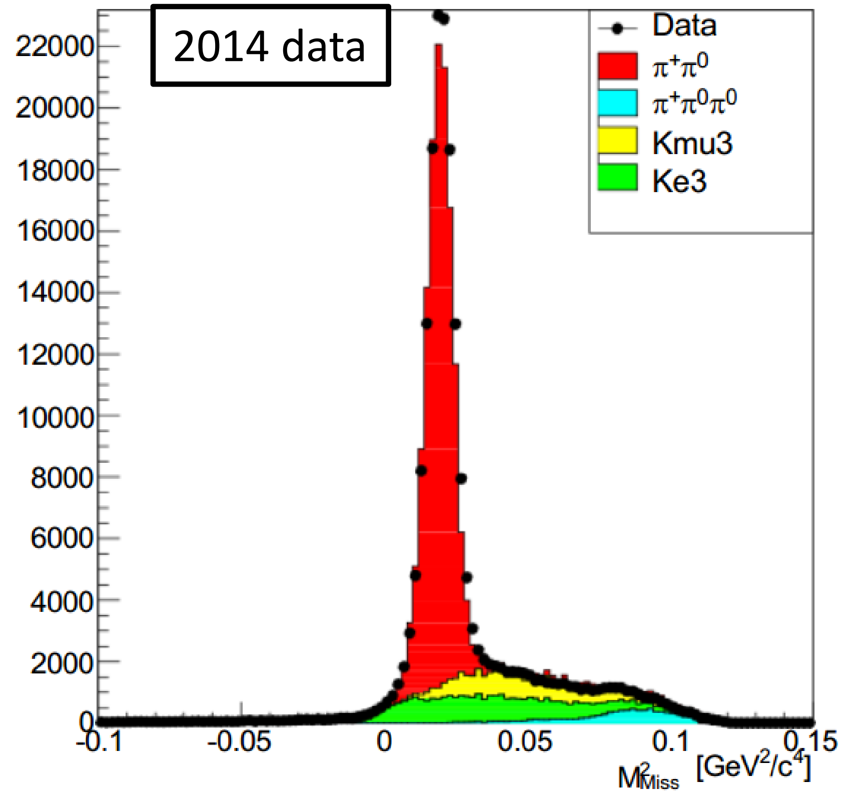
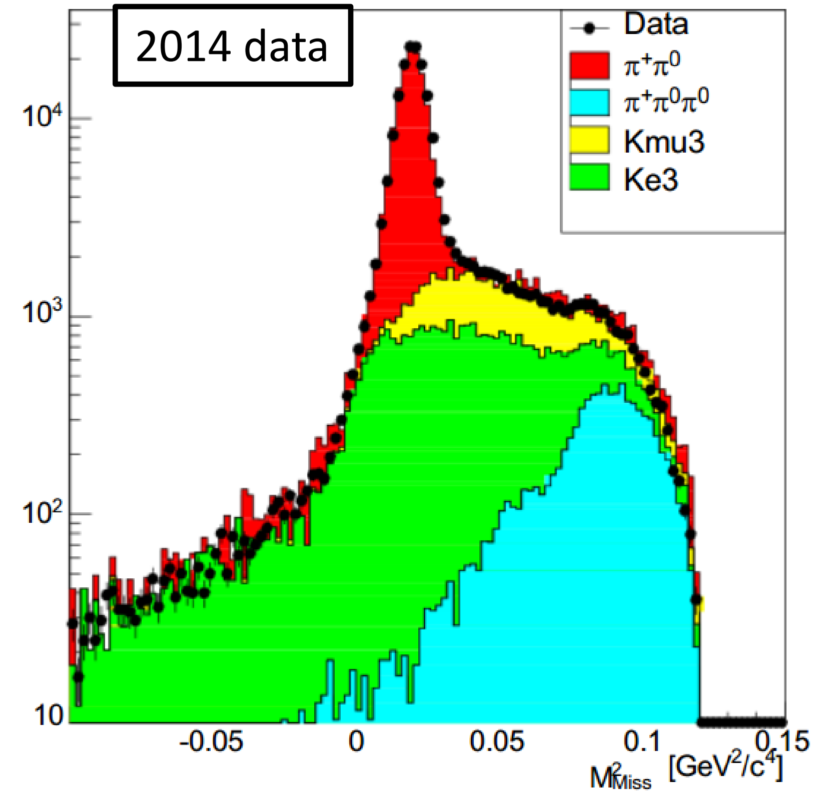


