KLOE Searches on Dark Forces

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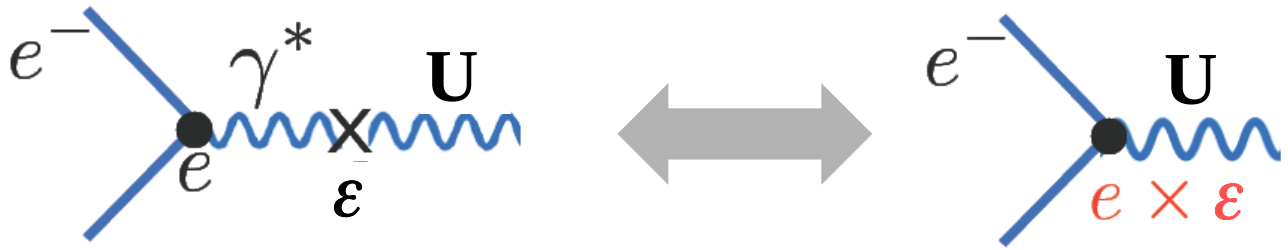
on behalf of the KLOE-2 Collaboration

Les Rencontres de Physique de la Vallée d'Aoste
La Thuile, February 26 – March 3, 2012

Low energy dark forces

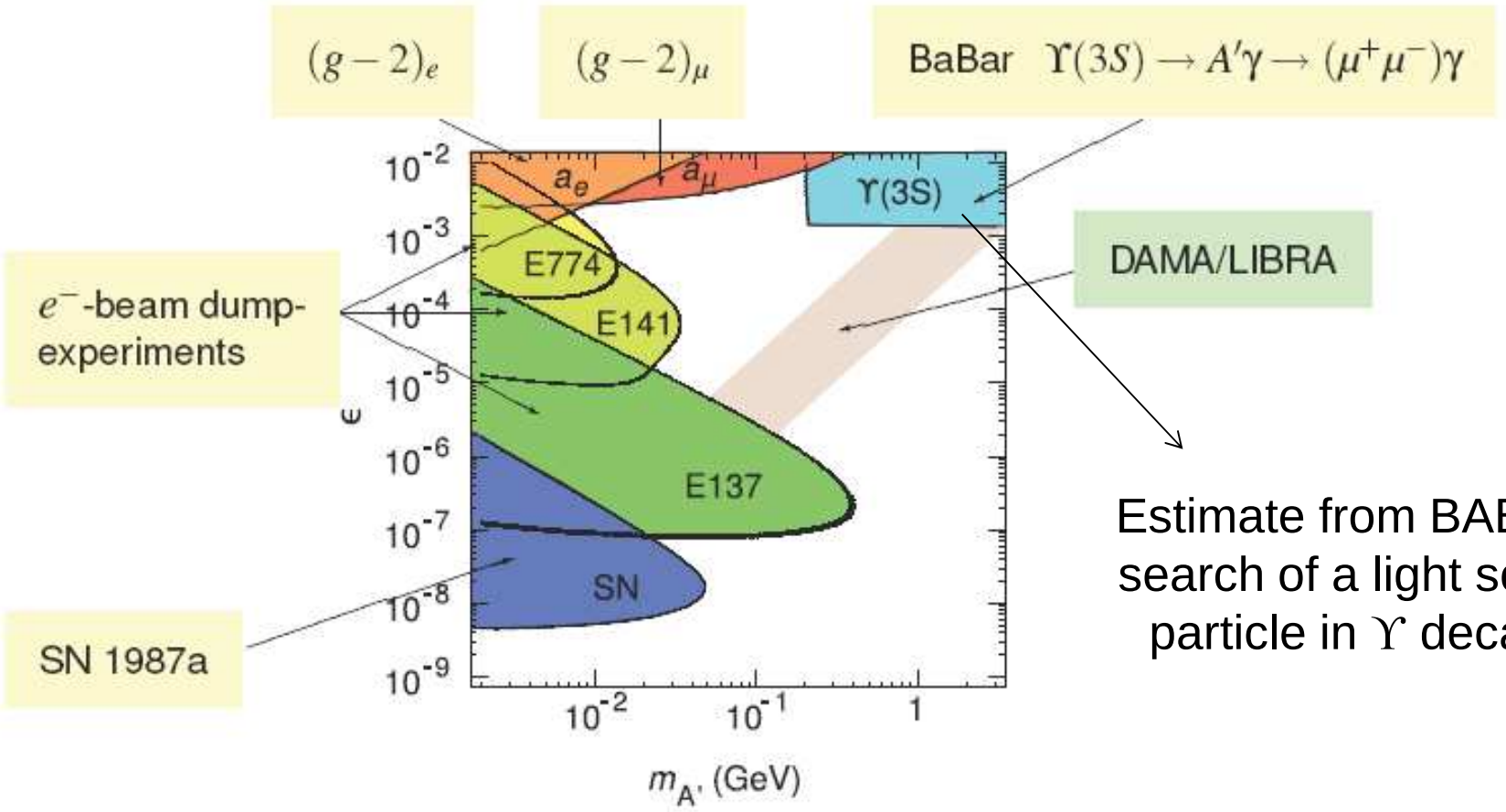
Several unexpected astrophysical observations (PAMELA, ATIC, INTEGRAL, DAMA/LIBRA, CoGent…) could be explained with the existence of a hidden gauge sector weakly coupled with SM through a mixing mechanism of a new **gauge boson (U, A', V…)** with the photon:

[Arkani-Hamed et al. PRD79 015014 (2009)]
[Essig et al., PRD80 015003 (2009)]



- ✓ U mass range: **1 MeV – few GeV**
- ✓ Coupling constant of electric charge to U: $\varepsilon \leq 10^{-3}$
- ✓ U production/decay through photon mixing

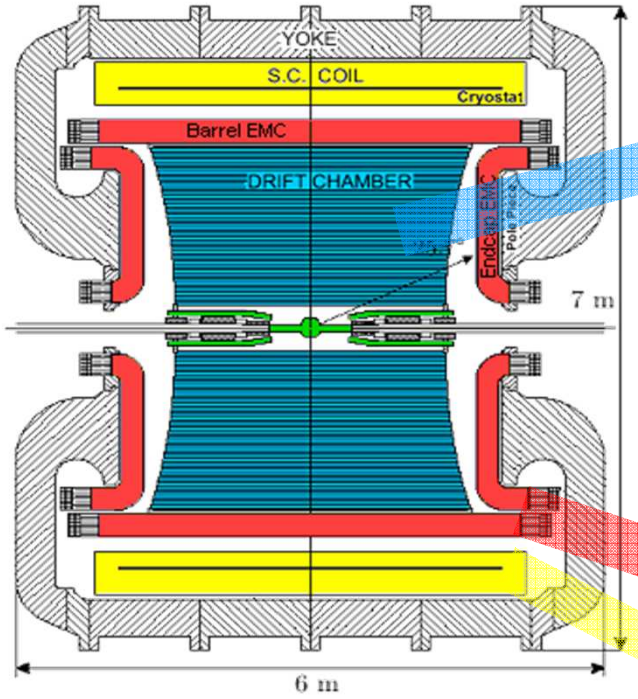
Constraints in ε-M_U plane, beginning 2011



Estimate from BABAR search of a light scalar particle in Υ decays

Most suitable region for U boson search unconstrained up to one year ago

KLOE and DAΦNE



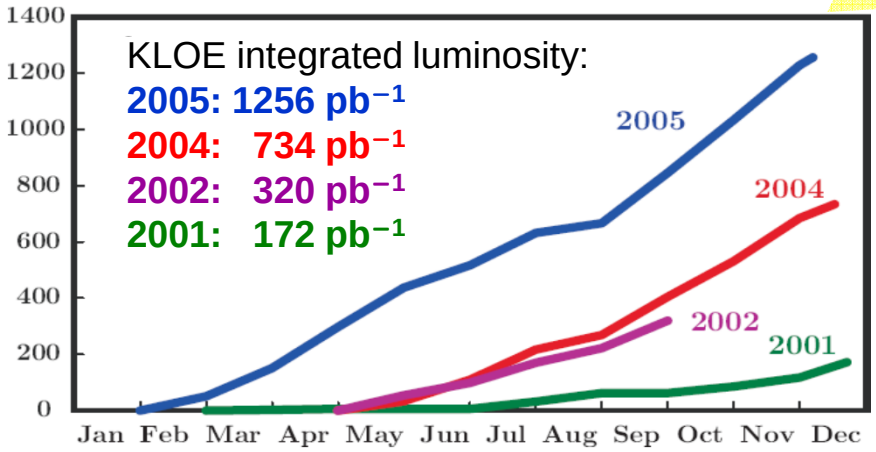
Drift chamber

- Gas mixture: **90% He + 10% C_4H_{10}**
- **$\delta p_t / p_t < 0.4\%$ ($\theta > 45^\circ$)**
- **$\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm**

Electromagnetic calorimeter

- lead/scintillating fibers
- 98% solid angle coverage
- **$\sigma_E / E = 5.7\% / \sqrt{(E(GeV))}$**
- **$\sigma_t = 57$ ps $/ \sqrt{(E(GeV))} \oplus 100$ ps**
- **PID capabilities**

Magnetic field: 0.52 T



DAΦNE: e^+e^- collider @ $\sqrt{s} \sim 1020$ MeV ~ M_ϕ

$\sigma_{peak} \sim 3.1\ \mu b$

KLOE: 2.5 fb^{-1} @ $\sqrt{s} = M_\phi$ (~ 8×10^9 ϕ produced)

+ 250 pb^{-1} @ 1000 MeV (off-peak data)

Search for dark forces @ KLOE

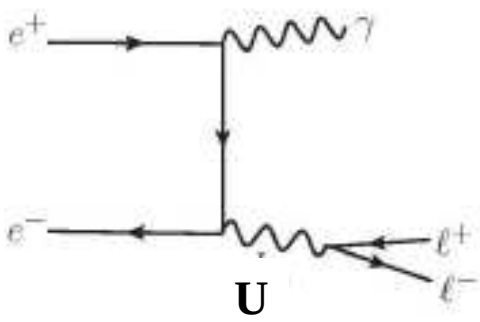
- **Meson decays**: $\phi \to \eta U$, $\eta/\pi^0 \to U\gamma$ ...

  Peculiar of a light meson factory

- **e^+e^- collisions**: $e^+e^- \to U\gamma \to \ell^+\ell^-\gamma$

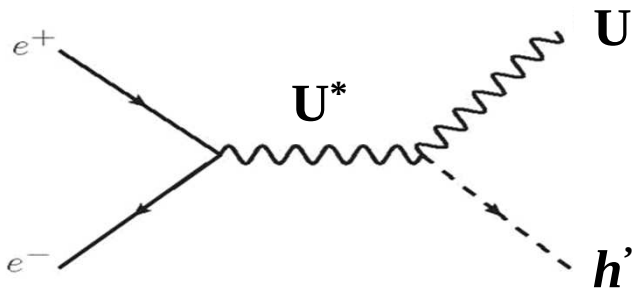
  x-sec ∝ 1/s

  100 times higher at DAΦNE w.r.t. b-factories
  Compensate lower luminosities



- ***h'*-strahlung**: $e^+e^- \to U^* \to Uh'$

  If the hidden simmetry is spontaneously broken by a Higgs-like mechanism, the existence of at least one other scalar particle, the *h'*, can be postulated



Search for dark forces @ KLOE: $\phi \to \eta U$

Meson having radiative decay to one photon can decay to a U boson with $BR(X \to YU) \sim \varepsilon^2 \times |FF_{XY\gamma}|^2 \times BR(X \to Y\gamma)$

$\sigma(\phi \to \eta U) \sim 40$ fb for $FF_{\phi\eta}=1$, $\varepsilon=10^{-3}$

Irreducible background: ϕ Dalitz decay $\phi \to \eta\gamma^* \to \eta l^+ l^-$ (σ = 0.7 nb)

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	$BR(X \to Y + \gamma)$	$BR(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

All KLOE stat.
All decay chains

[M.Reece and L.T.Wang, JHEP 0907:051 (2009)]

Selected decay chain: $U \to e^+e^-$ + $\eta \to \pi^+\pi^-\pi^0$ (BR = 22.7%) **Published**

$\eta \to \gamma\gamma / \pi^0\pi^0\pi^0$ (BR = 39.3/32.6%) **In progress**

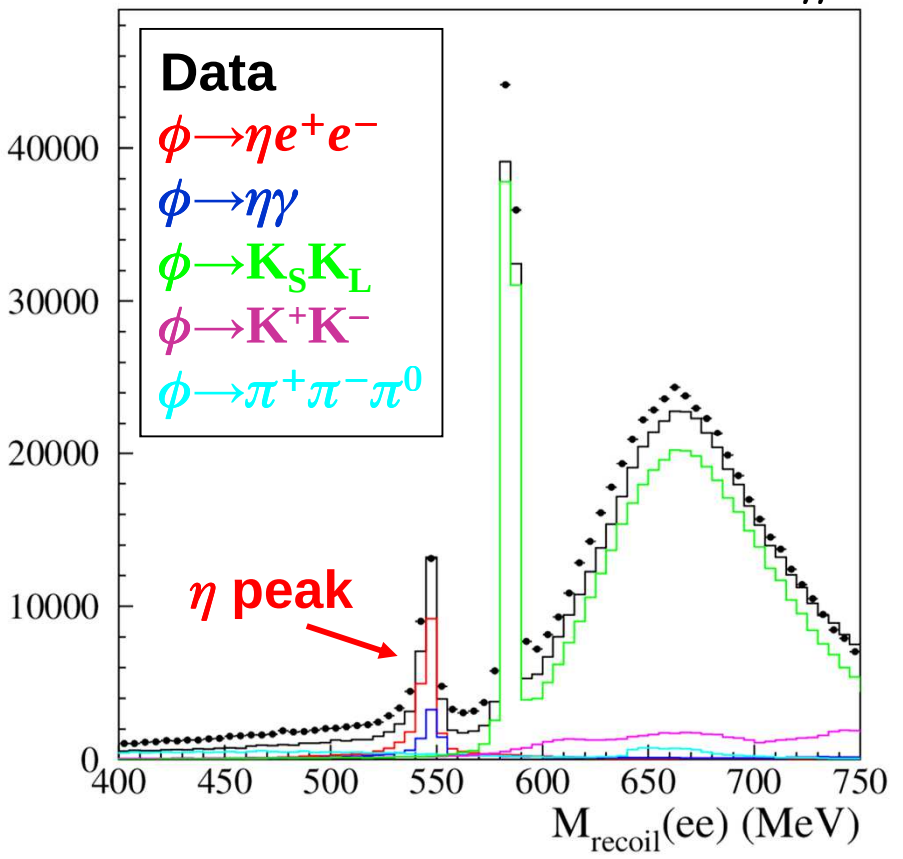
The $\phi \to \eta e^+e^-$, $\eta \to \pi^+\pi^-\pi^0$, decay

Analysis performed on **1.5 fb^{-1}**

BR($\phi \to \eta e^+e^-$) = 1.15×10^{-4} : **~123,000 events from irreducible bckg**

