U boson searches at KLOE(-2)

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on behalf of the KLOE and KLOE-2 Collaborations

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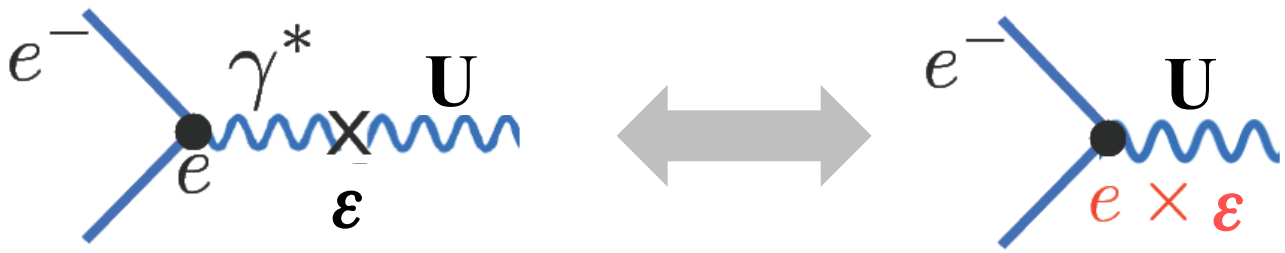
Low energy dark force

See talk by N. Weiner
Tuesday, plenary session

Several puzzling astrophysical results (DAMA, PAMELA, INTEGRAL…) could be explained with the existence of a new light vector boson (U/A′…), mediator of a non standard gauge interaction, weakly coupled to SM particles via a kinetic mixing mechanism: $\varepsilon F_{\mu\nu} F_{\mathrm{d}}^{\mu\nu}$

✓ **Dark gauge boson U mixes with photon**



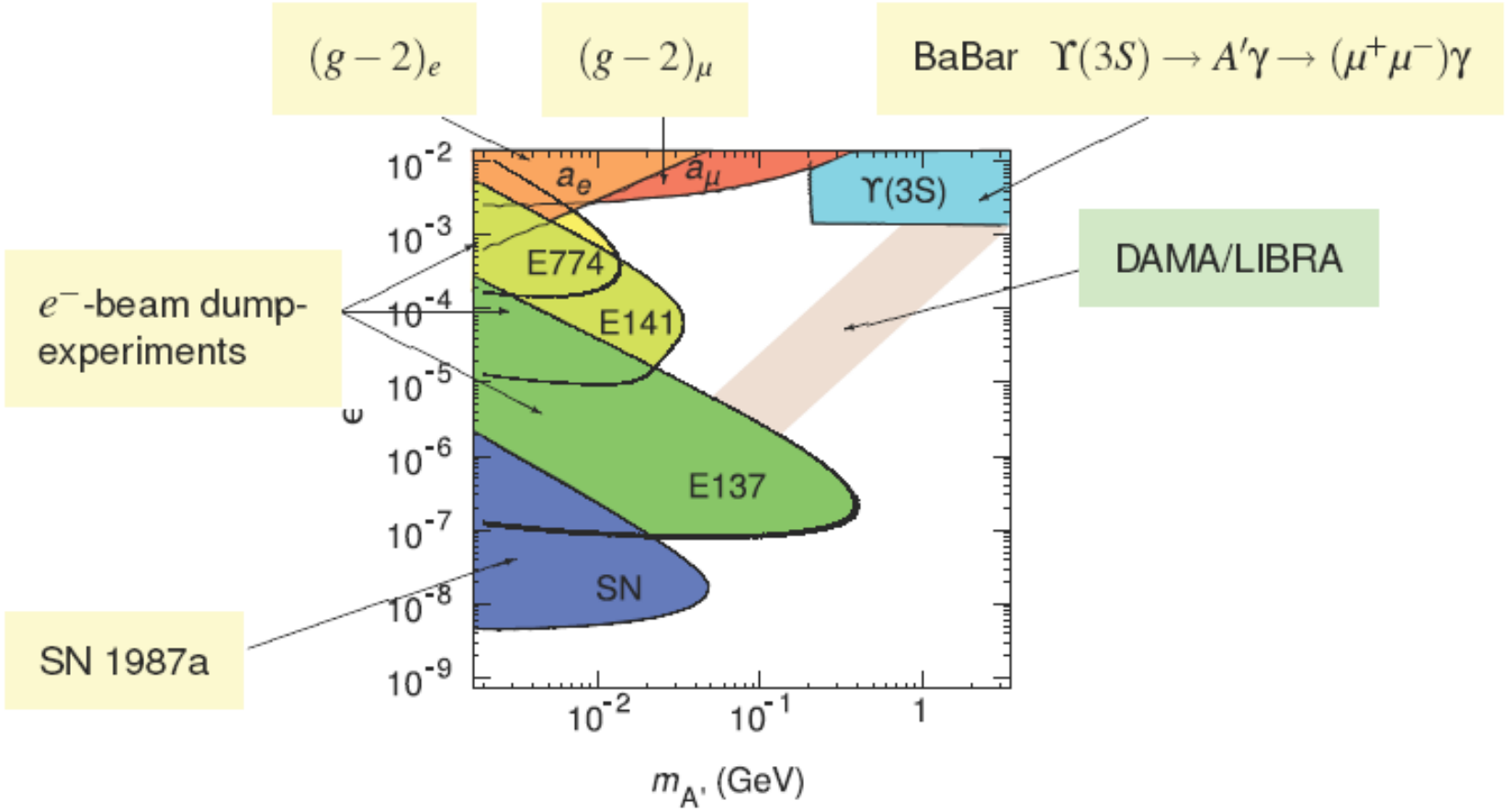
Coupling constant ε of electric charge to U expected to be $\leq 10^{-3}$