Photon veto – medium angles

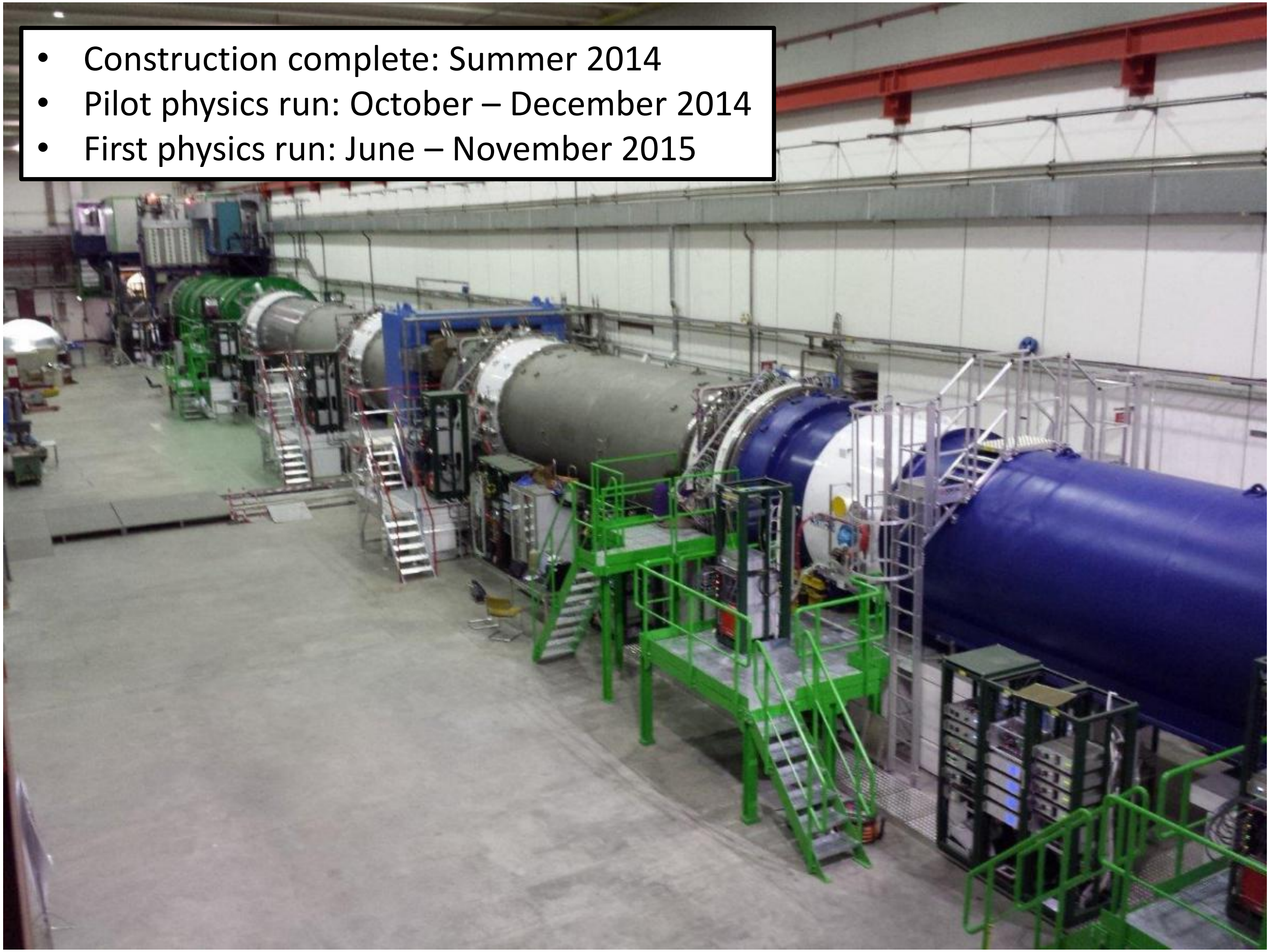
- The Liquid Krypton Calorimeter (LKr)
- For photons with $1 < \Theta < 8.5$ mrad, inefficiency $< 10^{-5}$
- Also provides electron identification, and photon – electron separation
- **Analysis of the LKr data already underway**