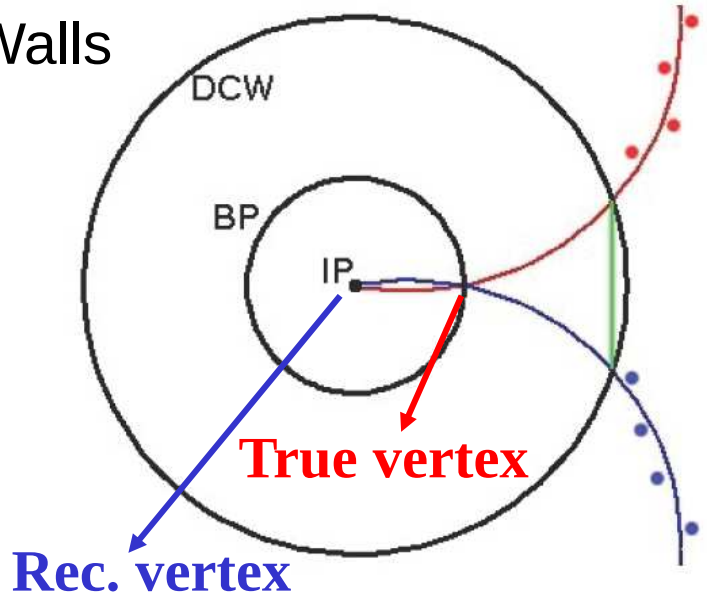
- 4 tracks in a cylinder around IP + 2 photon candidates
- Best $\pi^+\pi^-\gamma\gamma$ match to the η mass using the pion hypothesis for tracks. Other two tracks assigned to e^+/e^-
- $495 < M_{\pi\pi\gamma\gamma} < 600$ MeV
  $70 < M_{\gamma\gamma} < 200$ MeV
  $535 < M_{recoil}(ee) < 560$ MeV
- Photon conversion + ToF cuts

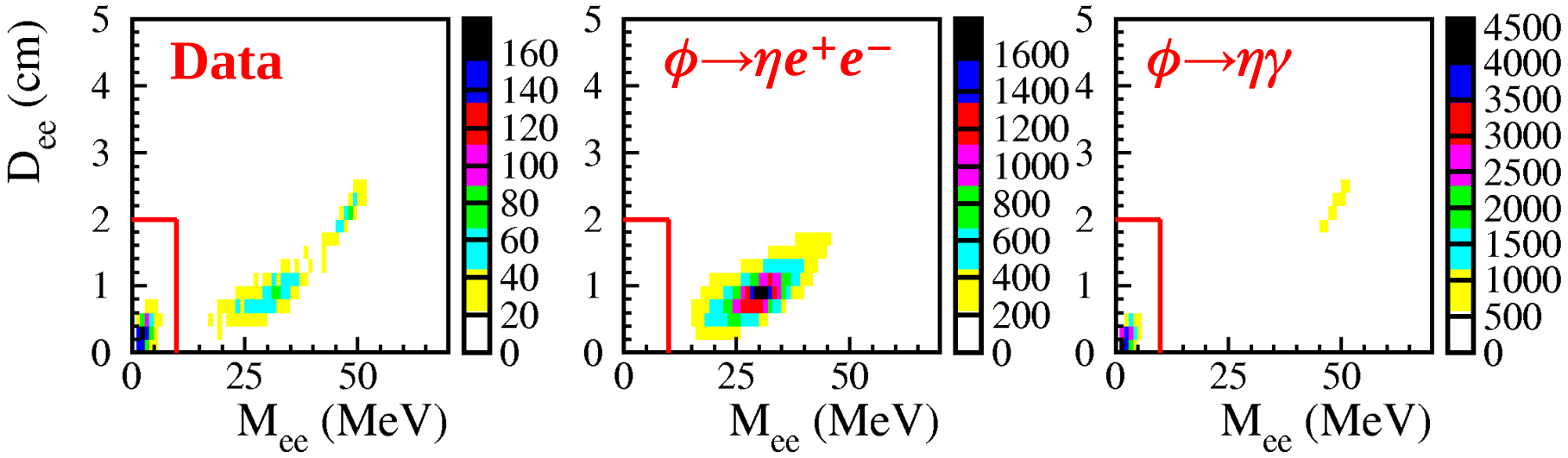
Recoil mass to the e^+e^- pair after $M_{\gamma\gamma}$ cut



Background rejection: photon conversions

Photon conversions on Beam Pipe/DC Walls rejected by tracking back to BP/DCW surfaces the two e^+, e^- candidates and reconstructing the e^+e^- invariant mass (M_{ee}) and the distance between the two particles (D_{ee}). Both quantities are small if coming from photon conversion

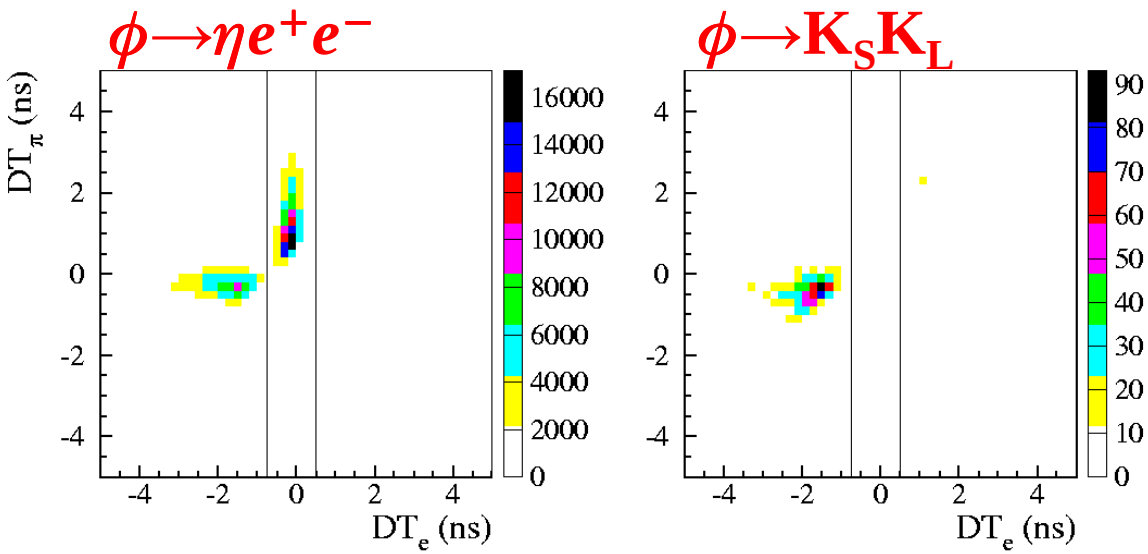


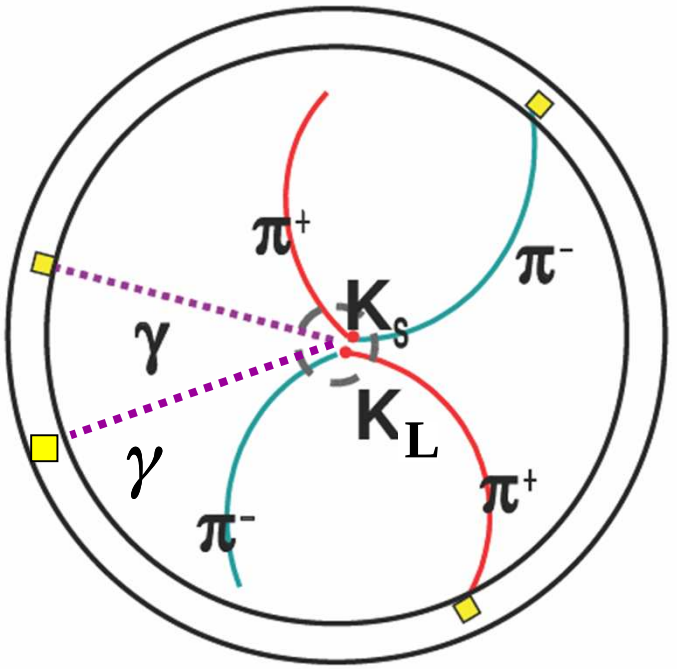


Background rejection: π-enriched events

A fraction of $\phi \to KKbar$ and $\phi \to \pi^+\pi^-\pi^0$ events survive analysis cuts. They can be rejected using Time-of-Flight (ToF) to the calorimeter when an EMC cluster is connected to the track

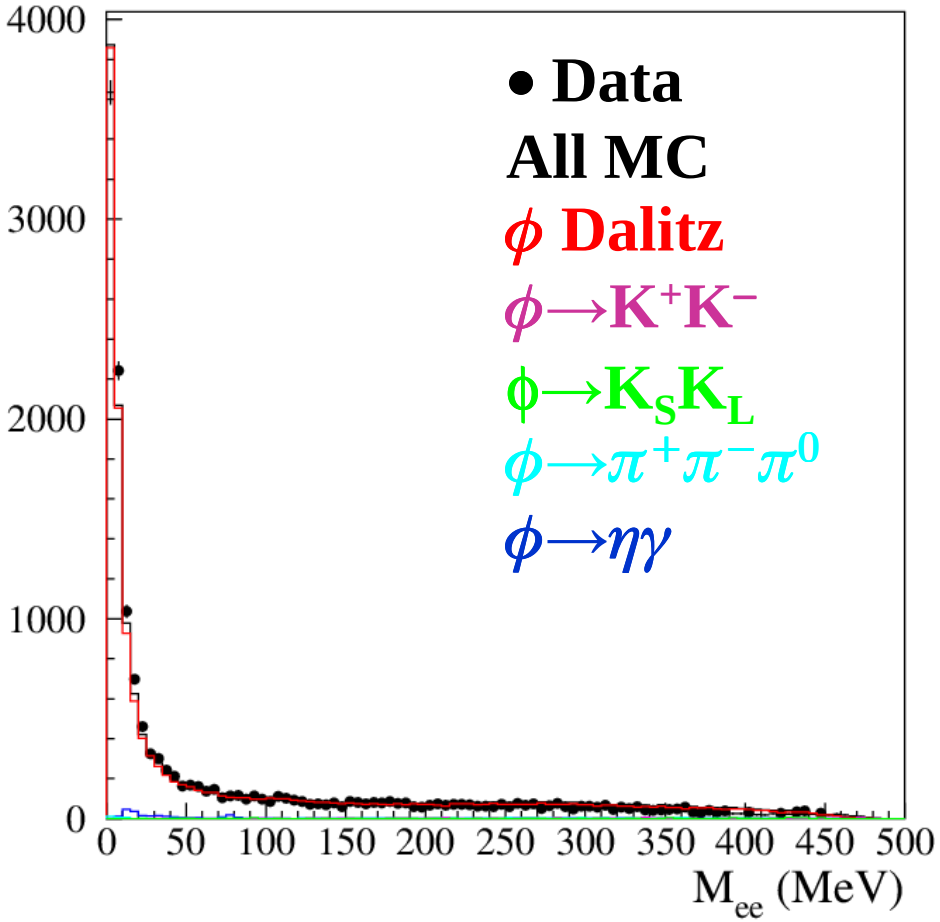
$DT = T_{track} - T_{cluster}$ variable evaluated in both electron (DT_e) and pion (DT_π) hypotheses

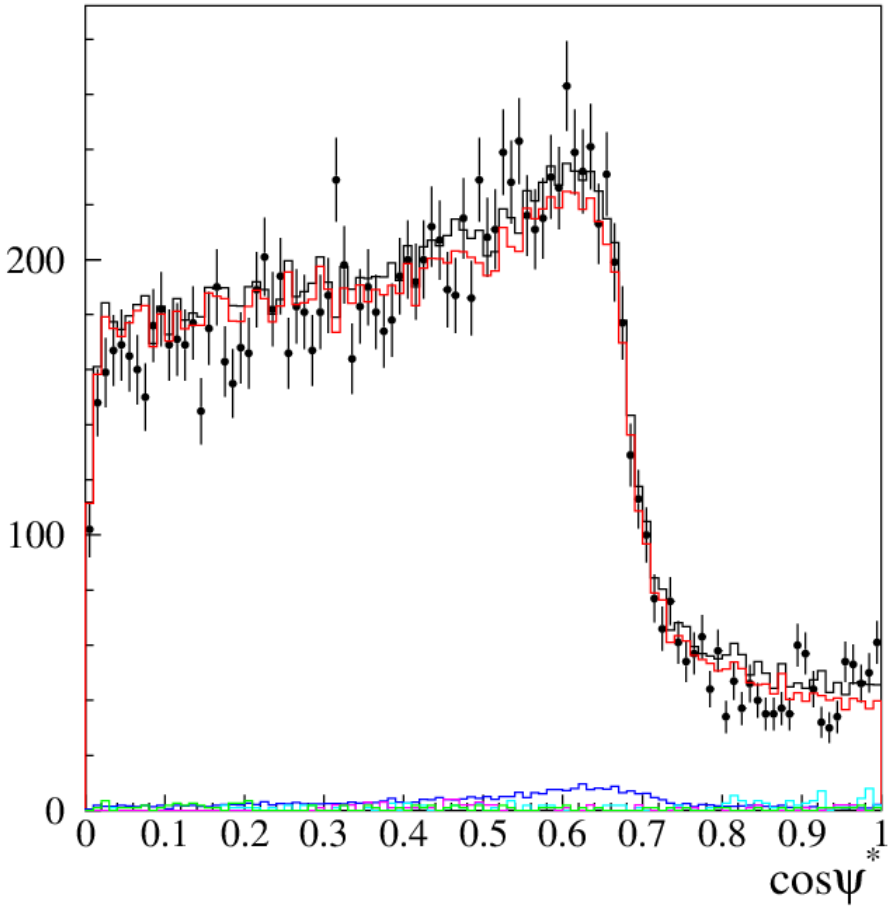




Events with e^+/e^- candidate with connected cluster outside a 3σ DT_e window removed

Data-MC comparison





- **~14000 $\phi\to\eta e^+e^-$ with $\eta\to\pi^+\pi^-\pi^0$ candidates**
- **Just very small residual contamination from $\phi\to\eta\gamma$ events**
- **MC M_{ee} shape from VMD with FF slope from SND (213 events)** [PLB504(2001) 275]

  ⇒ **Extract directly from our data!**

Fit to the M_{ee} shape

Decay parametrization from L.G. Landsberg, Phys. Rep. 128 (1985) 301:

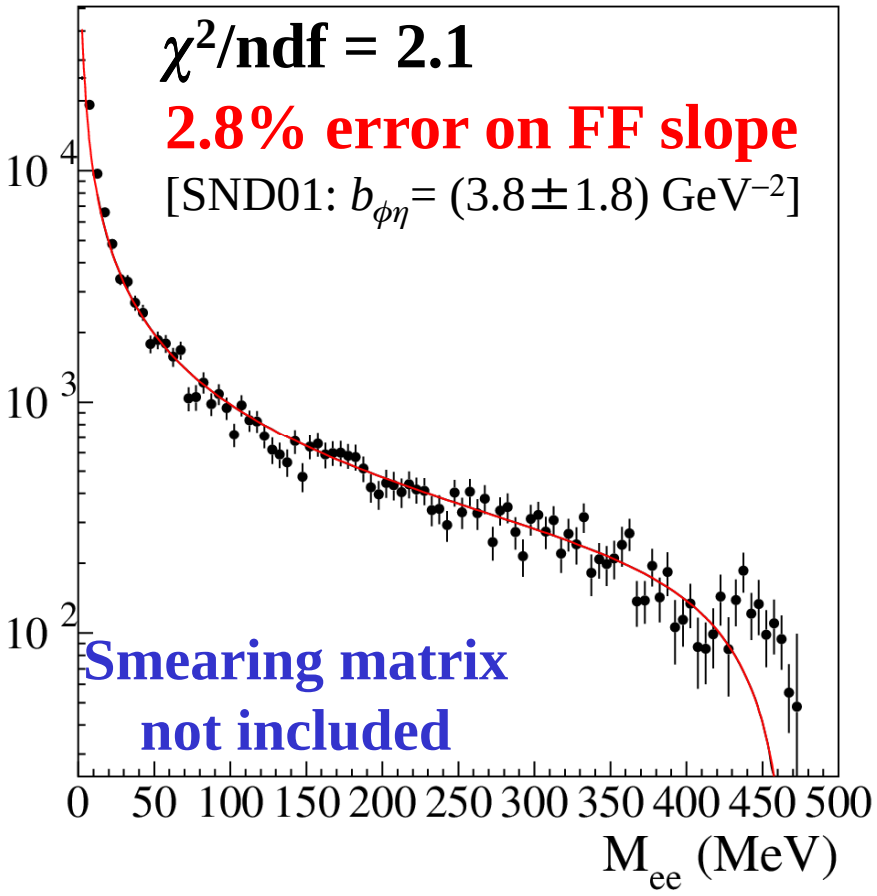
$$\frac{d}{dq^2}\frac{\Gamma(\phi\to\eta e^+e^-)}{\Gamma(\phi\to\eta\gamma)}=\frac{\alpha}{3\pi}\frac{|F_{\phi\eta}(q^2)|^2}{q^2}\sqrt{1-\frac{4m^2}{q^2}}\times$$

$$\times\left(1+\frac{2m^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{m_\phi^2-m_\eta^2}\right)^2-\frac{4m_\phi^2q^2}{(m_\phi^2-m_\eta^2)^2}\right]^{3/2}$$

$$F(q^2)=\frac{1}{1-q^2/\Lambda^2}$$

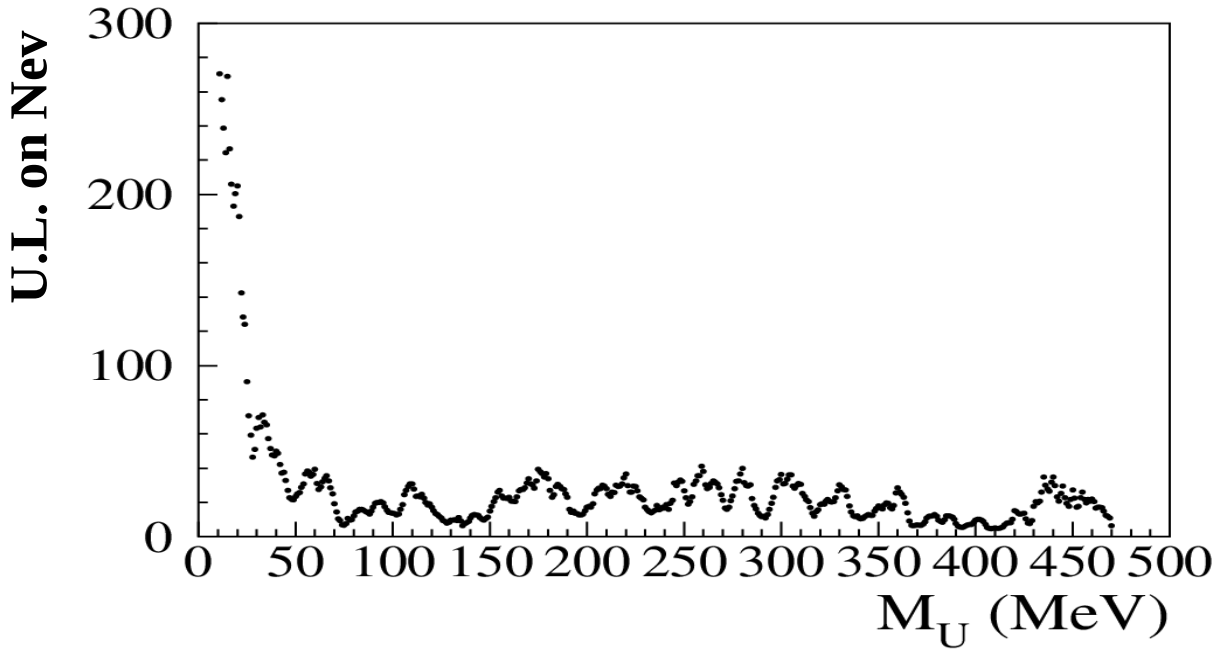
FF slope:

$$\begin{cases} b = dF/dq^2|_{q^2=0} \\ b_{\phi\eta} = \Lambda_{\phi\eta}^{-2} \approx 1/m_\phi^2 \approx 1\ \text{GeV}^{-2} \end{cases}$$



Exclusion plot for number of events

- $\phi \to \eta U$ MC sample [M.Reece and L.T.Wang, JHEP 0907:051 (2009)] divided in subsamples of 1 MeV width in 5< M_U<470 MeV
- For each M_U sub-sample, average value of $\phi \to \eta e^+ e^-$ background from fit to M_{ee} distribution, excluding the 5 bins centered at M_U
- For each M_U value, signal hypothesis excluded **@ 90% C.L.** using the CL_S method (error on bckg included)



Exclusion plot for α'/α

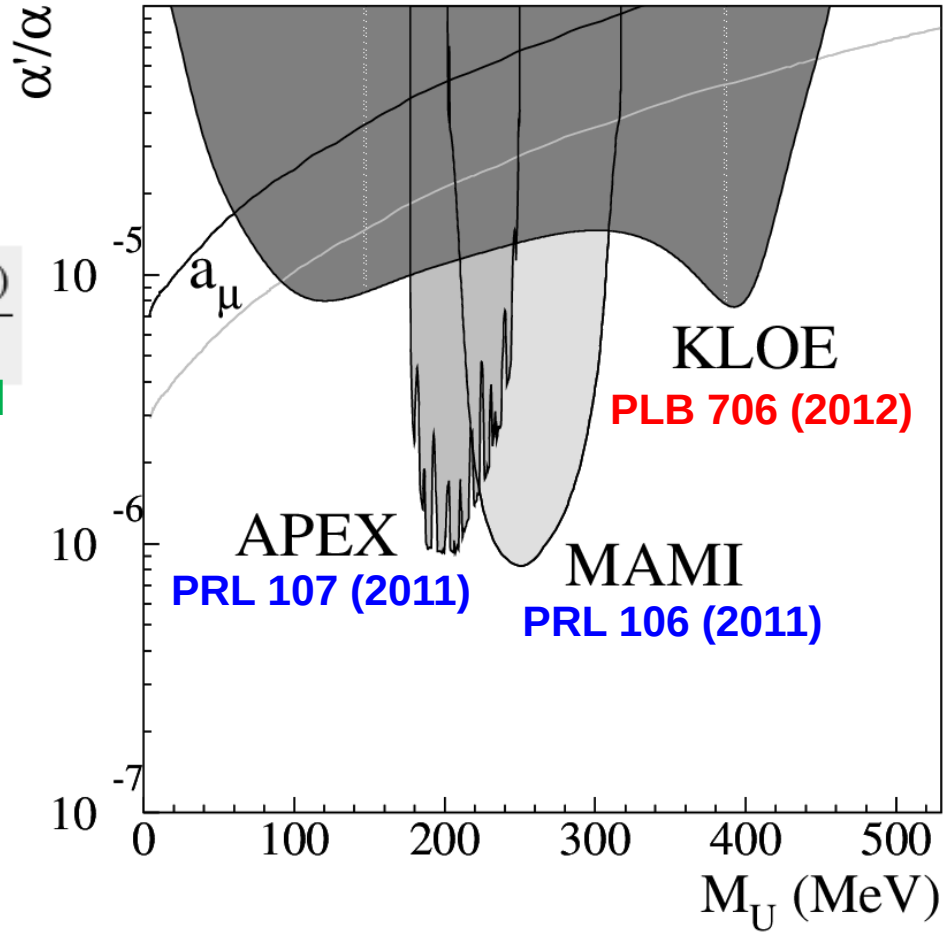
UL on $\alpha'/\alpha = \varepsilon^2$ takes into account:

- the kinematic factors

$$\frac{\Gamma(\phi \to \eta U)}{\Gamma(\phi \to \eta\gamma)} = \varepsilon^2 \, |F_{\phi\eta\gamma}(m_U^2)|^2 \, \frac{\lambda^{3/2}(m_\phi^2, m_\eta^2, m_U^2)}{\lambda^{3/2}(m_\phi^2, m_\eta^2, 0)}$$

[Reece-Wang, JHEP0907:051 (2009)]

- the opening of the $U \to \mu^+\mu^-$ threshold

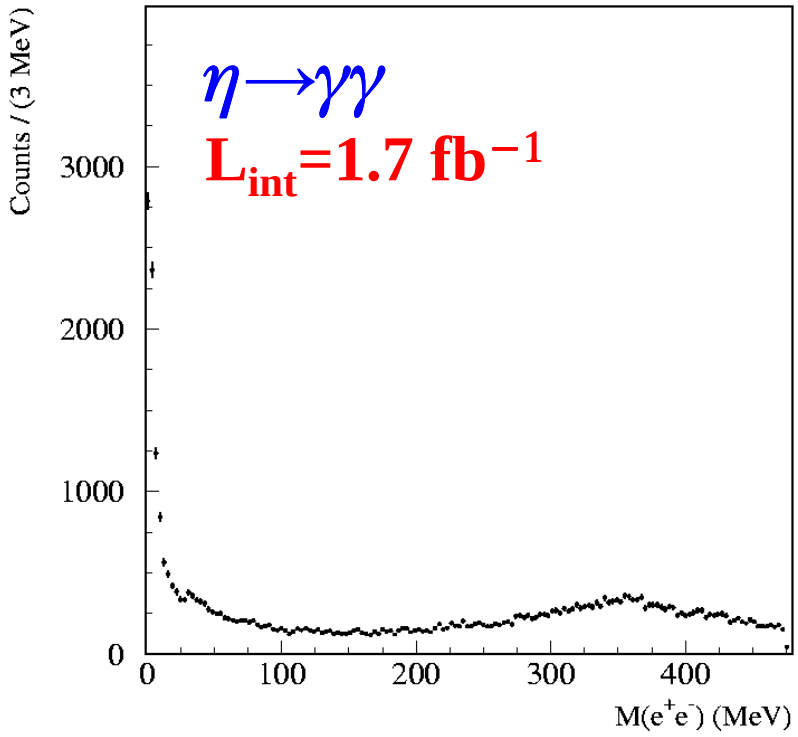


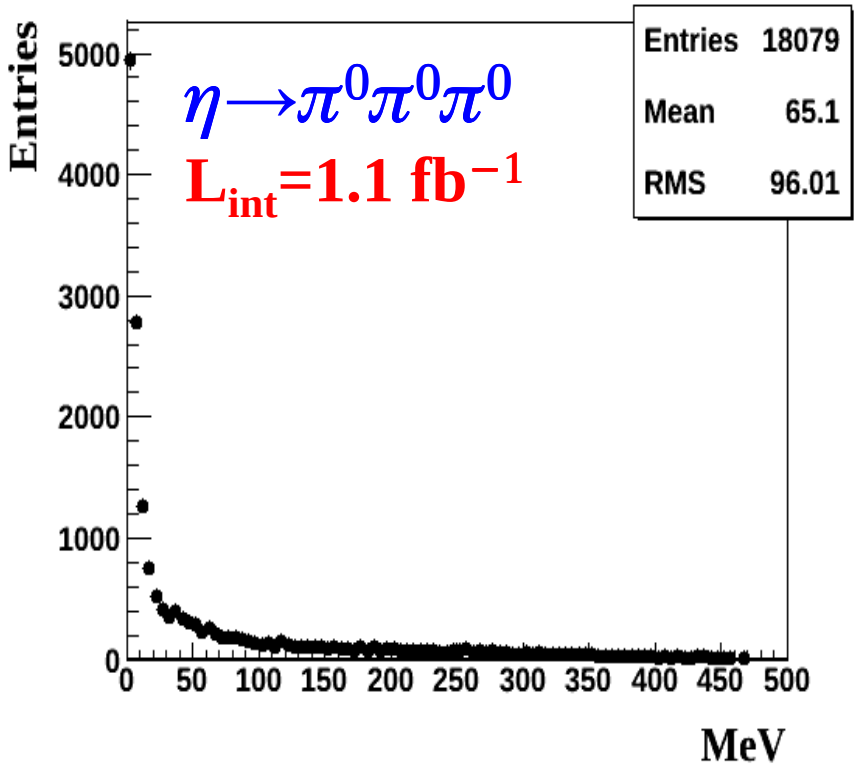
$\alpha'/\alpha \leq 2 \times 10^{-5}$ @ 90% C.L. for $50 < M_U < 420$ MeV

$\phi \to \eta$U: other ongoing studies

PRELIMINARY

Preliminary studies on $\eta \to \gamma\gamma$ and $\eta \to \pi^0\pi^0\pi^0$ decay channels produce encouraging results