✓ **Mass range: 1 MeV – few GeV**

✓ **U production allowed in charged particle scattering**

✓ **U decays through photon mixing, i.e. $e^+e^-/\mu^+\mu^-$…**

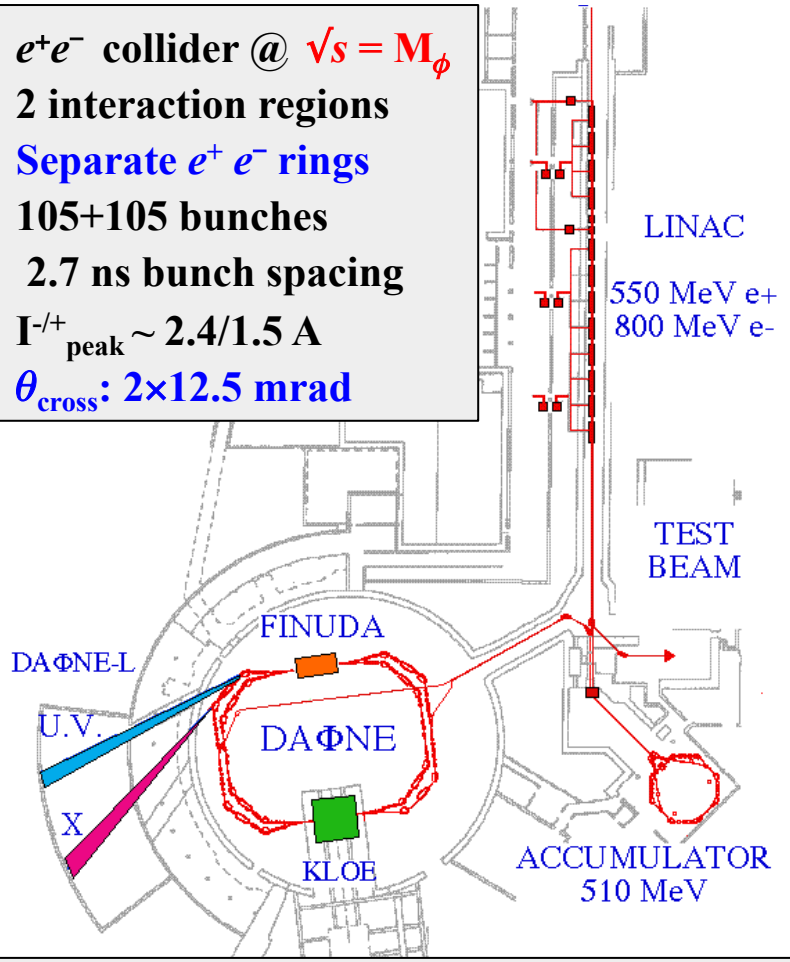
Existing constraints on ε-m_U plane



DAΦNE: the Frascati ϕ-factory

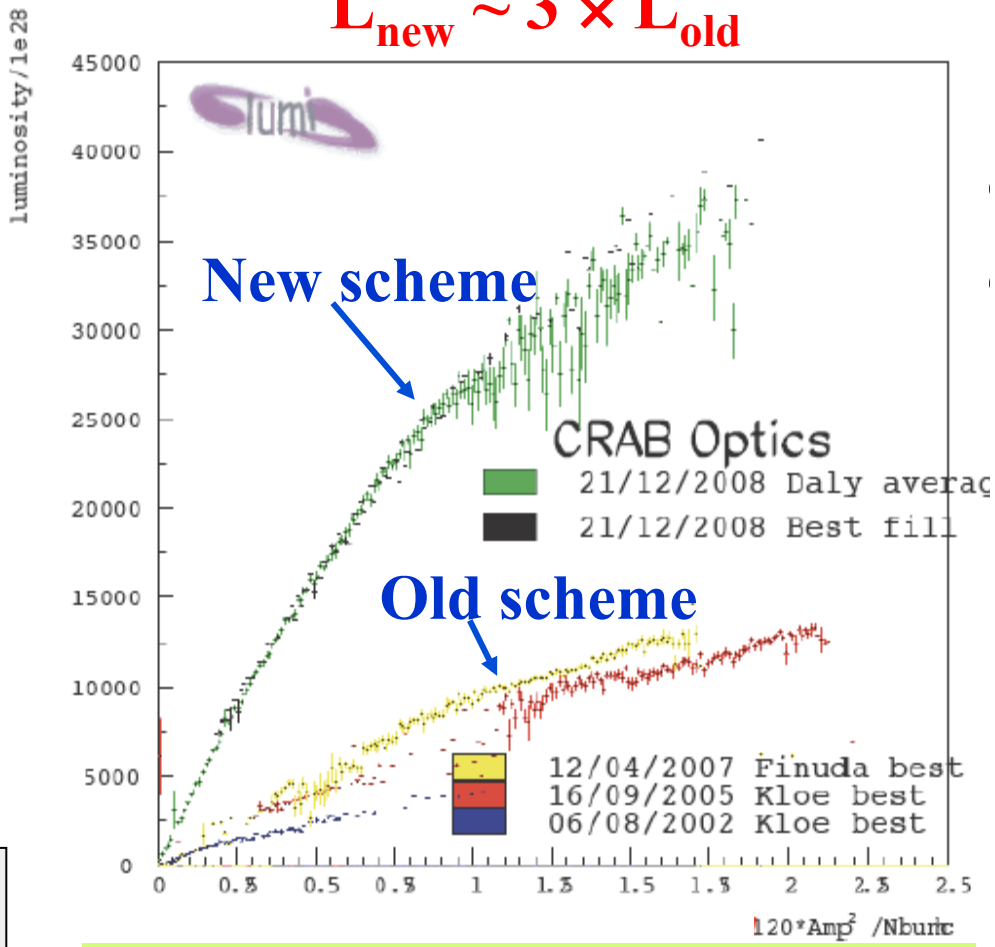
More details on S.Miscetti's talk (parallel, yesterday afternoon)

- 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:

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



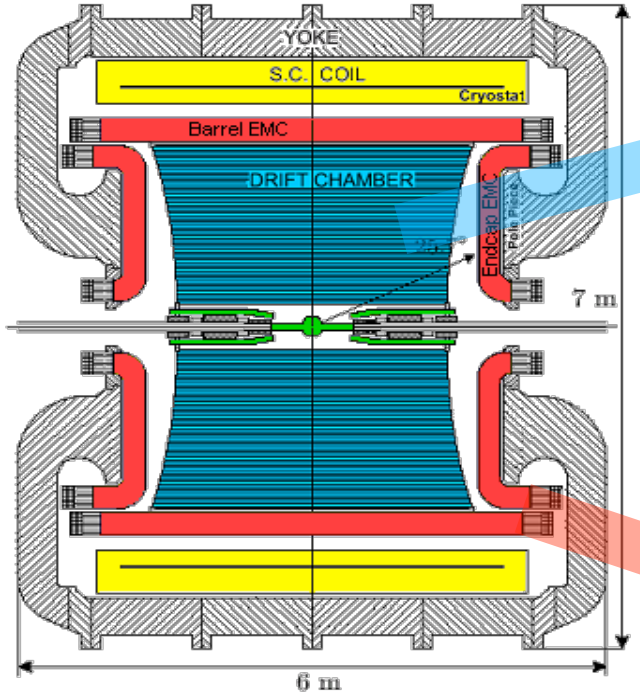
Best performances (1999-2007):

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

Machine commissioning for KLOE-2 run started few weeks ago

The KLOE Experiment @ DAΦNE

More details on S.Miscetti's talk (parallel, yesterday afternoon)



Drift chamber

- Gas mixture: **90% He + 10% C_4H_{10}**
- **$\delta p_t / p_t < 0.4\%$ (θ>45°)**
- **$\sigma_{xy} \approx 150$ μm ; $\sigma_z \approx 2$ 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**

KLOE data taking ended on March 2006

- **2.5 fb^{-1} on tape @ $\sqrt{s} = M_\phi$ (8×10^9 ϕ)**
- **~10 pb^{-1} @ 1010,1018,1023,1030 MeV**
- **250 pb^{-1} @ 1000 MeV**

First KLOE-2 run will start **mid-January**: **≈5 fb^{-1} / 1 year**

Overall run: ×10 increase on integrated luminosity (**20 fb^{-1}**)

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

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

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

Irreducible background: ϕ Dalitz decay $\phi \to \eta\gamma^* \to \eta l^+ l^-$ ($\sigma = 0.7$ 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%) **prel. results**