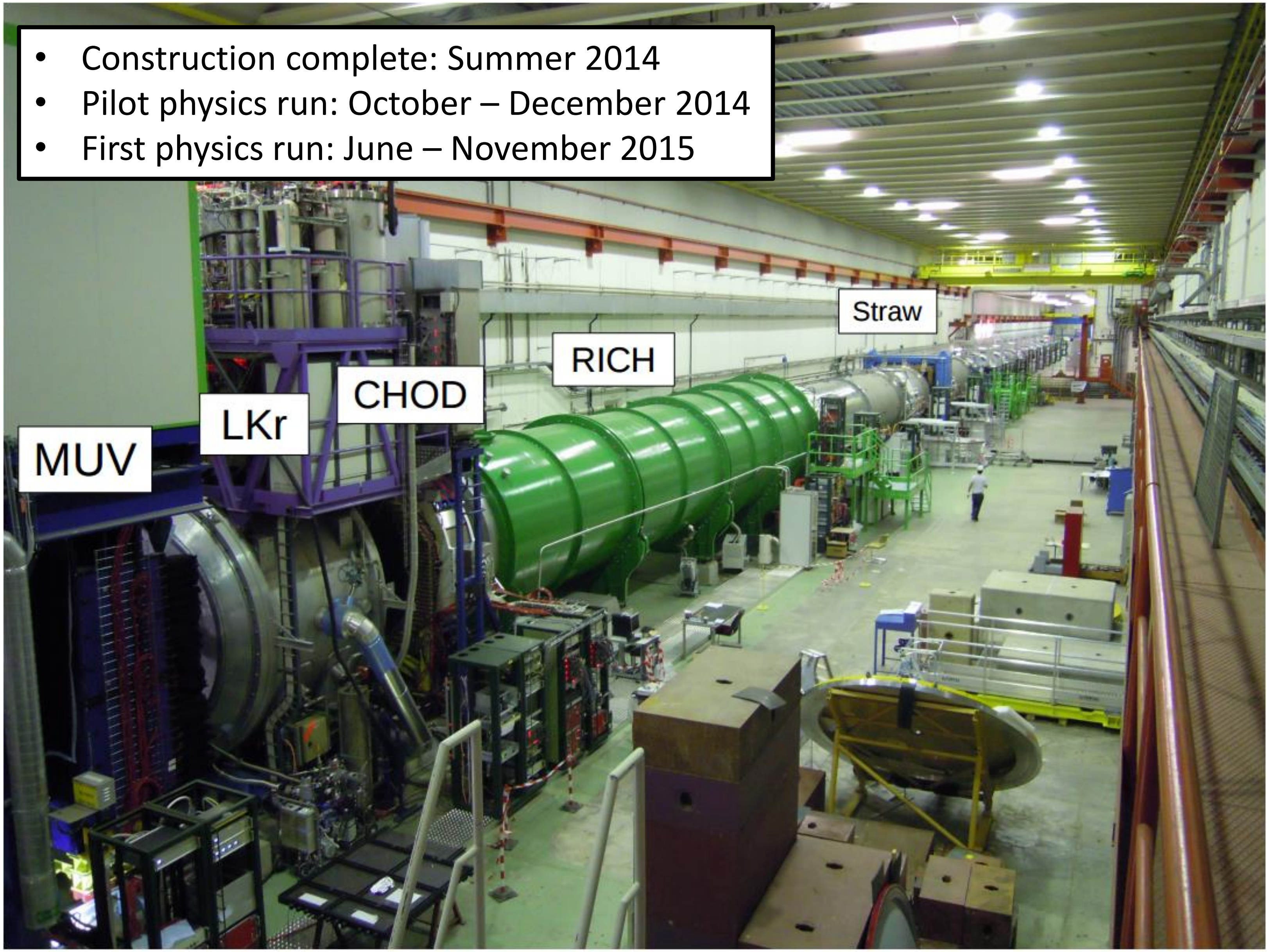


NA62

- Construction complete: Summer 2014
- Pilot physics run: October – December 2014
- First physics run: June – November 2015



NA62


• Construction complete: Summer 2014
• Pilot physics run: October – December 2014
• First physics run: June – November 2015
Straw
RICH
CHOD
LKr
MUV

The NA62 physics programme

- The NA62 detector is designed to identify a single charged pion, produced simultaneously with a ***K***$^+$ traversing the detector, in an otherwise empty event.