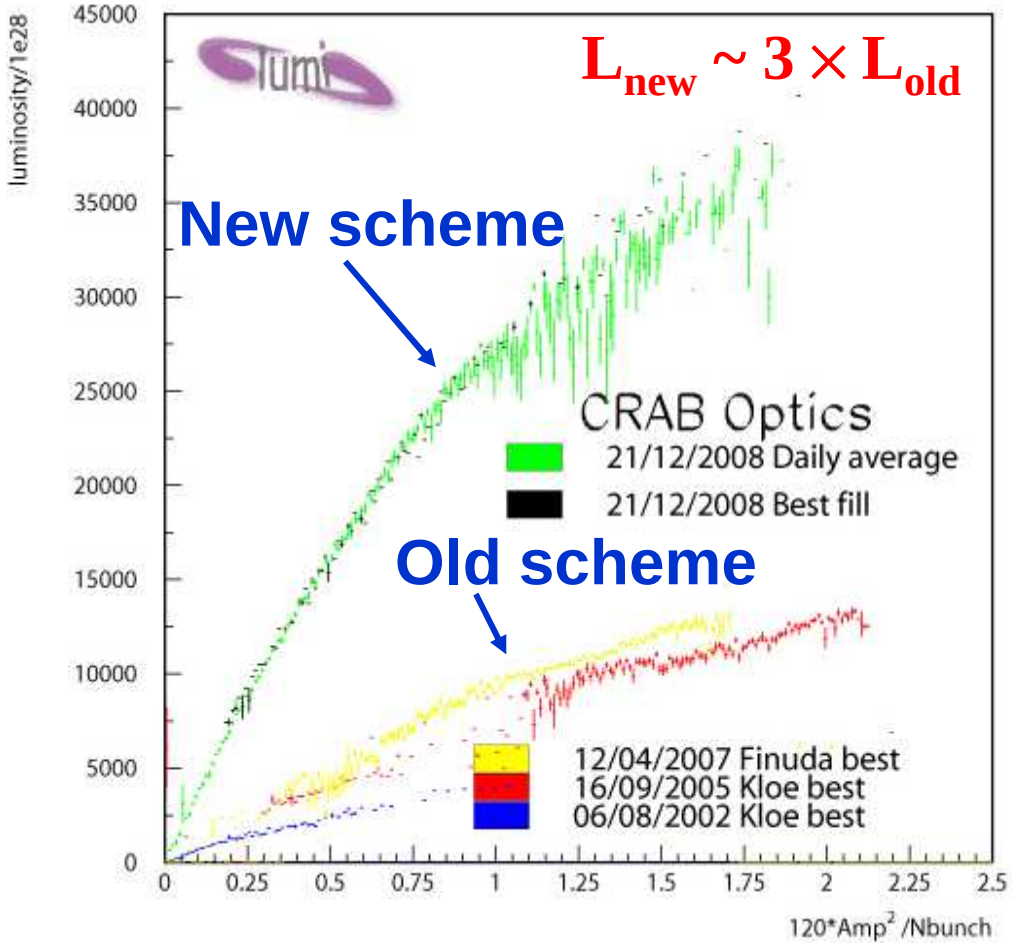




U.L. can be improved by a factor ≈ 2

DAΦNE upgrade

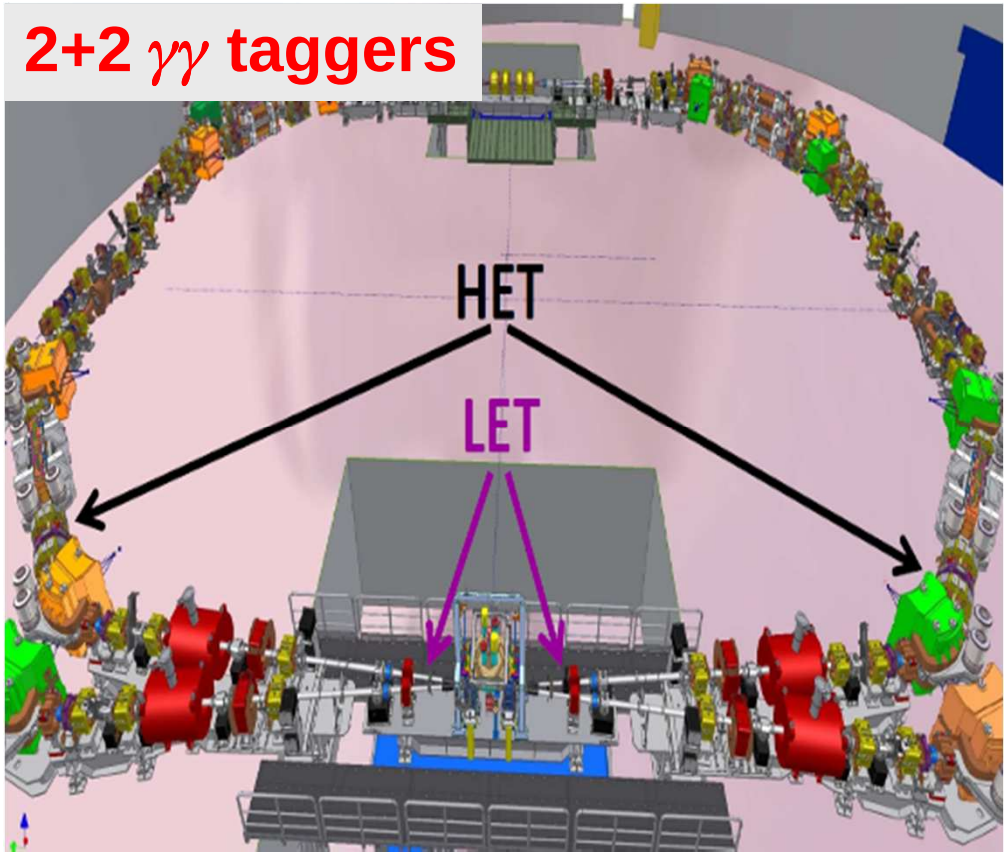
DAΦNE: new interaction scheme with large beam crossing angle + sextupoles for crabbed waist optics



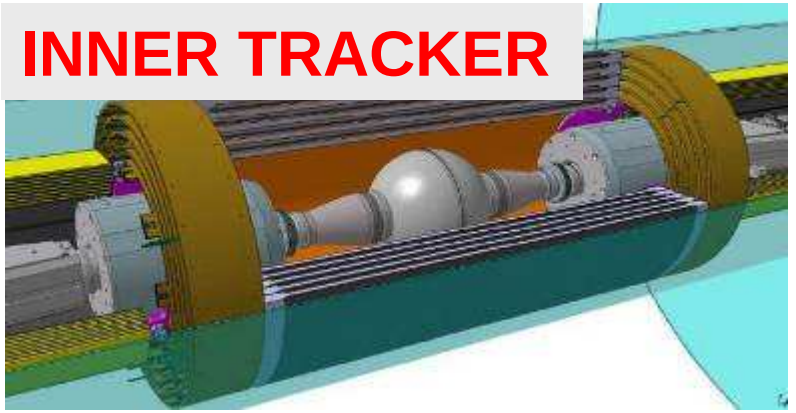
- DAΦNE run for KLOE-2 originally scheduled for 2010
- First collisions end 2010, but long machine shut downs due to severe hardware problems
- DAΦNE commissioning started on November 2011
- December 2011:
  $L = 1.4 \times 10^{32}$ cm^{-2}s^{-1}
  with 0.9 mA + 0.7 mA
  (as best KLOE run with 1.8 A + 1.3 A)
- After Christmas shutdown, optimization of optics still in progress ⇒ not stable running yet

From KLOE to KLOE-2

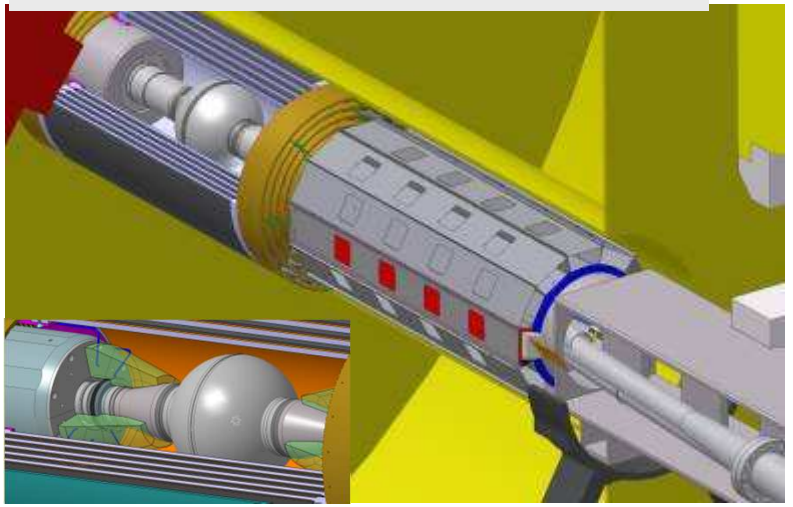
2+2 $\gamma\gamma$ taggers



INNER TRACKER

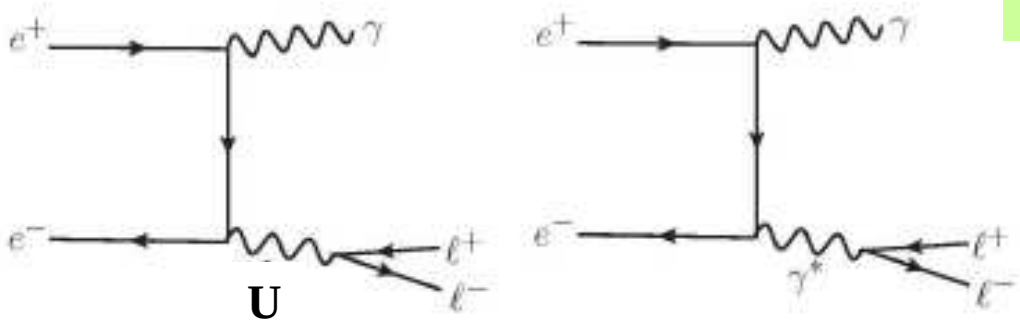


SMALL ANGLE EMCs

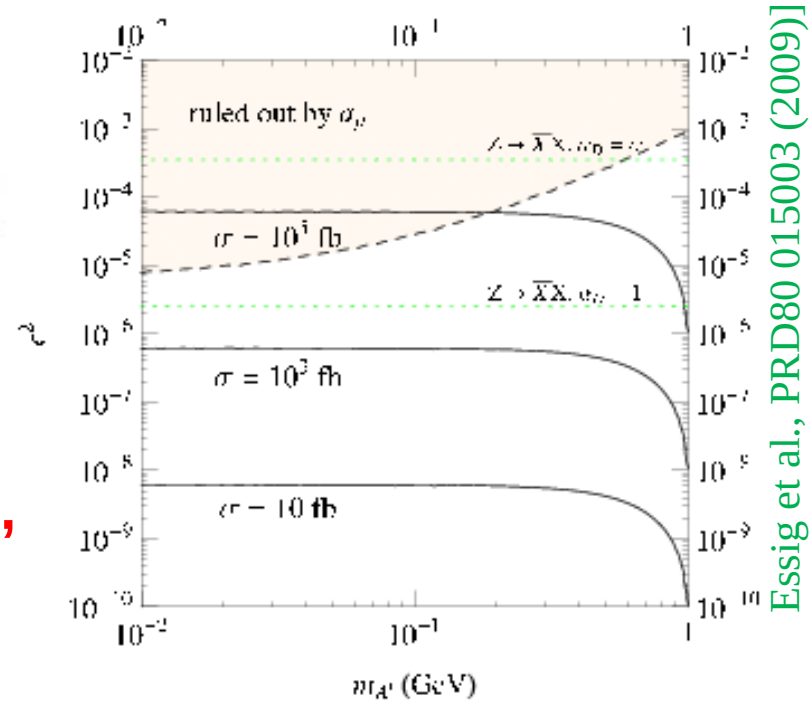


A sensible improvement of the $\phi \rightarrow \eta U$ analysis can be obtained from a successfull KLOE-2 run

Perspectives on $e^+e^- \to U\gamma$ @ KLOE/KLOE-2



Production x-sec for on-shell Uγ @ DAΦNE



Essig et al., PRD80 015003 (2009)]

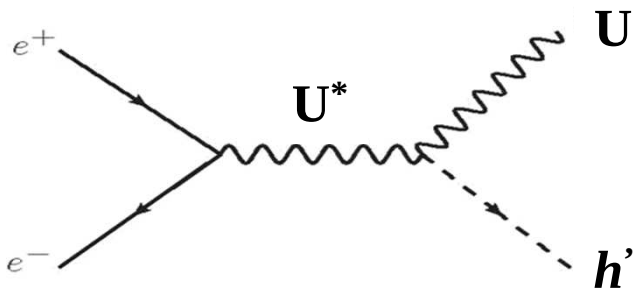
- Huge (not-resonant) QED bckg
- **10^3 events/fb^{-1} produced for $\varepsilon \sim 10^{-3}$, with few MeV mass resolution**

For low masses and low couplings the lifetime of the U boson becomes long and pontentially measurable:

$$\gamma c\tau \approx 1\,\mathrm{mm}\,(\gamma/10)\left(10^{-4}/\varepsilon\right)^2\,(100\,\mathrm{MeV}/M_U)$$

The KLOE-2 IT detector, under construction and planned to be installed in fall 2012, will provide two-track vertex position with an accuracy of 1-2 mm

Search for U boson @ KLOE: *h'*-strahlung



$e^+e^- \to U\,h'$ (dominant if $m_h < m_U$)

$$\sigma \approx 20\,fb \times \left(\frac{\alpha'}{\alpha}\right)\left(\frac{\varepsilon^2}{10^{-4}}\right)\frac{10^2 GeV^2}{s}$$

[B. Batell, M. Pospelov, A. Ritz: PRD79 (2009) 115008]

$m_h > m_U$: $h' \to UU \to 4l$

$m_h < m_U$: ***h'* → "invisible"**
U→*ll*

Feasibility studies performed

$\varepsilon = 10^{-3}$
$\alpha' = \alpha$
$m_u >> m_h$

$\sigma_{hU} \approx 20$ fb

$\tau_h > 10\ \mu s$

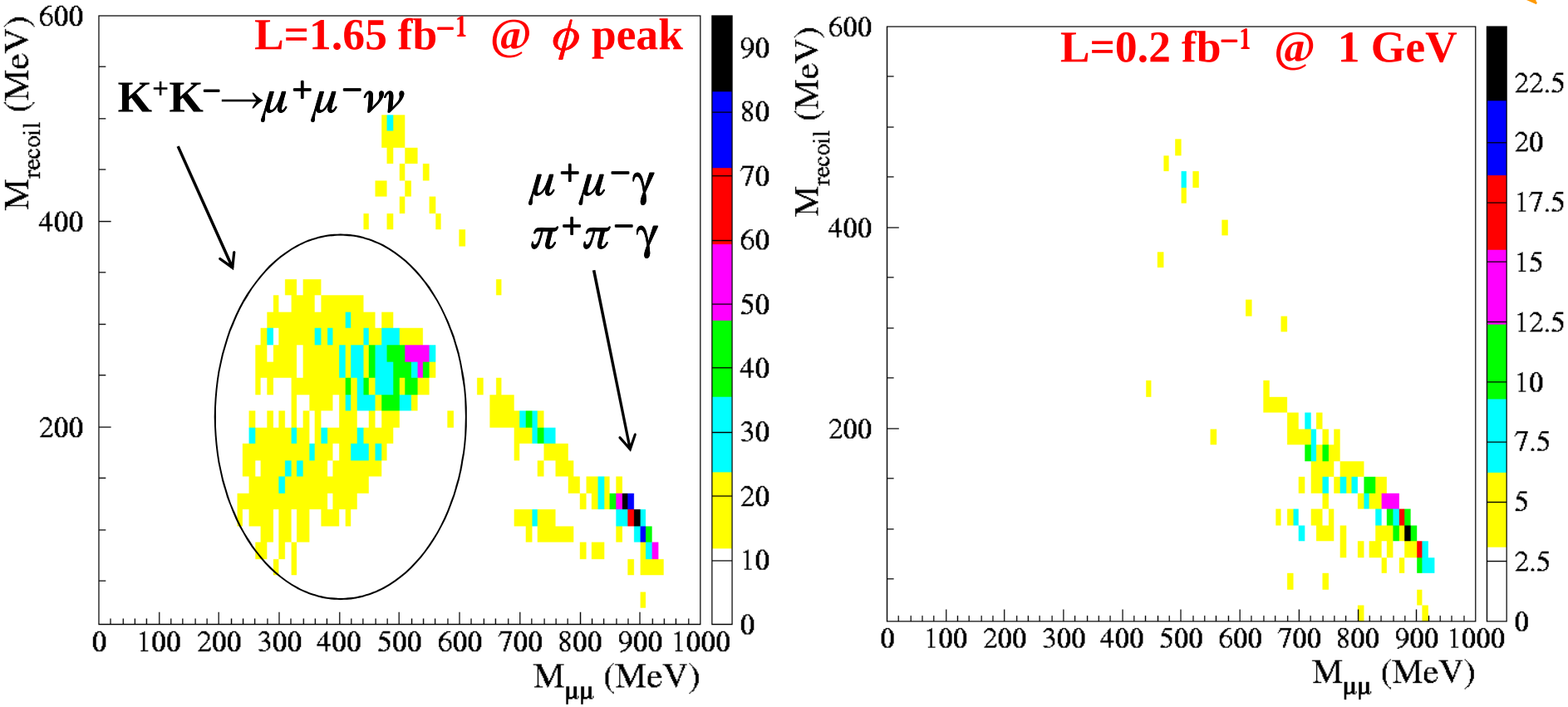
increasing with decreasing ε

Signature (in the hypothesis that the U decays only to SM particles): a pair of leptons + missing energy