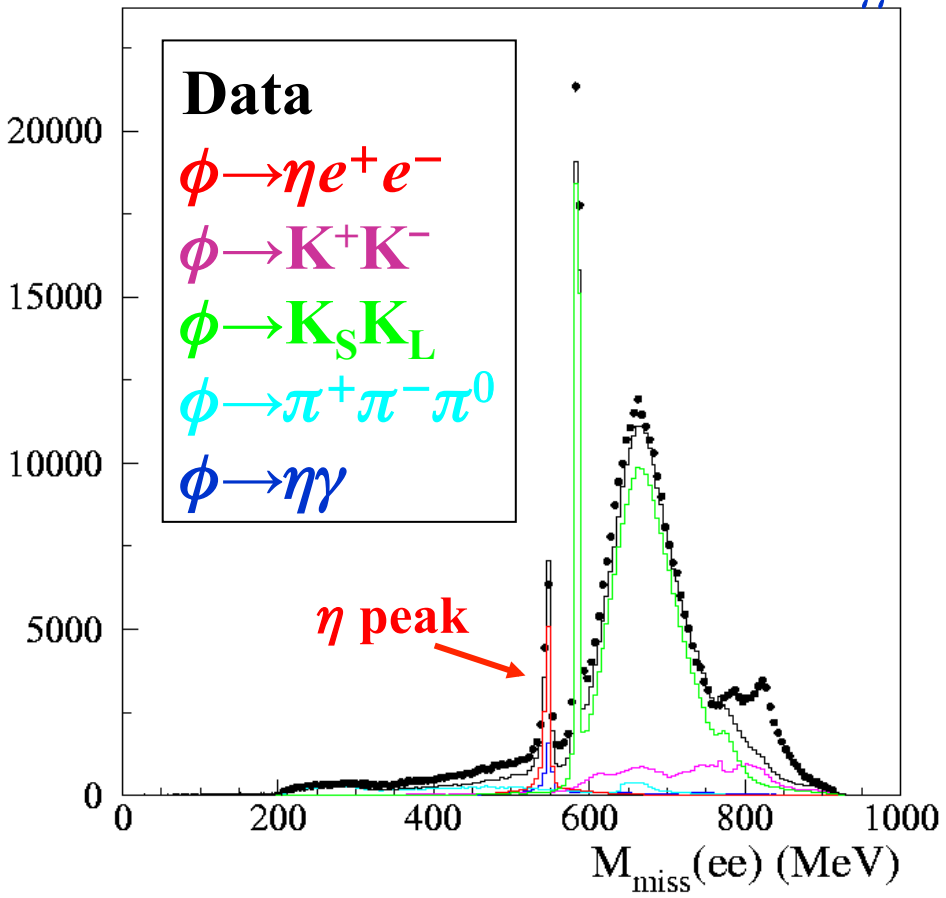
$\eta \to \gamma\gamma$ (BR = 39.3%) **in progress**

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

Analysis performed on **739 pb^{-1}** (~0.4 of the total lumin.)

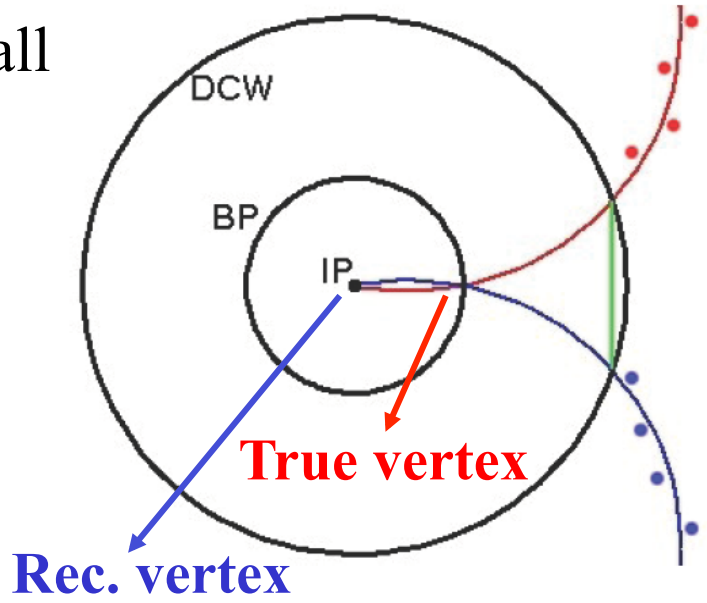
- 4 tracks in a cylinder around IP + 2 photon candidates
- Best $\pi^+\pi^-\gamma\gamma$ match to the η mass using the pion hypothesis for tracks. Other two tracks assigned to e^+/e^-
- $495 < M_{\pi\pi\gamma\gamma} < 600$ MeV
  $70 < M_{\gamma\gamma} < 200$ MeV
  $535 < M_{miss}(ee) < 560$ MeV

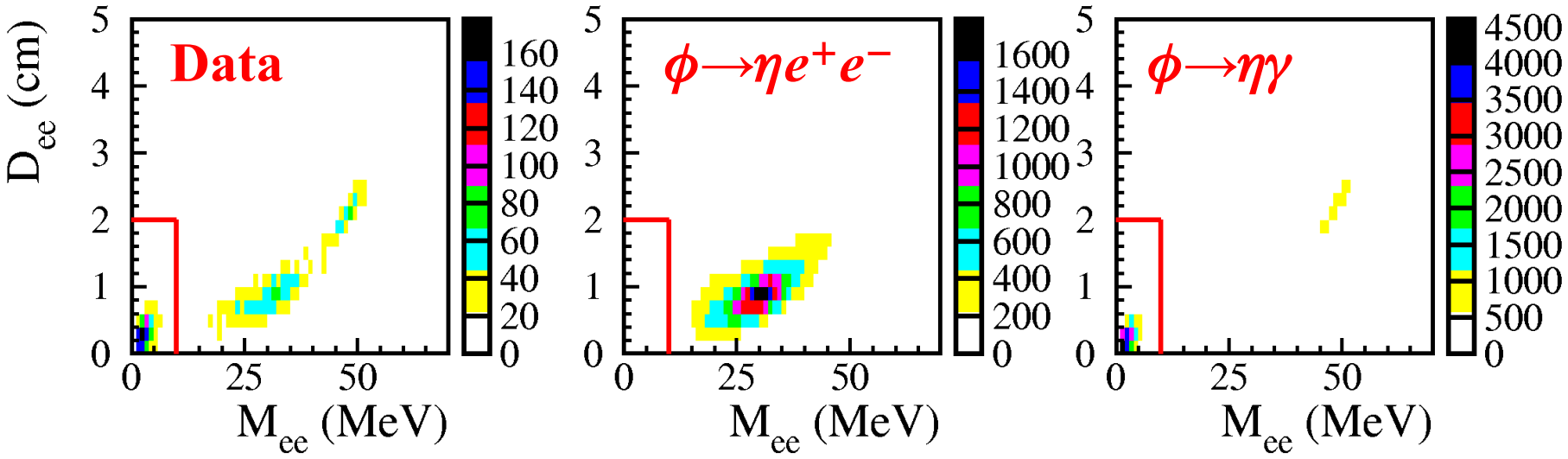
Missing mass to the e^+e^- pair after $M_{\gamma\gamma}$ cut



Background rejection: photon conversions

Photon conversions on Beam Pipe/DC Wall 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