- How much signal and background do we expect?

Signal selection sketch:

- K–π association,
- $15 < P_\pi < 35$ GeV/c,
- Decay vertex in fiducial volume,
- No photon / muon / inelastic activity.

Decay	Event/year
$\pi^+\nu\bar{\nu}$	45
Signal	45
$\pi^+\pi^0$	5
$\mu^+\nu$	1
$\pi^+\pi^+\pi^-$	< 1
$\pi^+\pi^- e^+\nu$, others 3 trk.	< 1
$\pi^+\pi^0\gamma$(IB)	1.5
$\mu^+\nu\gamma$(IB)	0.5
$\pi^0 e^+(\mu^+)\nu$, others	neg.
Background	< 10

The NA62 physics programme

- The NA62 detector is designed to identify a single charged pion, produced simultaneously with a K^+ traversing the detector, in an otherwise empty event.

- What other physics can be done with this experimental setup?

The NA62 physics programme

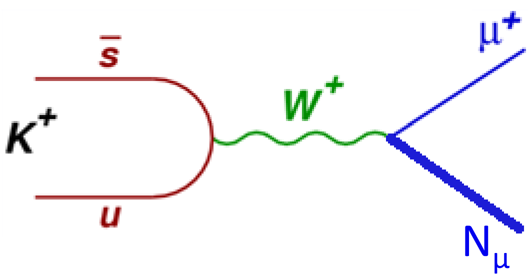
- The NA62 detector is designed to identify a single charged pion, produced simultaneously with a K^+ traversing the detector, in an otherwise empty event.

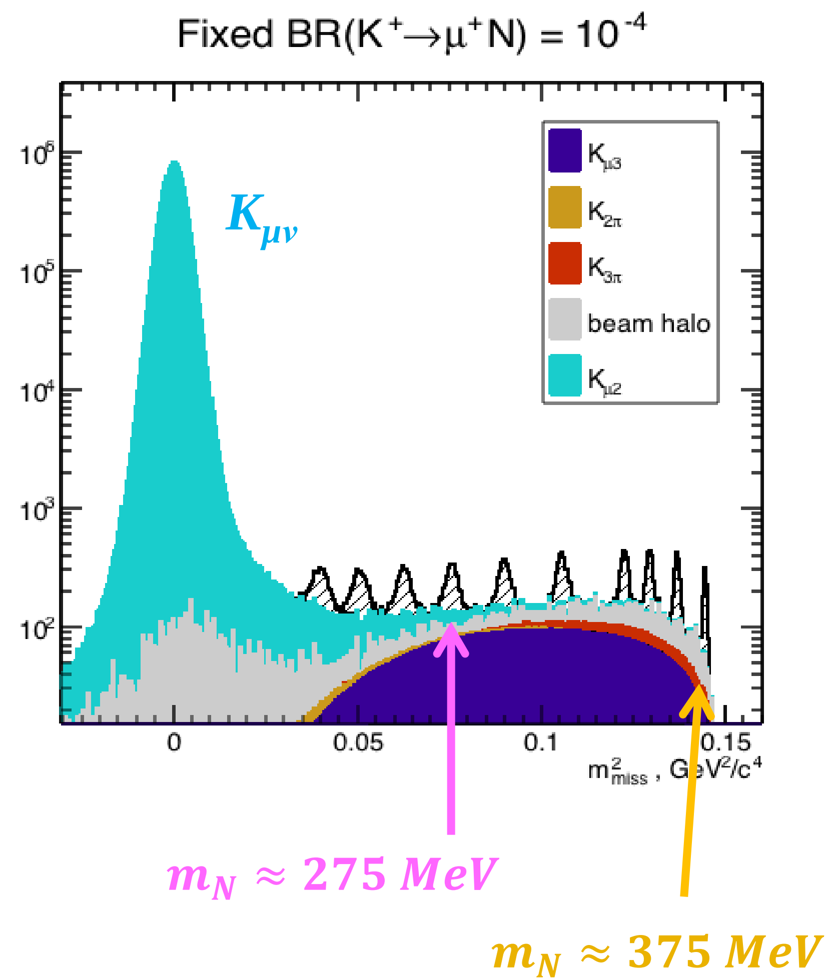
- What other physics can be done with this experimental setup?
  1. Select muons: $K^+ \rightarrow \mu^+ \nu$ decays
  2. Select electrons: $K^+ \rightarrow e^+ \nu$ decays
  3. Select multi-track decays: **LFV and LNV** decays
  4. Select π^0 decays: Dark matter search