Feasibility studies for *h*'-strahlung

PRELIMINARY

$U \to \mu^+\mu^-$ final state



A signal would show up as a sharp 2D peak with ≈ 10 events for $\varepsilon \sim 10^{-3}$

$e^+e^- \to \pi^+\pi^-\gamma$ continuum bckg could be rejected with π/μ PID

Possibility for a long KLOE-2 run at $\sqrt{s} = 1$ GeV under discussion

Conclusions

- Several intriguing experimental hints suggest that a ‘secluded world’, with manifestation at low energies, could explain the puzzle of the dark matter

- KLOE/KLOE-2 experiments well suited for the search of the boson mediator of this dark force in a wide mass range and with different production mechanism

- The most advanced search is through the $\phi \to \eta U$, $\eta \to \pi^+\pi^-\pi^0$, decay, which allow to set a limit of:

$$\alpha'/\alpha \leq 2 \times 10^{-5} \text{ @ 90\% C.L. for } 50 < M_U < 420 \text{ MeV}$$

- Further improvements in progress in other η decay channels, together with feasibility studies for $e^+e^- \to U\gamma$ and $e^+e^- \to Uh$’

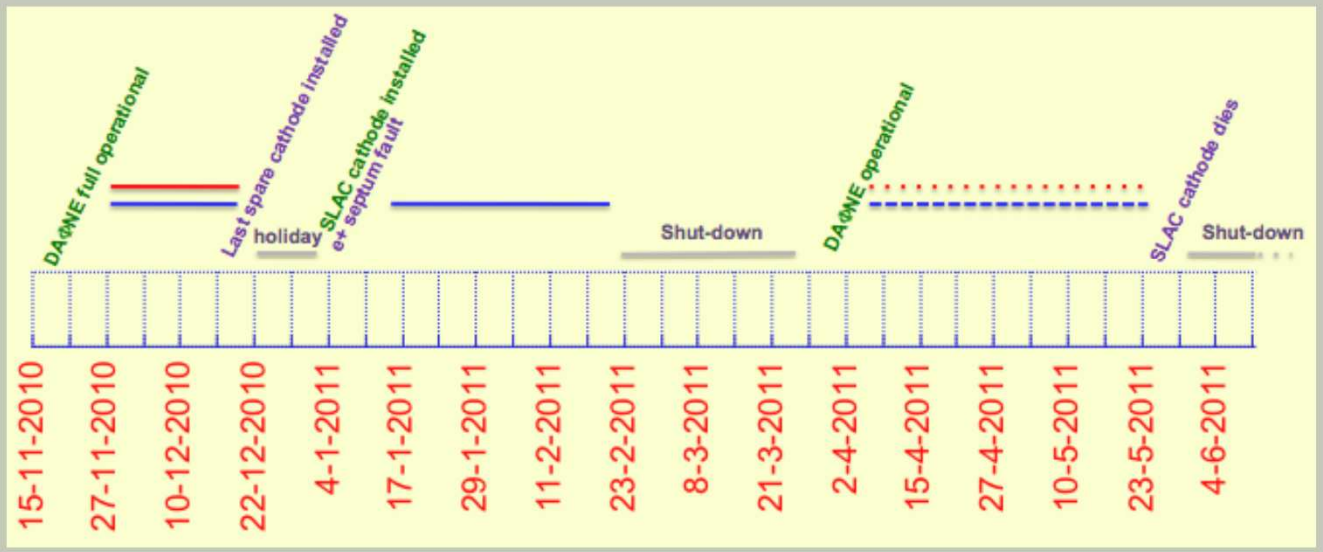
- The KLOE-2 run might explore weaker couplings and cover a larger portion of the interesting parameter’s space

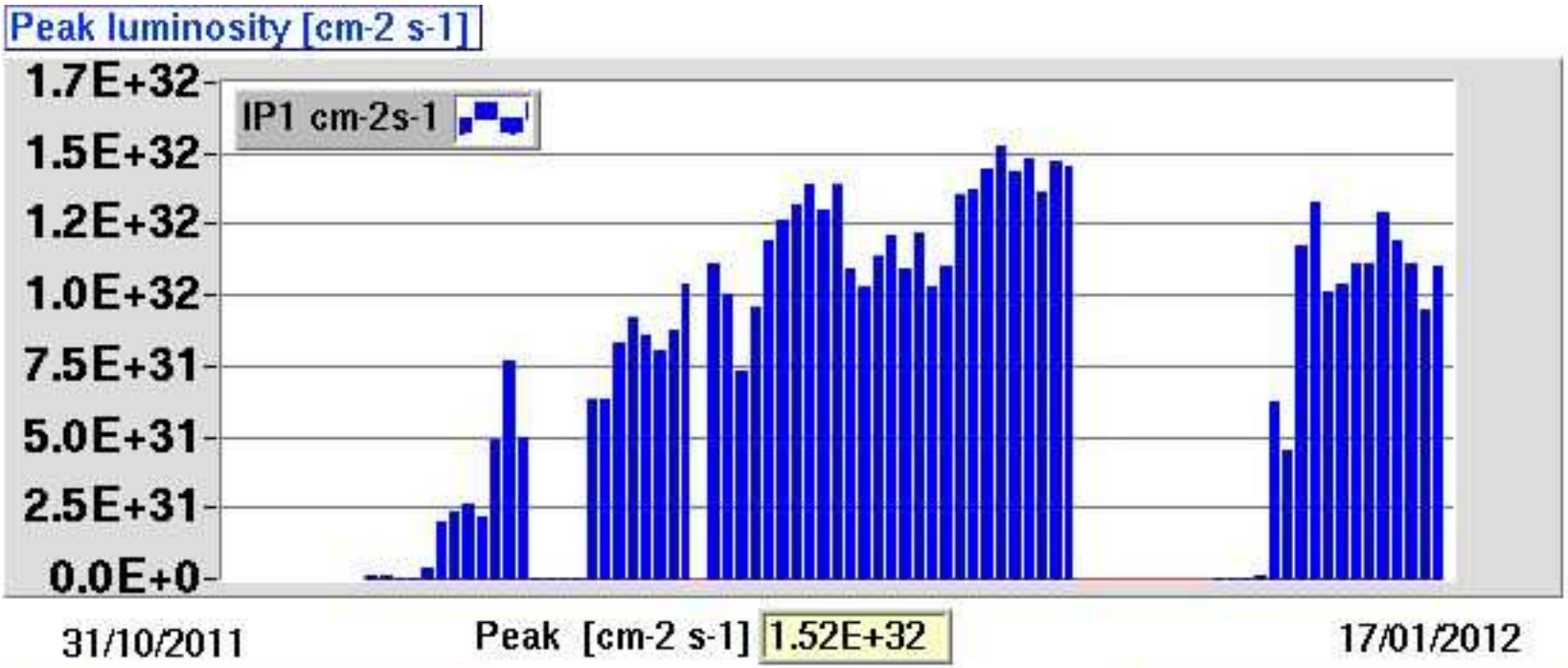
P. Raimondi @ LNF SC, Jan 2012

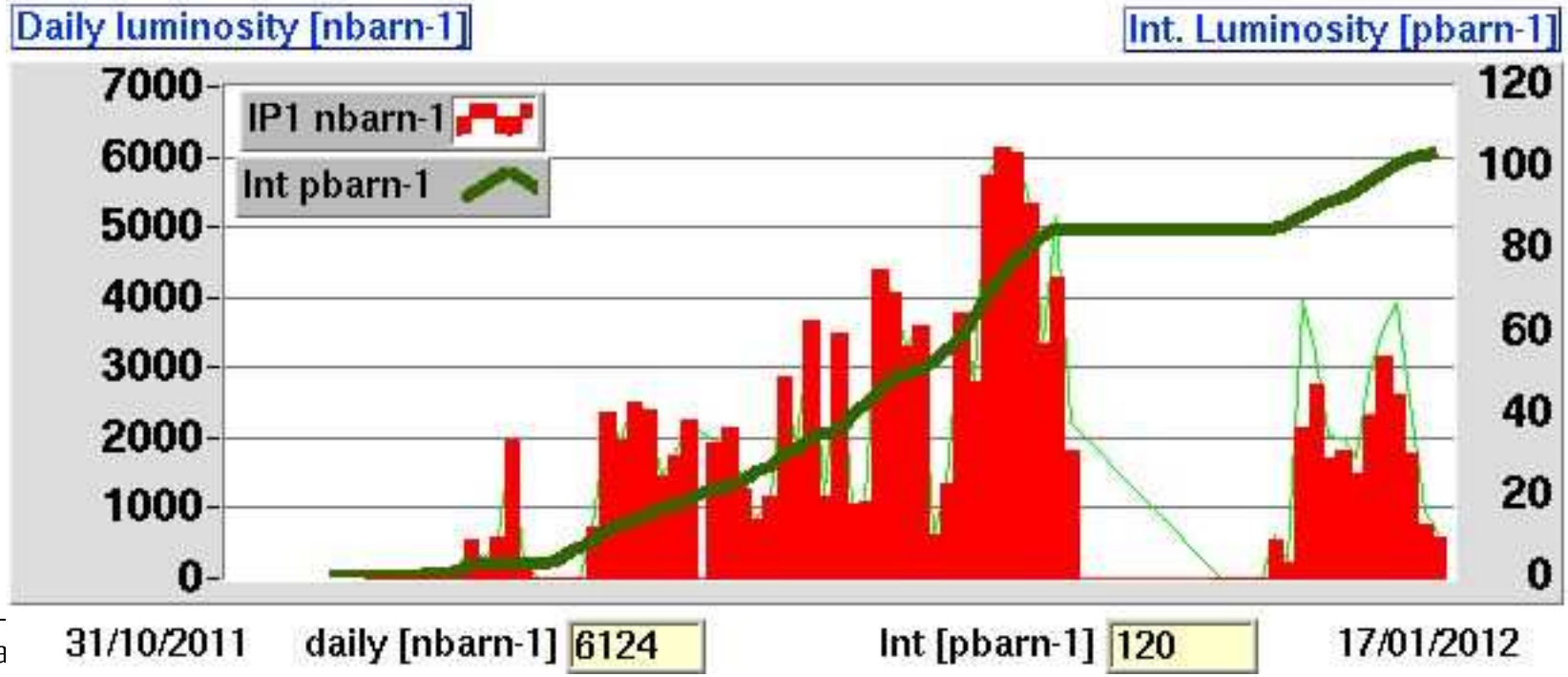
Commissioning overview

- *DAΦNE upgrade for the KLOE-2 run completed on July 2010*
- *KLOE cool-down started on the second half of April 2010, however several problems involving the cryo-plant prevented to energize the detector till October 25th*
- *Since November 2010 till June 2011 several faults:*
  - *Injection septum of the positron ring*
  - *Injection system: Linac gun cathode and D modulator*
  - *Cooling system of the KLOE magnet power supply*
  - Vertical orbit oscillation

  prevented stable operations leading to an unscheduled shut-down

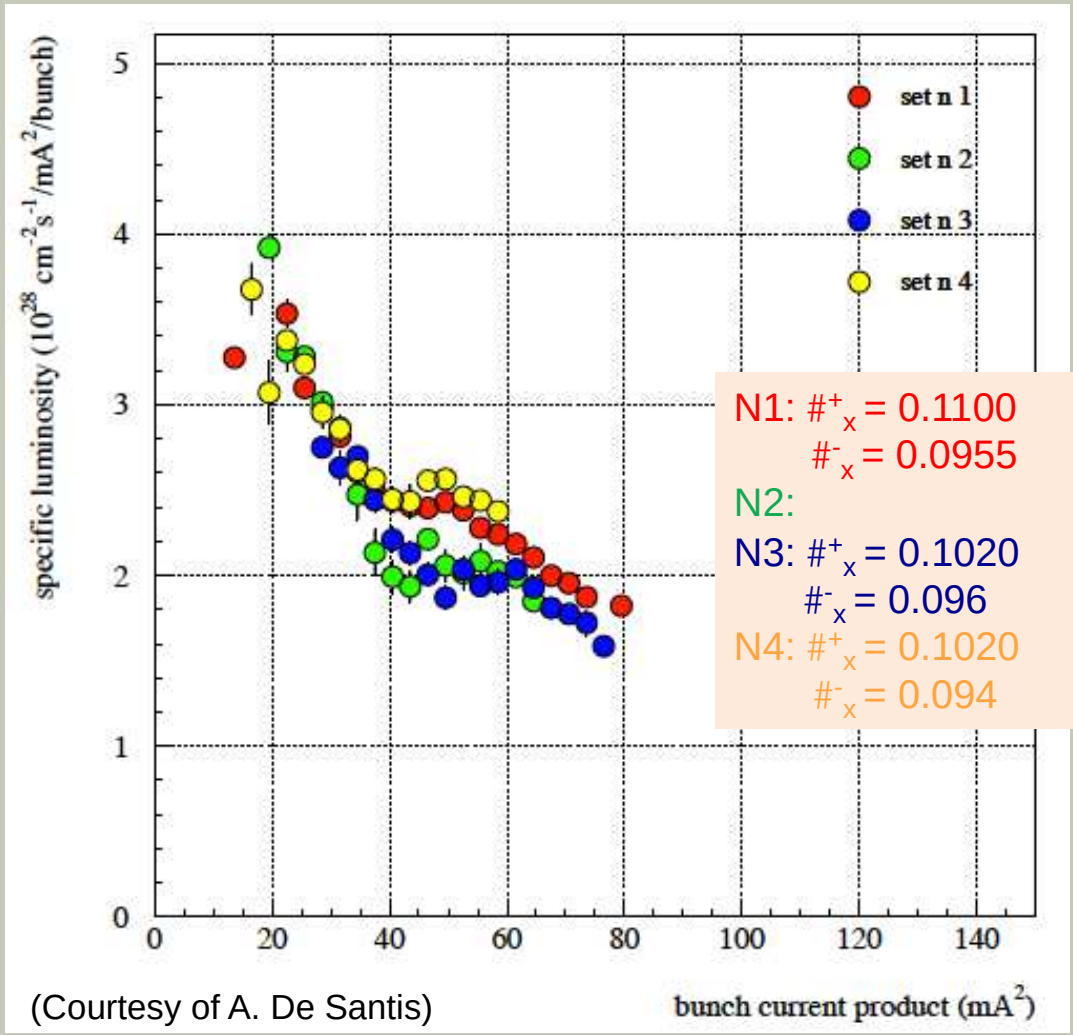



Peak luminosity [cm-2 s-1]
1.7E+32
1.5E+32
1.2E+32
1.0E+32
7.5E+31
5.0E+31
2.5E+31
0.0E+0
IP1 cm-2s-1
31/10/2011
Peak [cm-2 s-1] 1.52E+32
17/01/2012