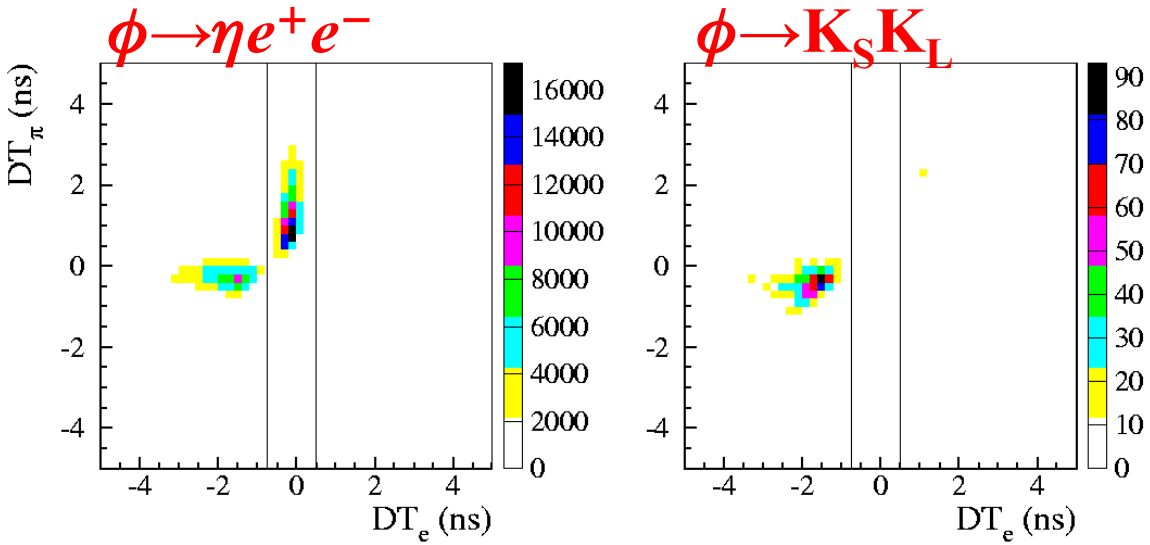


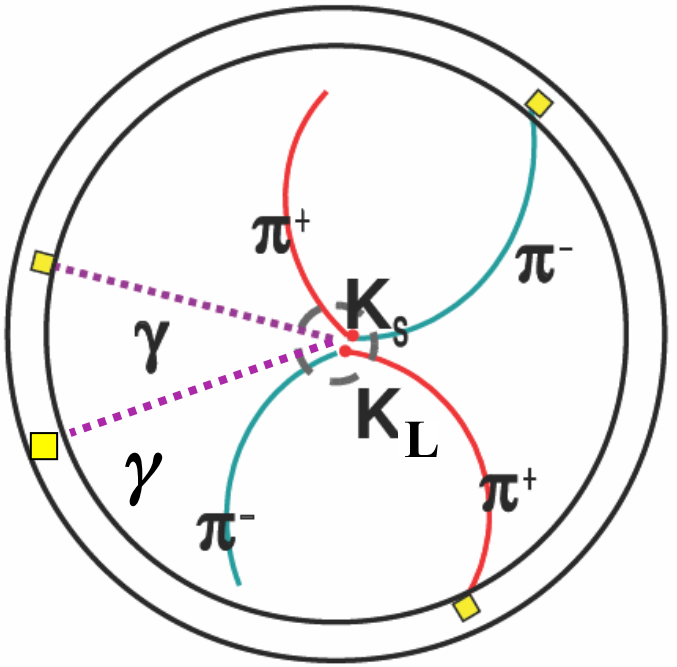


Background rejection: π-enriched events

$\phi\rightarrow$KKbar and $\phi\rightarrow\pi^+\pi^-\pi^0$ events surviving analysis cuts have more than two pions in the final state. They can be rejected using Time-of-Flight (ToF) to the calorimeter when an EMC cluster is connected to the track

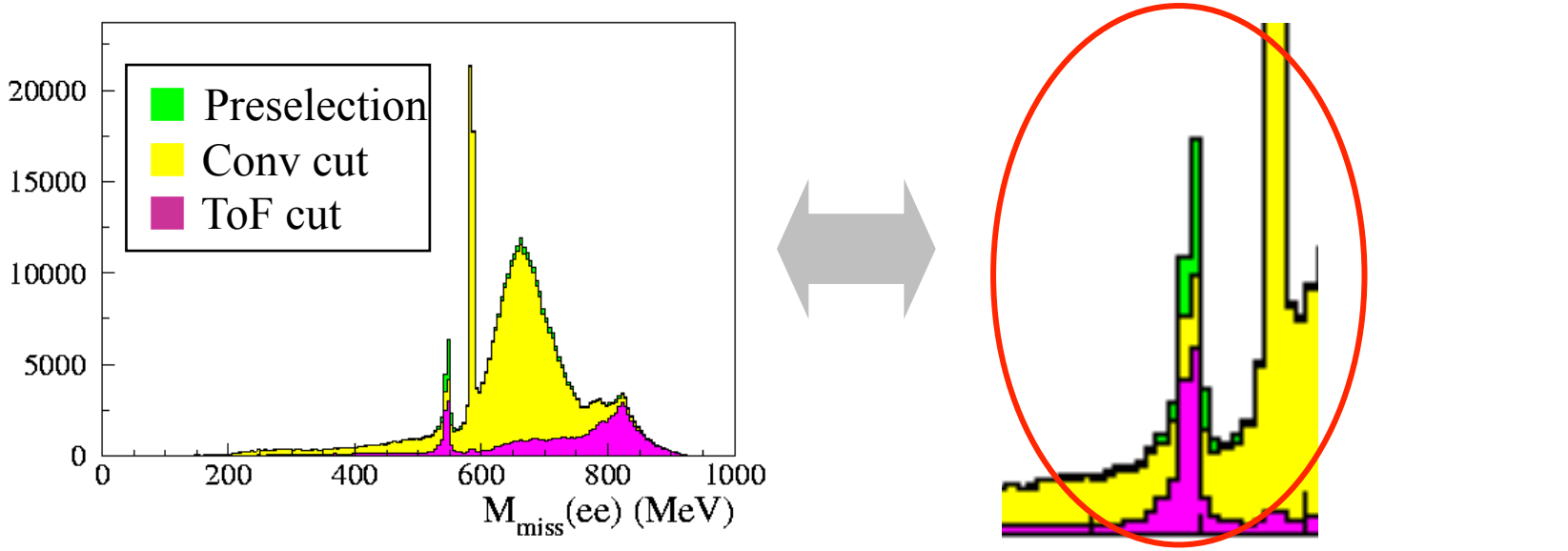
$DT = T_{track} - T_{cluster}$ variable evaluated in both electron (DT_e) and pion (DT_π) hypotheses