Next few slides will show why these selections are interesting, using recent results from the $\mathbf{NA62_{RK}}$ and **NA48/2** experiments

1. $K^+ \rightarrow \mu^+ N_\mu$ @ NA62$_{RK}$

- Search for long-lived neutrinos in $K^+ \rightarrow \mu^+ N_\mu$ decays
- A 'bump hunt' in the $K^+ \rightarrow \mu^+ \nu_\mu$ missing mass spectrum





- Analysis ongoing using the NA62$_{RK}$ data

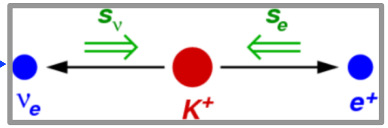
2. R_K @ $NA62_{RK}$

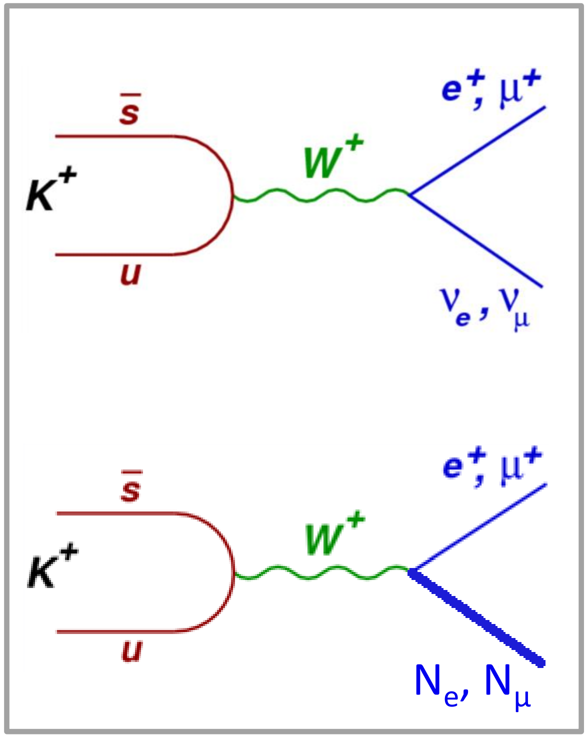
- Value of R_K can be precisely calculated in the SM

Helicity suppression ↓ Radiative corrections ↓

PRL 99 (2007) 231801

$$R_K^{SM} \equiv \frac{\Gamma(K \to e\nu(\gamma_{IB}))}{\Gamma(K \to \mu\nu(\gamma_{IB}))} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_K^{EM}) = 2.477(1) \times 10^{-5}$$





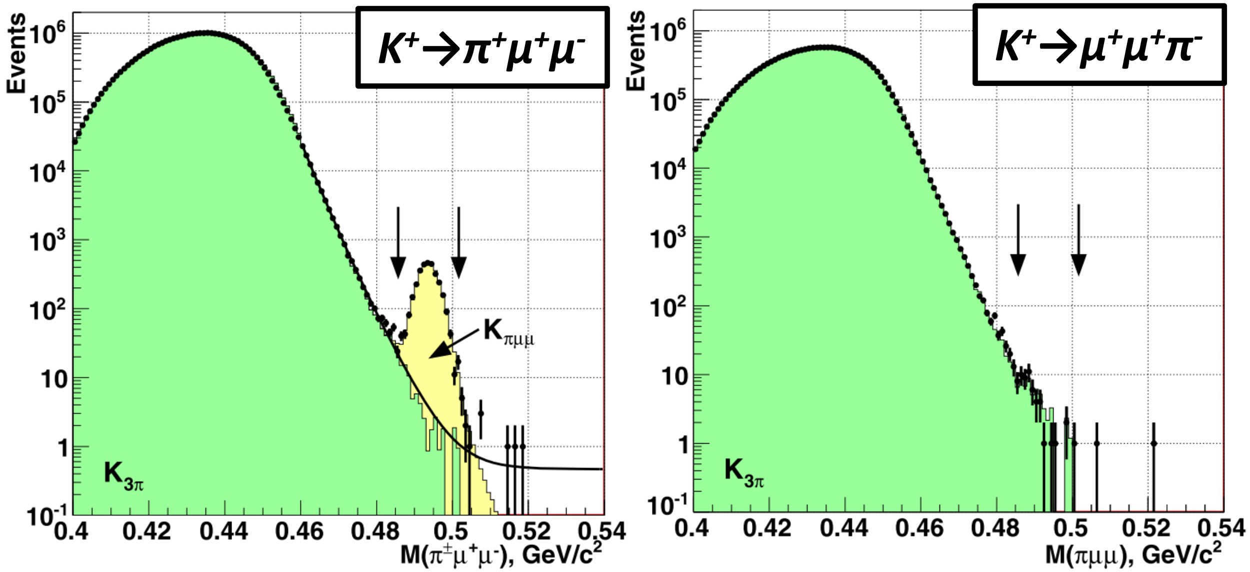
- R_K is sensitive to:
  - Ratio of mixing parameters of 4th neutrino $U_{e4}/U_{\mu4}$ at O(1) [JHEP 1302 (2013) 048]