Daily luminosity [nbarn-1]
Int. Luminosity [pbarn-1]
7000
6000
5000
4000
3000
2000
1000
0
120
100
80
60
40
20
0
IP1 nbarn-1
Int pbarn-1
31/10/2011
daily [nbarn-1] 6124
Int [pbarn-1] 120
17/01/2012

P. Raimondi @ LNF SC, Jan 2012

Specific Luminosity



(Courtesy of A. De Santis)

$$L_{sp} = \frac{L_{sb}}{I_{sb}^{+} \cdot I_{sb}^{\#}}$$

N1: $\#^{+}_x = 0.1100$ $\#^{+}_y = 0.1810$ nominal tunes
$\#^{-}_x = 0.0955$ $\#^{-}_y = 0.1615$

N2: betratron coupling optimized

N3: $\#^{+}_x = 0.1020$ $\#^{+}_y = 0.1690$ e^+ tunes lower
$\#^{-}_x = 0.096$ $\#^{-}_y = 0.1605$

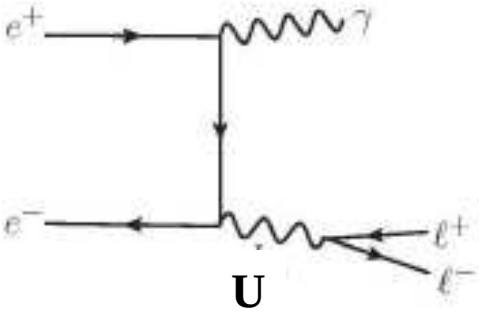
N4: $\#^{+}_x = 0.1020$ $\#^{+}_y = 0.1690$ e^+ e^- tunes lower
$\#^{-}_x = 0.094$ $\#^{-}_y = 0.1560$

At low currents L_s exceeds by 3 times the best value measured during the past KLOE runs

Experimental searches at low energies

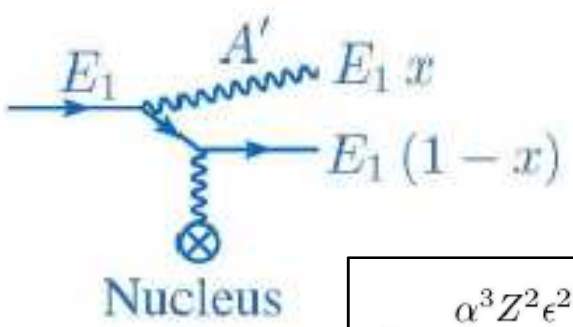
❖ **e^+e^- collisions**: $e^+e^- \to U\gamma \to \ell^+\ell^-\gamma$

Huge (not-resonant) QED bckg



❖ **Meson decays**: meson having radiative decay to one photon can decay to a U boson with BR(X→YU) ≈ ε^2 BR(X→Yγ)

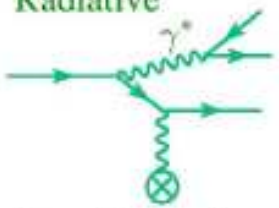
❖ **Fixed target $e^{\pm}$-N scattering**:



$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

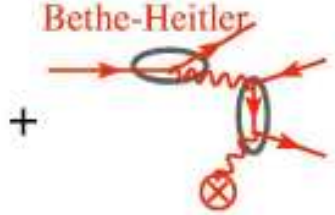
Backgrounds

Radiative



Same kinematics as signal, **IRREDUCIBLE:** (except vertex)

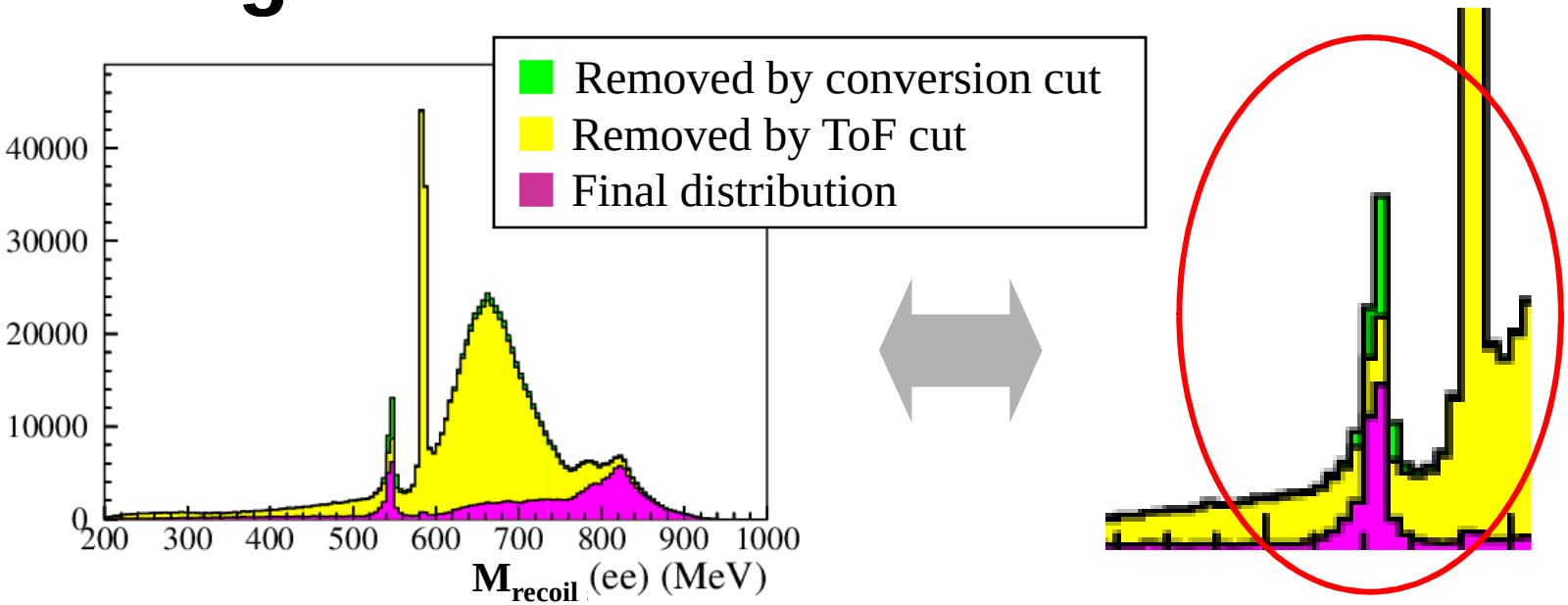
Bethe-Heitler



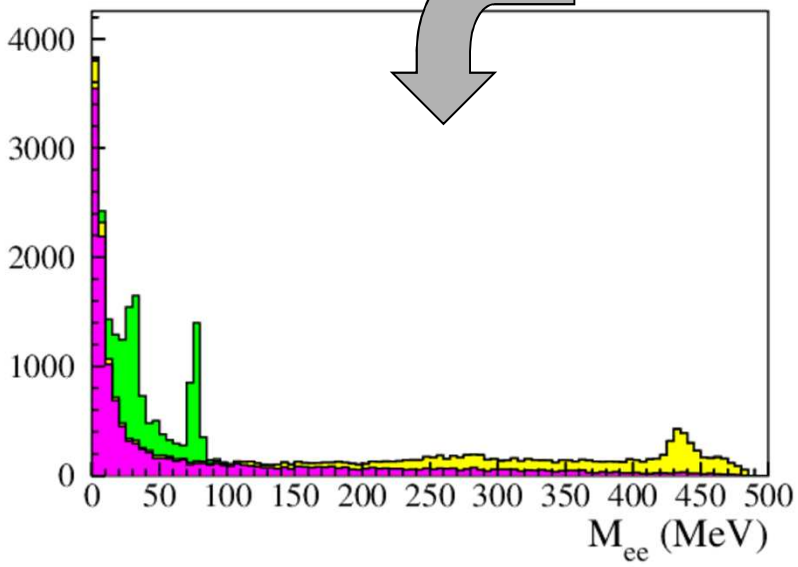
+

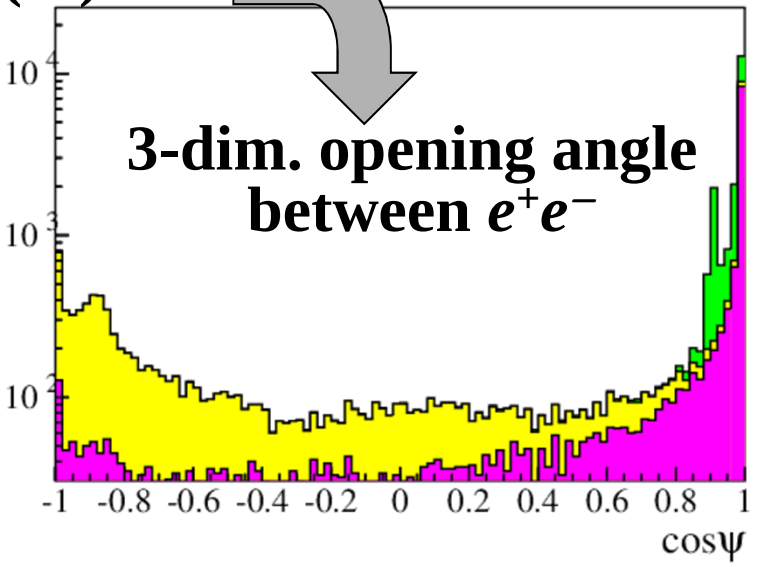
Larger rate, reject using very different kinematics

Background reduction on data



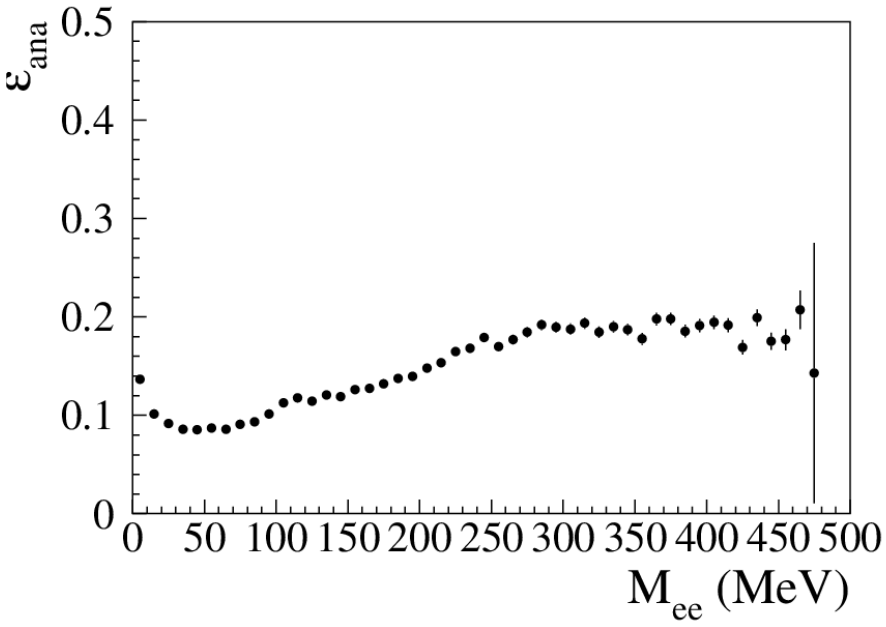
After M_{recoil}(ee) cut





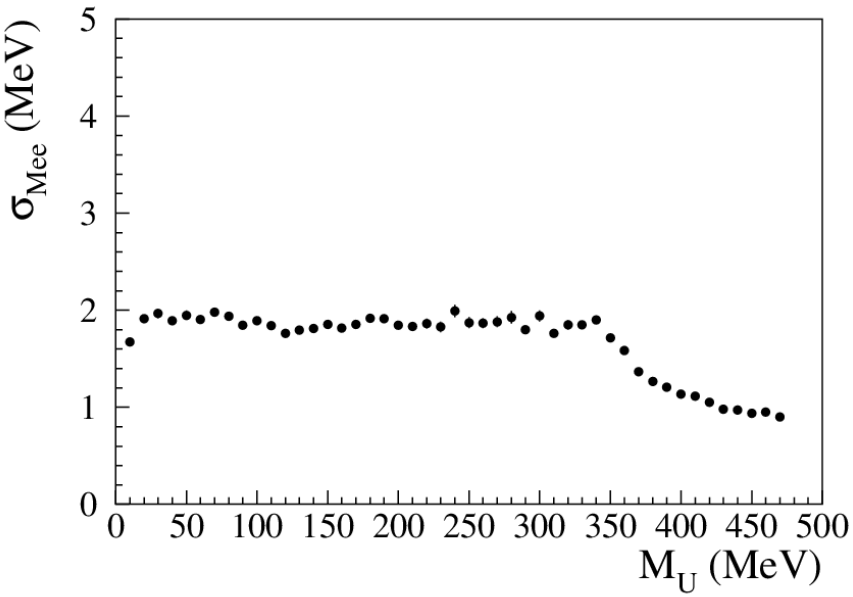
3-dim. opening angle between e^+e^-

Selection efficiency and mass resolution



Total selection efficiency between 10% and 20%

Mass resolution for signal events: 1-2 MeV



U.L. evaluation: the CL_S technique

Reference: T. Junk, Nucl. Instr. Meth. A 434 (1999) 435.

$$X = \prod_{i=i-2}^{i+2} X_i = \frac{\prod_{i=i-2}^{i+2} \frac{\exp[-(S_i + B_i)] \times (S_i + B_i)^{N_i}}{N_i!}}{\prod_{i=i-2}^{i+2} \frac{\exp[-(B_i)] \times (B_i)^{N_i}}{N_i!}}$$

N_i : number of observed events in ith bin
B_i : number of expected $\phi \to \eta e^+ e^-$ events from fit to M_{ee} shape
S_i : $N_{sig} \times f_i$ [f_i = fraction of DF signal events in i^{th} bin]