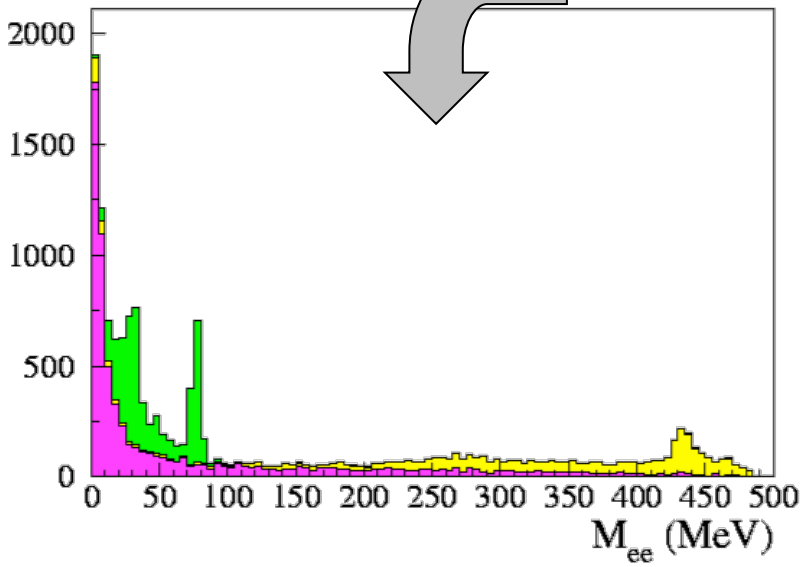


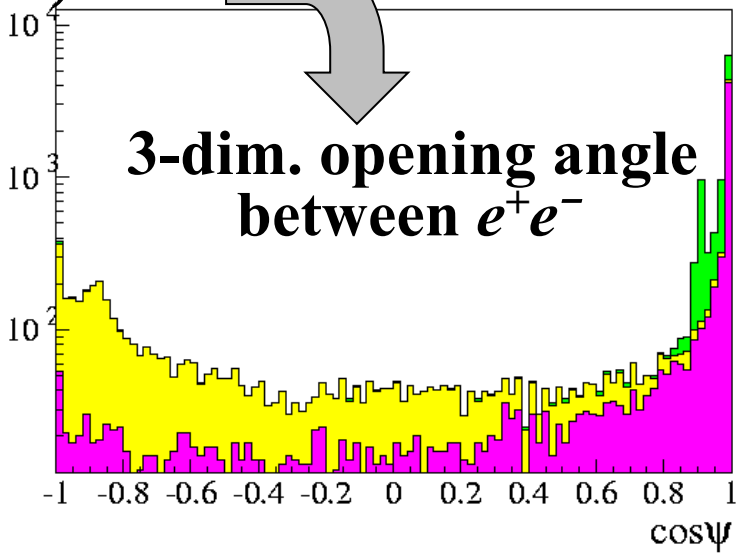
Events with e^+/e^- candidate with connected cluster outside a 3σ DT_e window removed

Background reduction on data



After M_{miss}(ee) cut

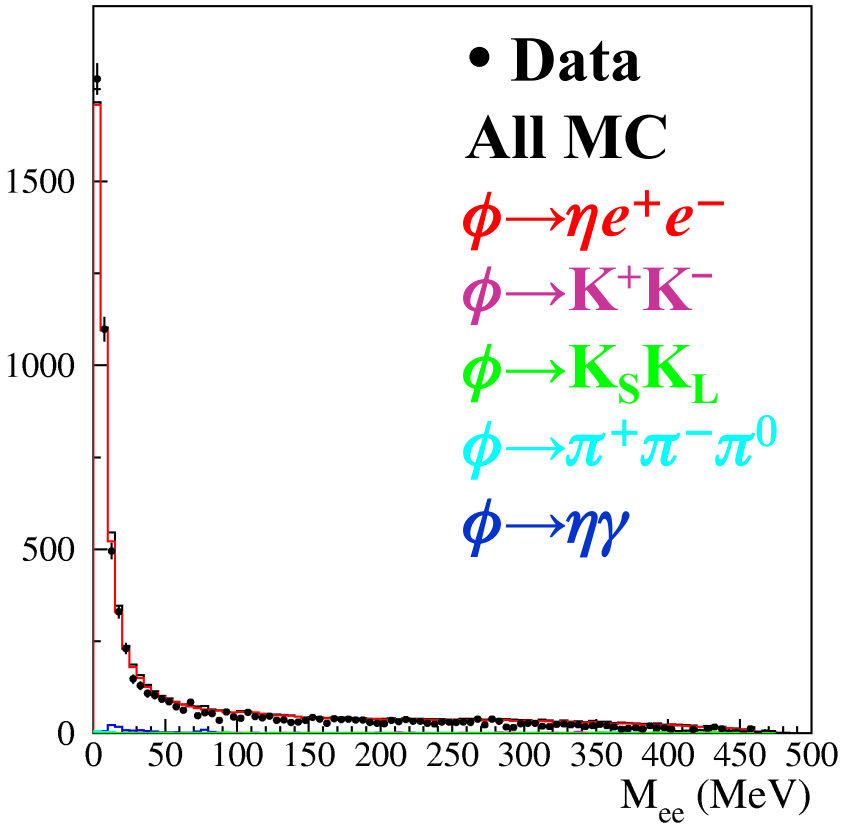


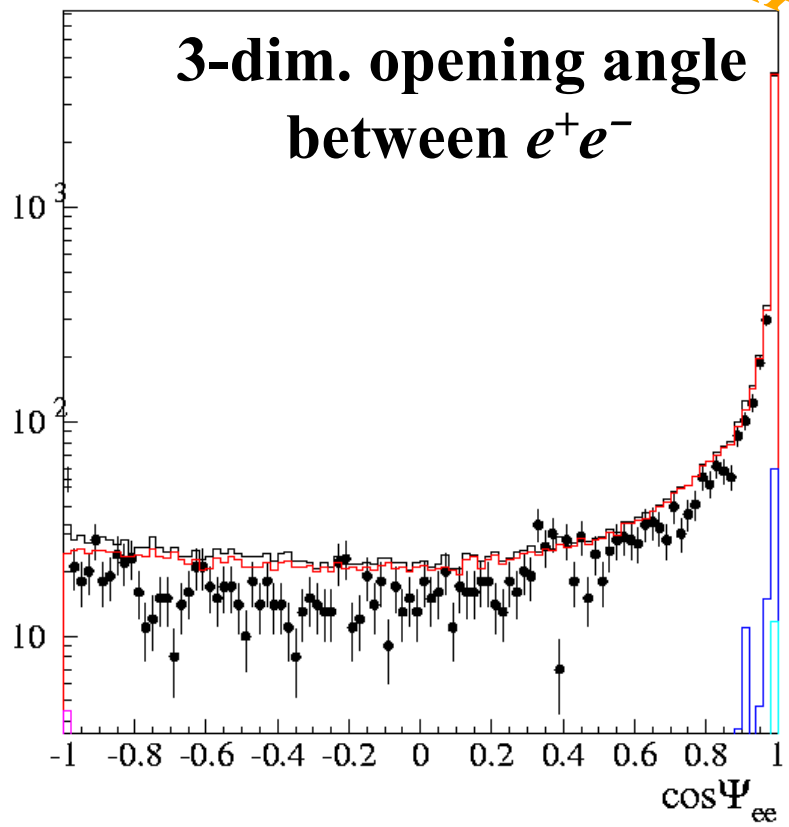


3-dim. opening angle between e^+e^-

Data-MC comparison

PRELIMINARY





- ~7000 $\phi\to\eta e^+e^-$ 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)
  - Extract directly from our data!