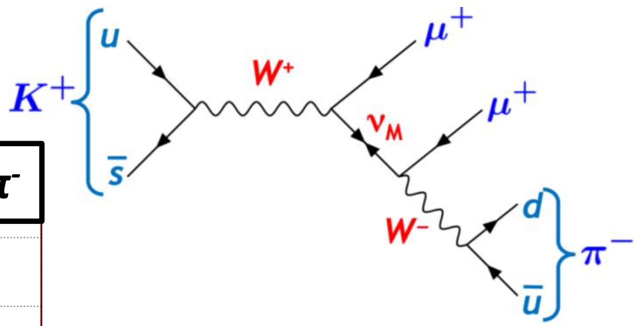
- **World's most precise** measurement of R_K [PLB 719 (2013) 326]

$R_K = 2.488(7)_{st}(7)_{sy} \times 10^{-5}$
$= 2.488(10) \times 10^{-5}$ — 0.4% precision
$\Delta r_K = (4 \pm 4) \times 10^{-3}$

3. $K^+ \to \mu^+\mu^+\pi^-$ @ NA48/2

- Search for N_μ in the mass range $240 \approx m_N \approx 400$ MeV using $K^+ \to \mu^+\mu^+\pi^-$ decays





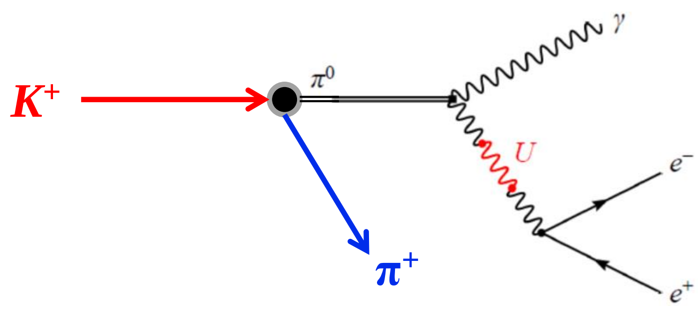
NA48/2
$N_{data} = 52$
$N_{bkg} = 52.6 \pm 19.8_{sy}$