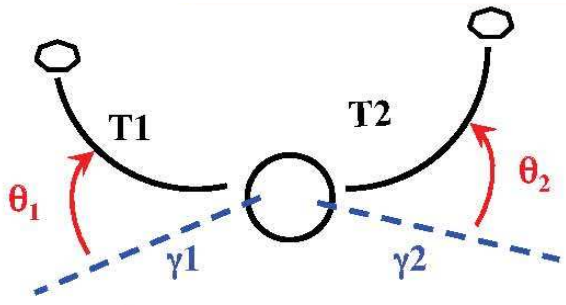
$$CL_{S+B} = P_{S+B}(X \le X_{obs}) = \sum_{X(\{N_i'\}) \le X(\{N_i\})} \prod_{i=i-2}^{i+2} \frac{\exp[-(S_i + B_i)] \times (S_i + B_i)^{N_i}}{N_i!}$$

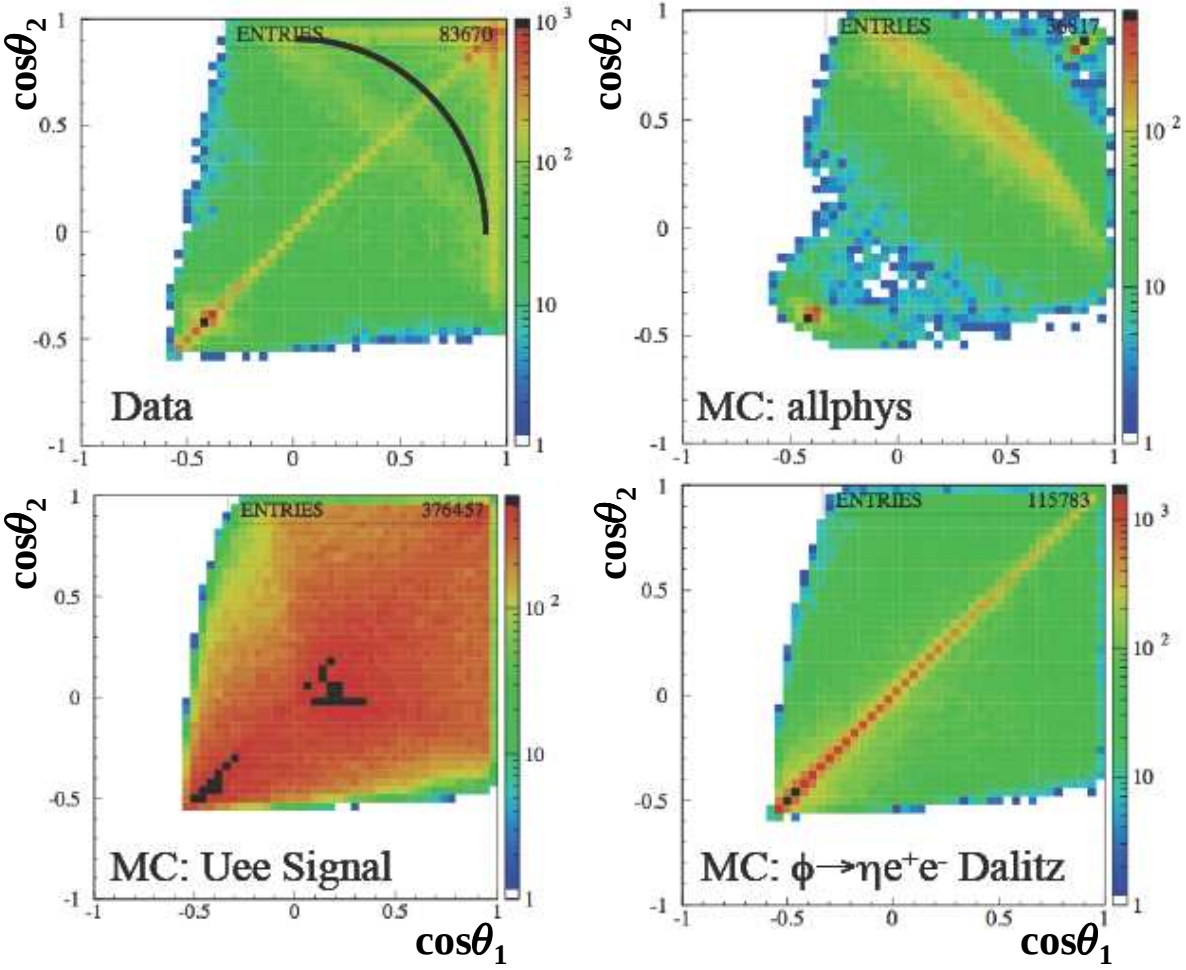
CL_S evaluated using TLimit class in ROOT

- $\phi \to \eta$U MC sample divided in sub-sample of 1 MeV in M_{ee}(true)
- For each sub-sample evaluate CL_S for $0<S<S(MAX)$ using 5 rec. bins
- **Signal hypothesis excluded @ 90% C.L. when $CL_S<0.10$**

The $\phi \to \eta e^+ e^-$, $\eta \to \gamma\gamma$, decay

- 2 “electron” tracks (ToF) in a cylinder around IP + 2 photon candidates
- Photons back-to-back in η rest frame
- $950 < M_{tot} < 1150$ MeV

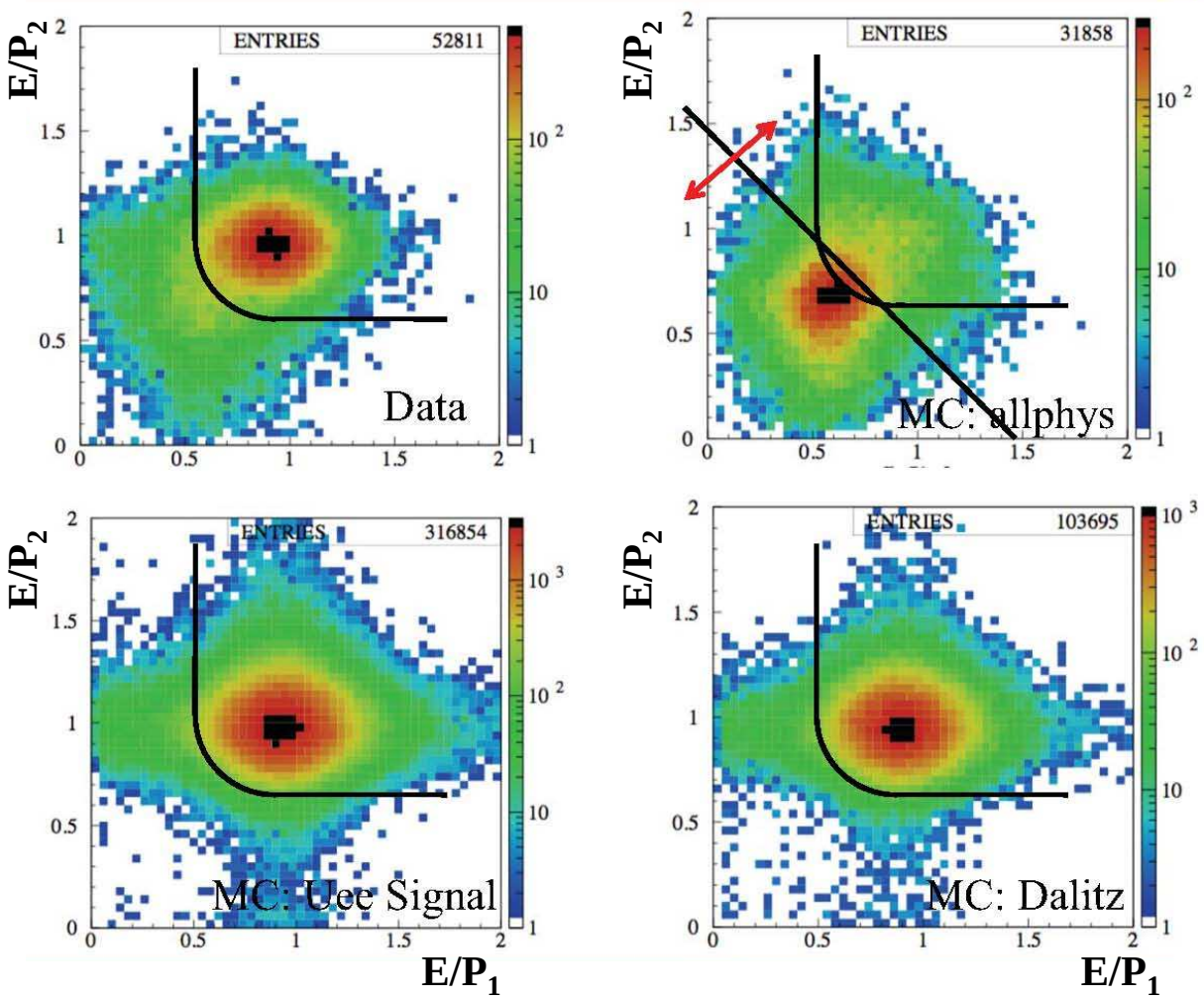




Most severe background from double radiative Bhabha events is strongly reduced by looking at the angle between the charged tracks and the photons

The $\phi \to \eta e^+ e^-$, $\eta \to \gamma\gamma$, decay

Residual non-Bhabha background can be rejected by using further electron identification based on E/P for both tracks



Feasibility studies for *h*'-strahlung

MC signal according to: B. Batell, M. Pospelov, A. Ritz: PRD79 (2009) 115008

✓ $U \to e^+e^-$ not selected by our Event Classification algorithms

✓ $U \to \mu^+\mu^-$ selected with high efficiency for $m_h < 300$ MeV ➡ **Selected channel**

- QED background suppressed because of:
  - ✓ high detection efficiency for γ's of the KLOE calorimeter
  - ✓ missing energy = missing momentum for γ's but not for massive particles
  - ✓ angular distribution of higgs-strahlung $\sin^3\theta$

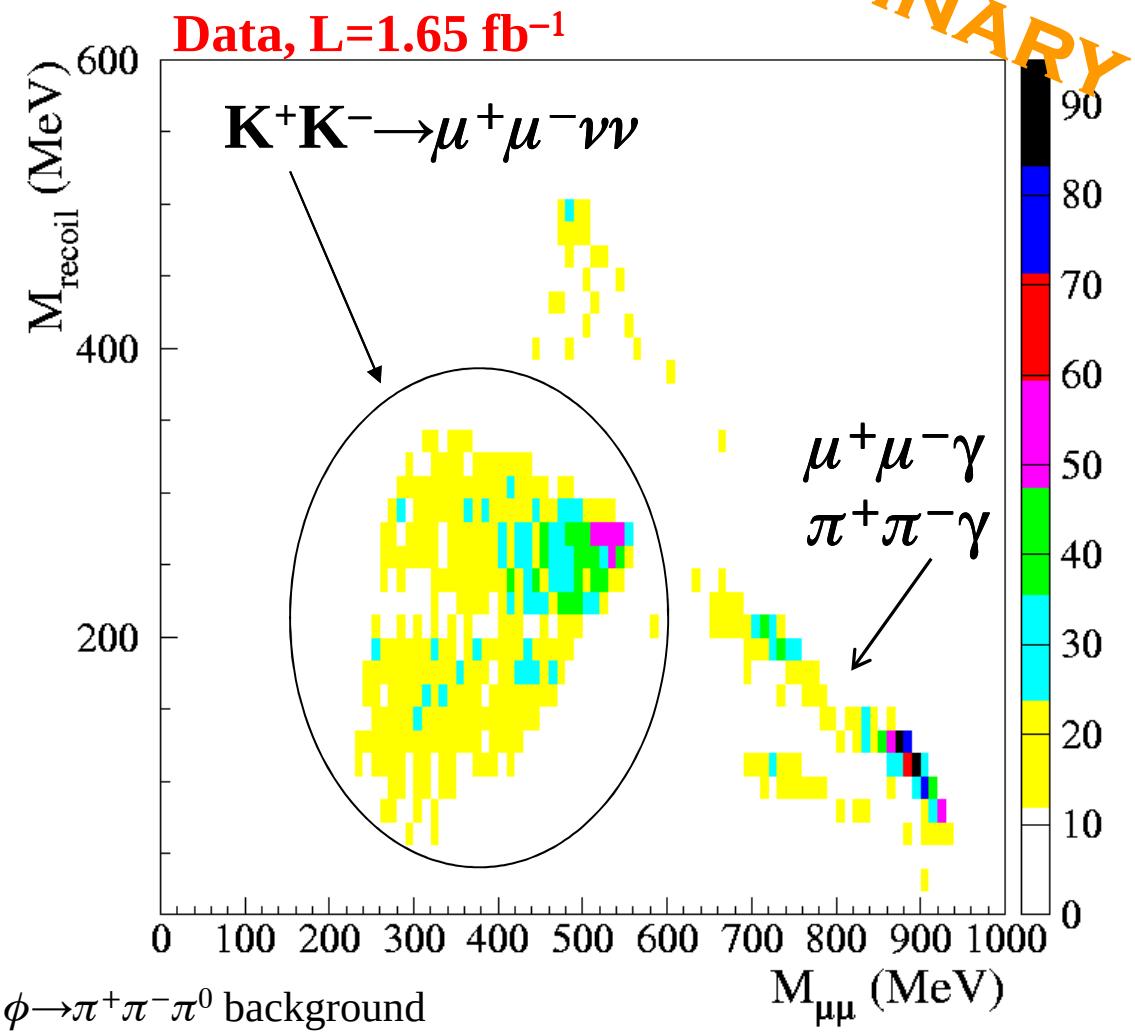
- Large contamination from $\phi \to K^+K^- \to \mu^+\mu^-\nu\nu$ background

$e^+e^- \to hU$, $U \to \mu^+\mu^-$ @ ϕ–peak

PRELIMINARY

Selection:

- 1 vertex @ IP, two (associated) tracks with associated clusters in EMC
- $q_1+q_2=0$
- Total (missing) momentum direction in barrel
- $p_1 < 460$ MeV
- $p_2 < 460$ MeV
- $p_1 + p_2 > 450$ MeV
- $p_{miss} > 40$ MeV
- Tight cut on vertex-IP distance
- No hits in EMC but the ones associated with the 2 tracks (calorimeter veto)
- PID: two muons (e/μ and μ/π)



Reject $\phi \to \pi^+\pi^-\pi^0$ background

Efficiency for MC signal: (15÷40)%, depending on m_h, m_U

A signal would show up as a sharp 2D peak with ≈ 10 events or less

Higgs'-strahlung: signal efficiency

All u masses, m_h=100 MeV

cut	ε (hu, u→μμ)
ppg tag	80 %
barrel	65%
$p_{1,2} < 460$	58%
$p_1+p_2 > 450$	58%
veto cal	53%
$p_{miss} > 40$	53%
vtx cut	35%
PID (e/μ)	30%
PID (π/μ)	~ 20%