[PLB504(2001) 275]

Fit to the M_{ee} shape

PRELIMINARY

Decay parametrization from Landsberg85 + $F(q^2)$ approximation from Achasov, Kozhevnikov, Sov. J. Nucl. Phys. 55 (1992) 449

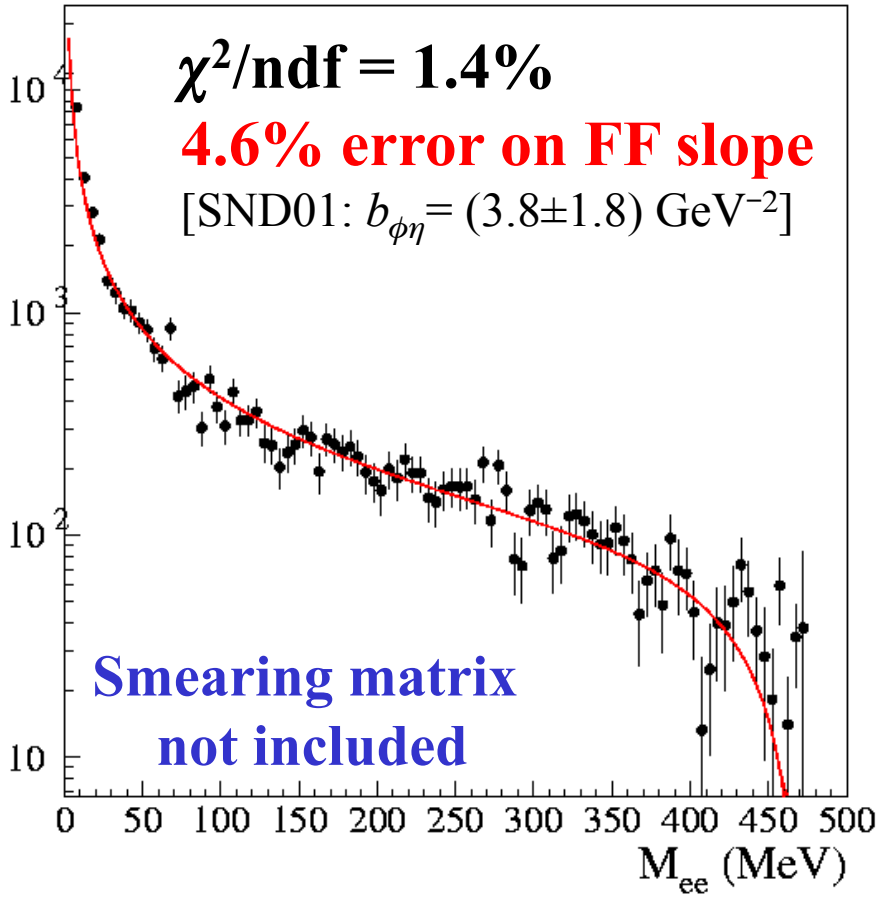
$$\frac{d}{dq^2}\frac{\Gamma(\phi\to\eta e^+e^-)}{\Gamma(\phi\to\eta\gamma)} = \frac{\alpha}{3\pi}\frac{|F_{\phi\eta}(q^2)|^2}{q^2}\sqrt{1-\frac{4m^2}{q^2}}\times$$

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

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

FF slope:

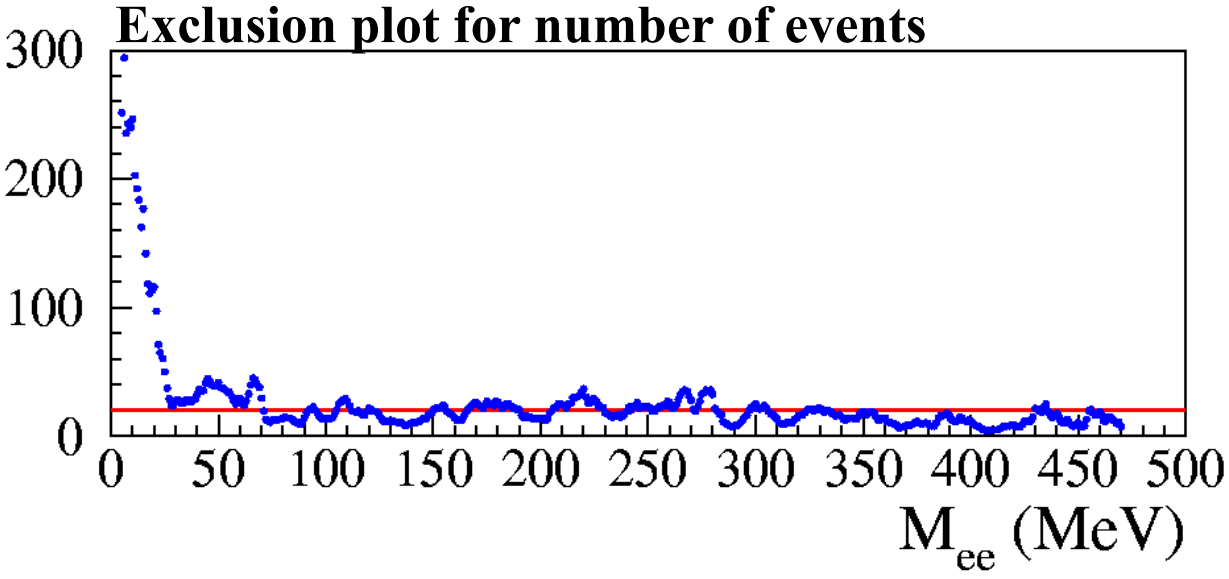
$$\begin{cases} b = dF/dq^2|_{q^2=0} \\ b_{\phi\eta} = \Lambda_{\phi\eta}^{-2} \approx 1/m_\phi^2 \approx 1\ \text{GeV}^{-2} \end{cases}$$



Exclusion plot for $\phi \to \eta U$, $\eta \to \pi^+\pi^-\pi^0$

PRELIMINARY

- $\phi \to \eta U$ MC sample [M.Reece and L.T.Wang, JHEP 0907:051 (2009)] divided in sub-samples of 1 MeV in M_{ee}(true)
- Expected background ($\phi \to \eta e^+e^-$) shape from our fit to M_{ee} distribution
- For each M_{ee}(true) bin, signal hypothesis excluded @ 95% C.L. using CL_S technique
- Consistent results with Bayesian approach