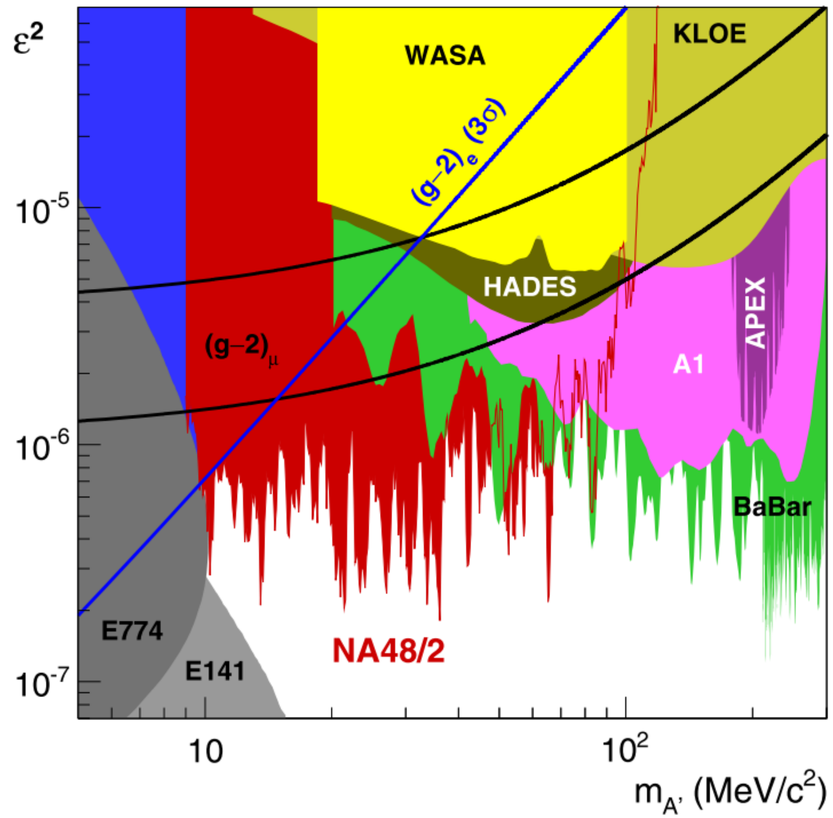
- **World's best limit** set by NA48/2: [PLB 697(2011)107]

$$\mathcal{B}(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) < 1.1 \times 10^{-9} \quad \text{@90\% CL}$$

4. Dark Photon @ NA48/2

- The **$\pi^0 \to \gamma ee$** decay can be mediated by a **dark photon (A', U)**





- No excess in the data is found
- NA48/2 constraints exclude dark photon explanation of the $(g\text{-}2)_\mu$ discrepancy

- Recently published in PLB 746 (2015) 178-185

Triggering at NA62

The NA62 Trigger

- High particle flux of ~ 10 MHz demands a highly selective trigger
- The trigger is comprised of three stages:
- **L0 Trigger**: Hardware (FPGA). Input rate: 10MHz, Output rate: 1MHz
  - Around 200kHz required for $K^+ \to \pi^+ \nu\nu$ trigger
  - Leaves 800kHz for (other studies + control channels)

    ~ 400 kHz for exotic decay program
- **L1 Trigger**: Software (Single detector). Output rate: ~100kHz
- **L2 Trigger**: Software (Full information). Output rate: ~ few kHz

(Prospective numbers having assumed nominal intensity)

The proposed $K^+ \rightarrow \pi^+ \nu\nu$ trigger at L0

- The proposed L0 trigger scheme for $K^+ \rightarrow \pi^+ \nu\nu$ has four parts:

1. A single charged particle:
   - **At least three PMTs in the RICH**
   - **Coincident hits in a quadrant of the CHOD**
2. Consistent with a π^+ from $K^+ \rightarrow \pi^+ \nu\nu$:
   - **Less than 40 GeV of ANY energy**
3. Veto photons:
   - **Less than 20 GeV of EM energy**
   - **No signal in photon vetoes**
4. Veto muons:
   - **No signal in MUV3**
   - **More than 1.5 GeV in the LKr OR more than 8 GeV of hadronic energy**

- With rate of 200kHz, select $K^+ \rightarrow \pi^+ \nu\nu$ with 75% efficiency
  - 15% of signal loss is due to veto on 'accidental coincidence'