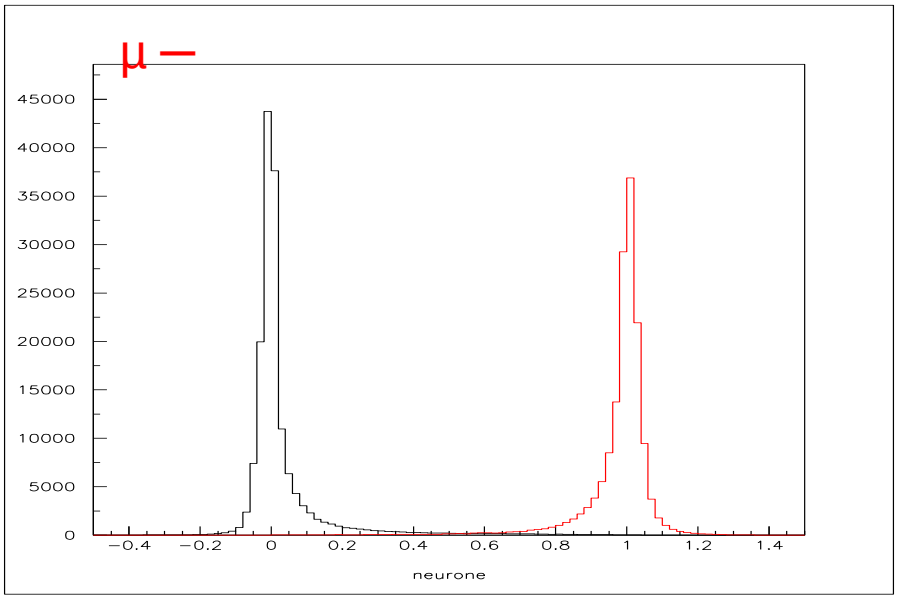
Apply π/μ ID only when kinematics is compatible with a $\pi^+ \pi^- \pi^0$ event: $|m_{recoil}-m_{\pi 0}| < 20$ MeV

Efficiencies: ~ 15% ÷ 40%

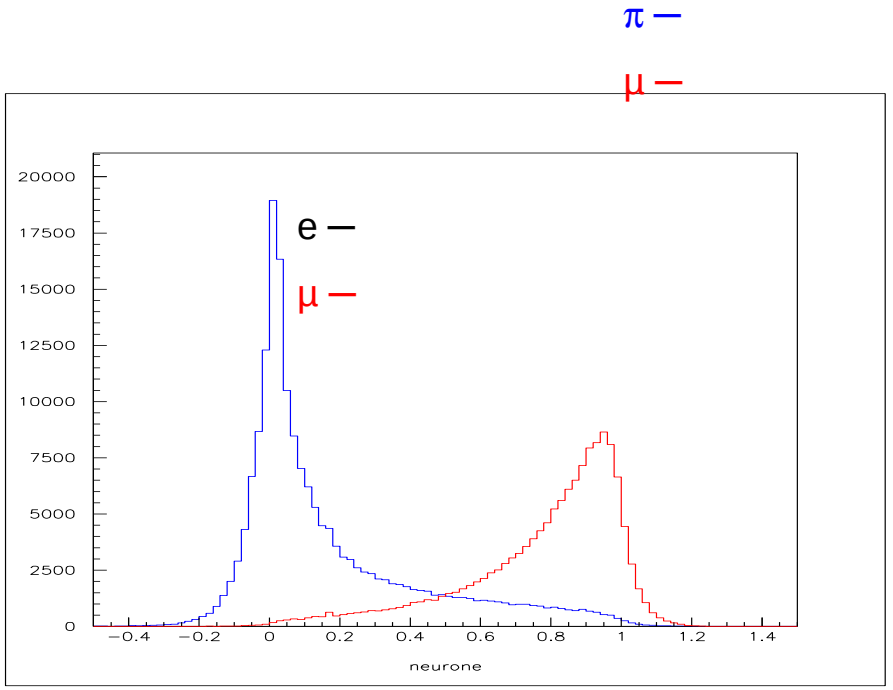
m_{recoil}

$m_{\mu\mu}$

Higgs'-strahlung: particle ID



neuron



output neuron

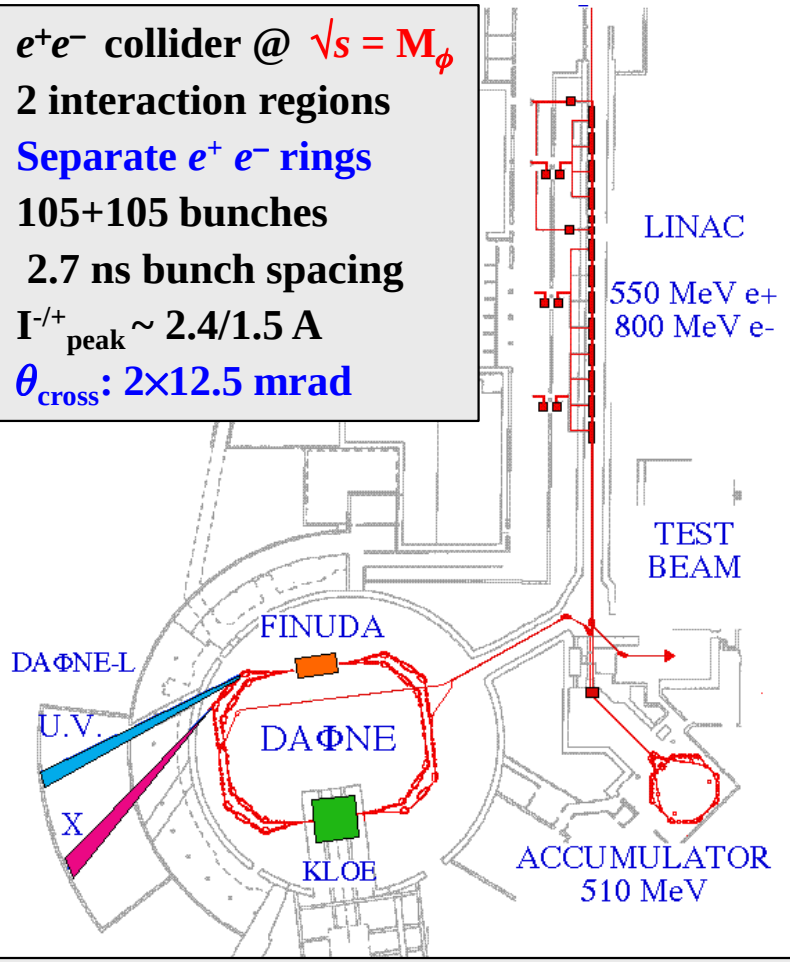
$\mu \rightarrow n_1>0.8 \cap n_2>0.8 \longrightarrow \varepsilon_{\mu\mu} \sim 88\%, \varepsilon_{ee} \sim 10^{-4}$

$e \rightarrow n_1<0.2 \cap n_2<0.2 \longrightarrow \varepsilon_{ee} \sim 89\%$ (Bhabha, data)

$n>0.5 \rightarrow \varepsilon_{\mu} \approx 85\%$, $\varepsilon_{\pi} \approx 15\%$

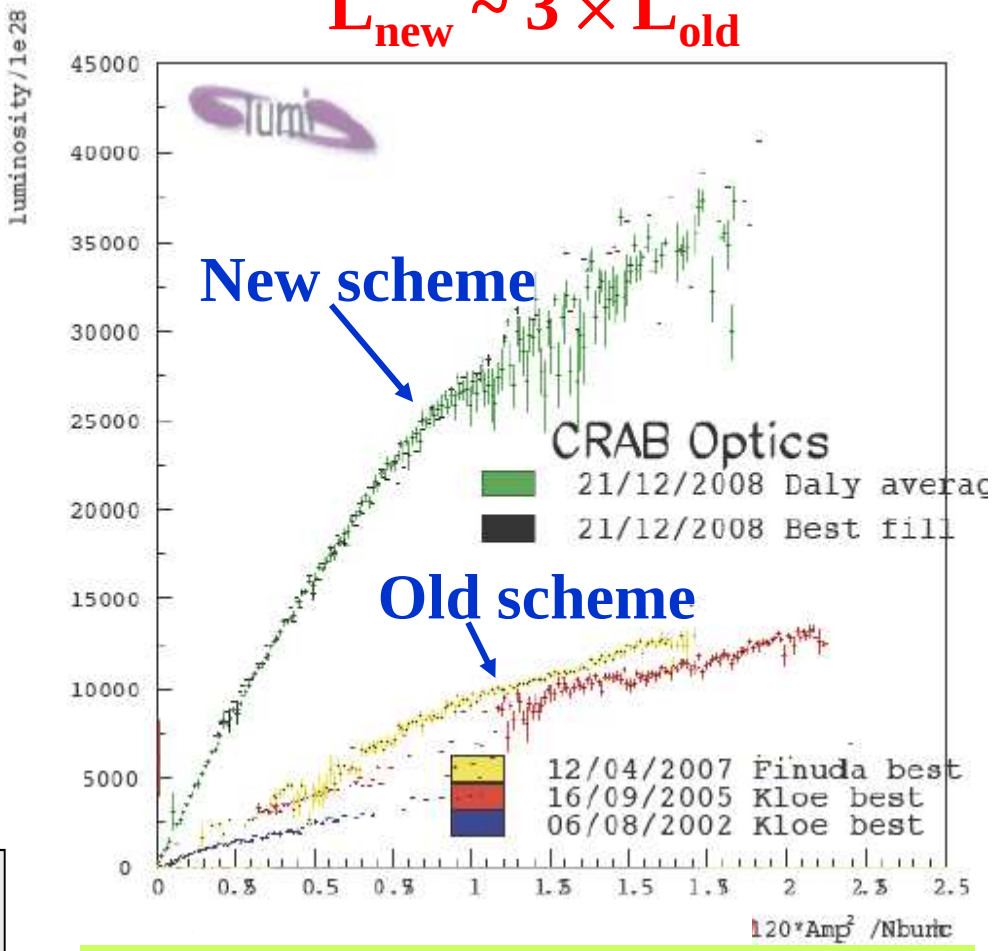
DAΦNE: the Frascati ϕ-factory

- e^+e^- collider @ $\sqrt{s} = M_\phi$
- 2 interaction regions
- Separate e^+ e^- rings
- 105+105 bunches
- 2.7 ns bunch spacing
- $I^{-/+}_{peak} \sim 2.4/1.5$ A
- θ_{cross}: 2×12.5 mrad



2008, new interaction scheme:

$L_{new} \sim 3 \times L_{old}$



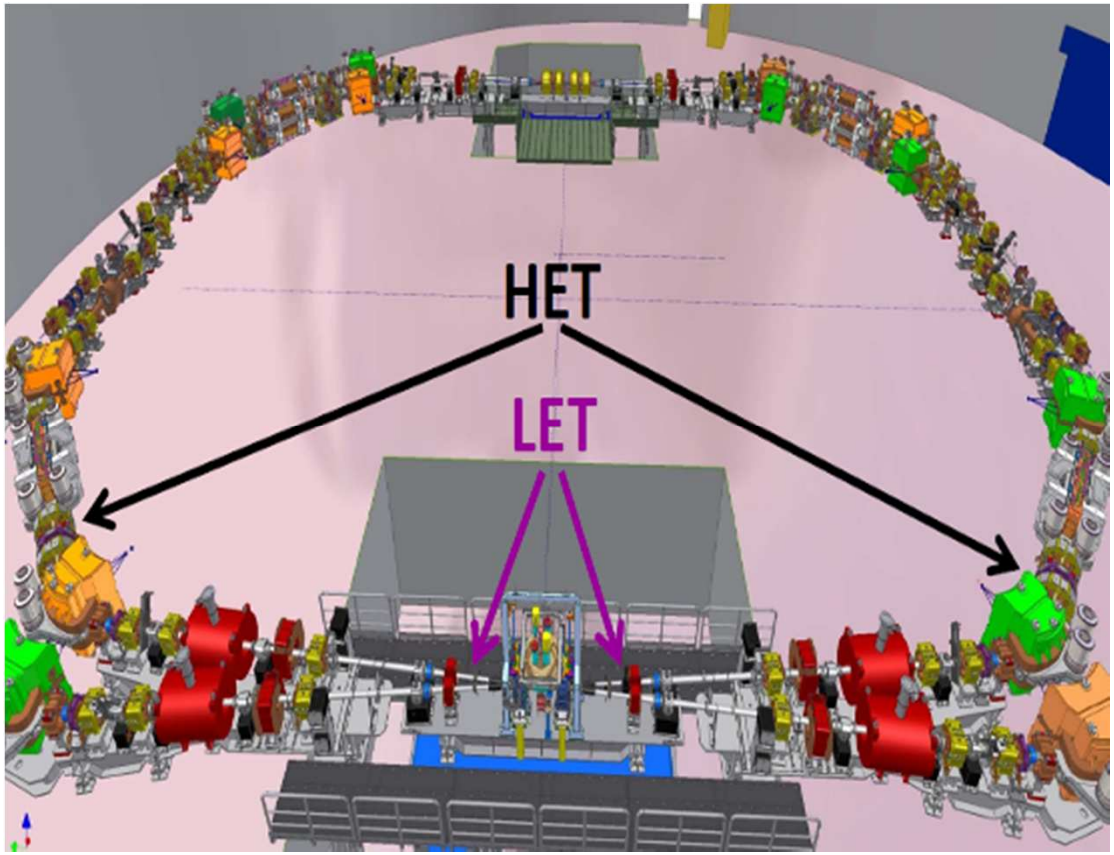
Best performances (1999-2007):

- $L_{peak} = 1.4 \times 10^{32}$ cm^{-2}s^{-1}
- $\int L dt = 8.5$ pb^{-1}/day

Machine commissioning for KLOE-2 in progress

From KLOE to KLOE-2: $\gamma\gamma$ taggers

Detector upgrade for the first KLOE-2 run: 2+2 taggers to detect momentum of leptons in $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$



LET : E=160−230 MeV

- Inside KLOE detector
- LYSO+SiPM
- s_E<10% for E>150 MeV

HET : E > 400 MeV

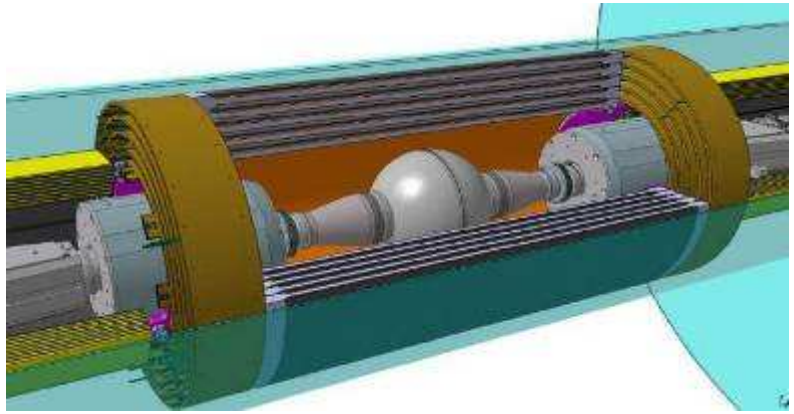
- 11 m from IP
- Scintillators + PMTs
- $\sigma_E \sim 2.5$ MeV
- $\sigma_T \sim 200$ ps

From KLOE to KLOE-2: IP detectors

Major detector upgrades for second KLOE-2 run:

INNER TRACKER

- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks



QCALT

- W + scintillator tiles + SiPM/WLS
- QUADS coverage for K_L decays

CCAL

- LYSO + SiPM
- Increase acceptance for γ's from IP (21° →10°)