Systematics not yet included

→ **~ 20**

for 25<M_{ee}<425 MeV

Exclusion plot for ε

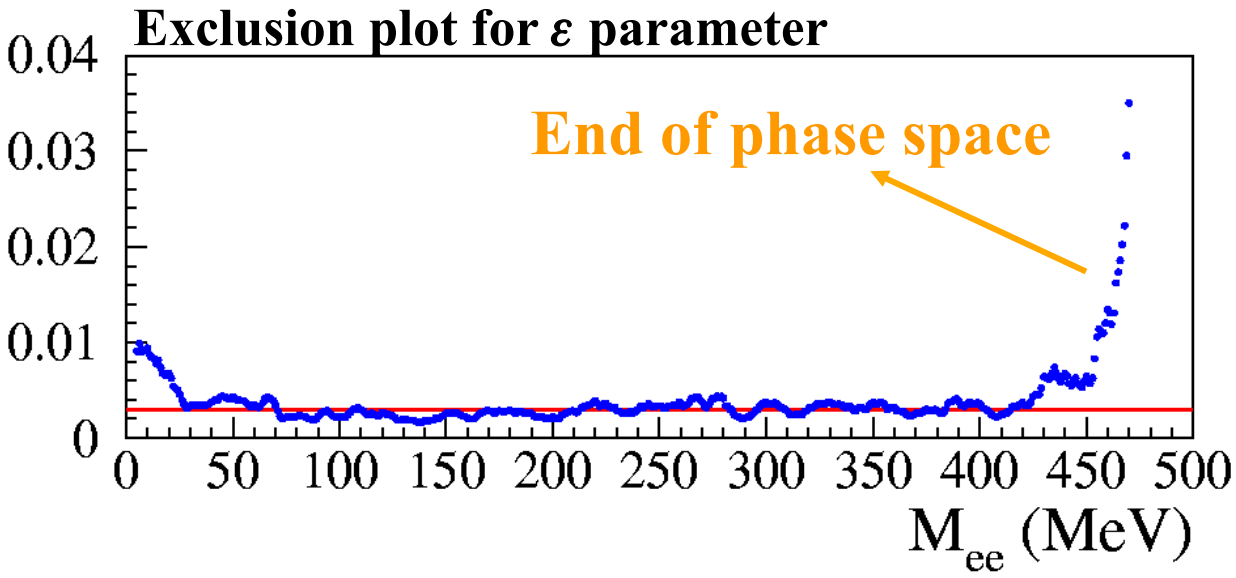
PRELIMINARY

From number of events to ε using:

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

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

$$N(\varphi \to \eta U; U \to e^+e^-; \eta \to \pi^+\pi^-\pi^0) = N(\varphi \to \eta U) \times \left[1 + \frac{\Gamma(U \to \mu^+\mu^-)}{\Gamma(U \to e^+e^-)}\right]^{-1} \times BR(\eta \to \pi^+\pi^-\pi^0)$$