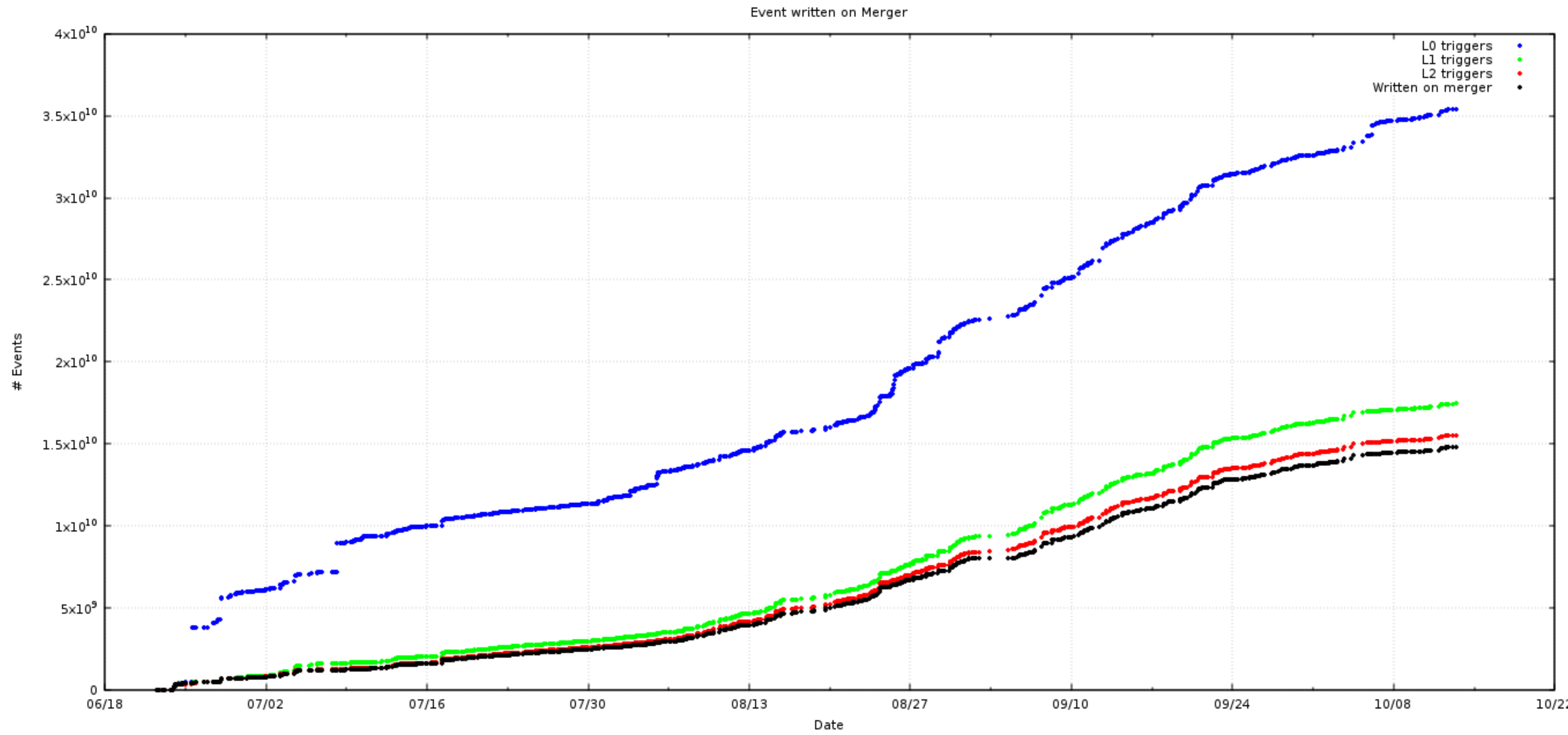
The proposed 'exotic decay' trigger at L0

- Five L0 trigger lines are proposed for the rest of the physics programme
- These numbers assume 400 kHz L0 output rate with nominal beam intensity

  - Single-track trigger (**ST**): $RICH_1$ * $CHOD_1$ (downscale = 1000)
  - Multi-track trigger (**MT**): $RICH_2$ * $CHOD_2$ (downscale = 100)
  - Dielectron trigger (**2E**): $RICH_2$ * $CHOD_2$ * LKR_{10} (downscale = 10)
  - Dimuon trigger (**2M**): $RICH_2$ * $CHOD_2$ * MUV_2
  - Dilepton trigger (**TME**): $RICH_2$ * $CHOD_2$ * MUV_1 * LKR_{10}

The NA62 trigger in 2015

- In 2015 'physics triggers' were largely not used: beam time dedicated to TDAQ and detector commissioning
- Nevertheless about 10^{10} events have been recorded with minimum bias triggers
- These events can be used to be used to "rediscover the Standard Model" as well as set more stringent constraints on heavy neutrino production
- Reconstruction and analysis of full 2015 data set already underway



Summary

- The NA62 experiment will study **a variety** of ***K***$^{+}$ decays
- NA62 expects to collect 100 $\boldsymbol{K^+ \rightarrow \pi^+ \nu\nu}$ decays in the next two years
- The "exotic decay" physics programme will set world beating constraints on new effects (LFV, LNV) and new particles (N_{μ})
- The NA62 experiment has begun operation
- Commissioning and analysis with 2015 data is proceeding

Watch this space!