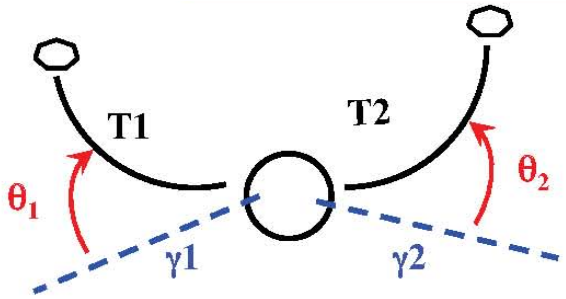
Systematics not yet included

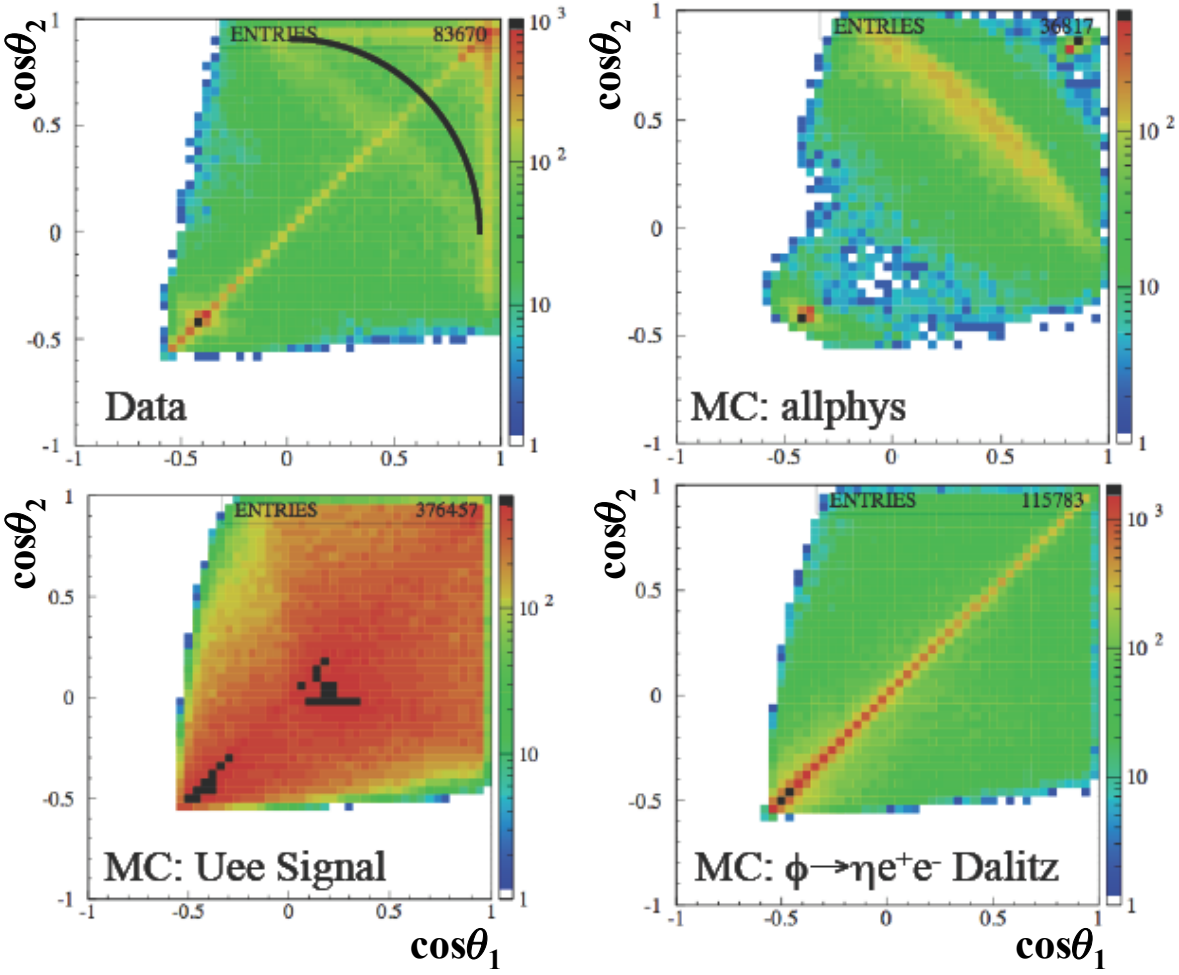
→ **~ 3×10^{-3}**

for 25<M$_{ee}$<425 MeV

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

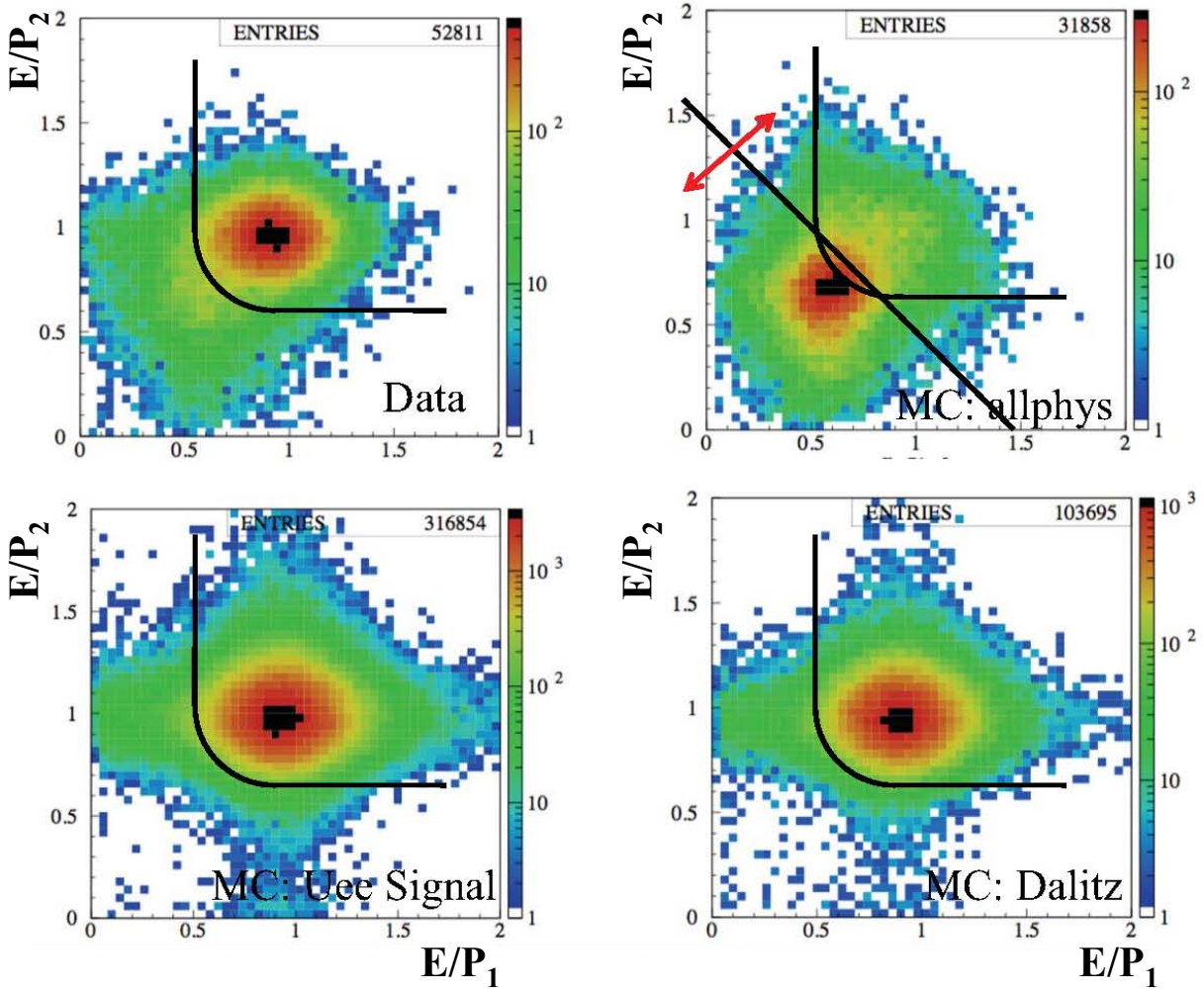




Most severe background from double radiative Bhabha events is strongly reduced by looking at the angle between the charged tracks and the photons

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

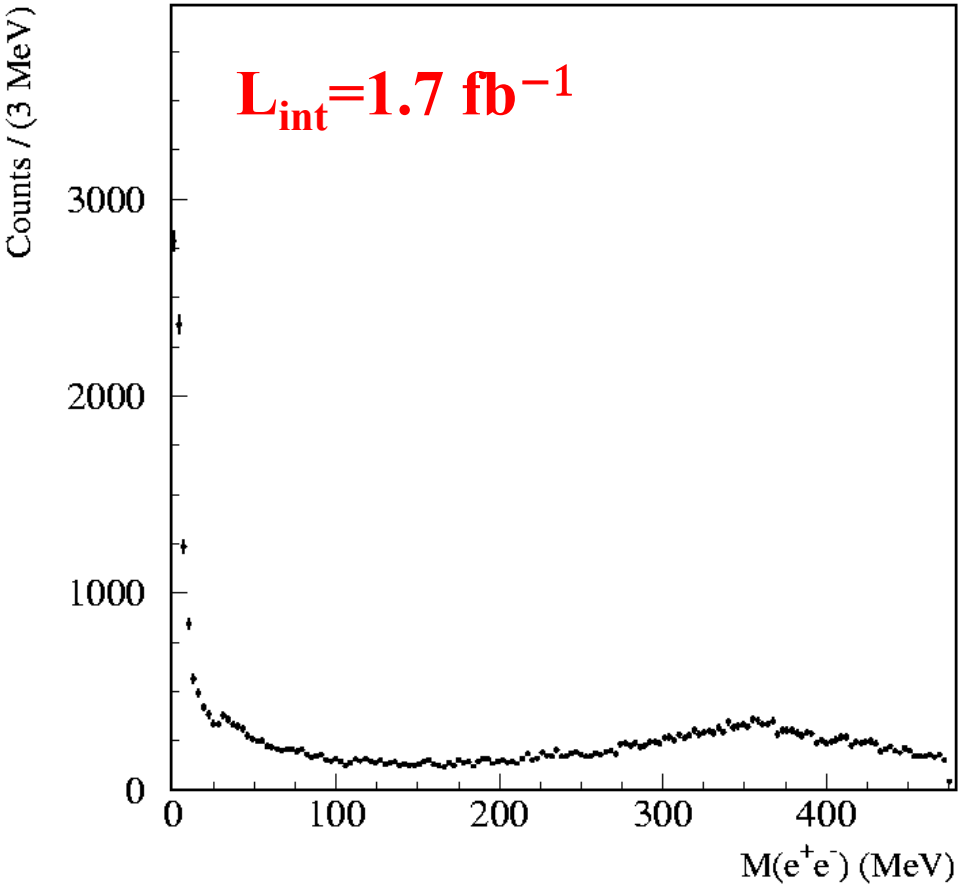
Residual non-Bhabha background can be rejected by using further electron identification based on E/P for both tracks



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

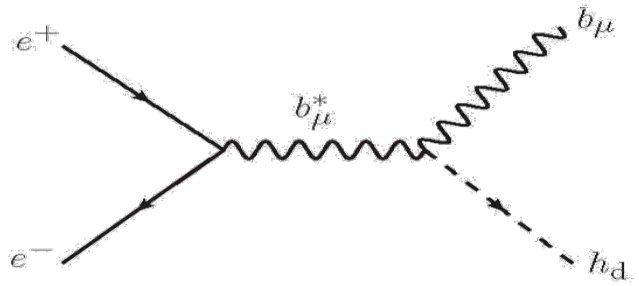
PRELIMINARY

M_{ee} spectrum after all cuts:



- Evidence for $\phi \to \eta e^+ e^-$, $\eta \to \gamma\gamma$, Dalitz decay in the low M_{ee} region
- Still some residual background contamination at high M_{ee} values

Search for U-boson @ KLOE: higgs'-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*

→ **Studied @ KLOE**

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

$\sigma_{hU} \approx 20$ fb

$\tau_h > 10\,\mu s$

increasing with decreasing ε

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

✓ U→e^+e^- not selected by our Event Classification algorithms

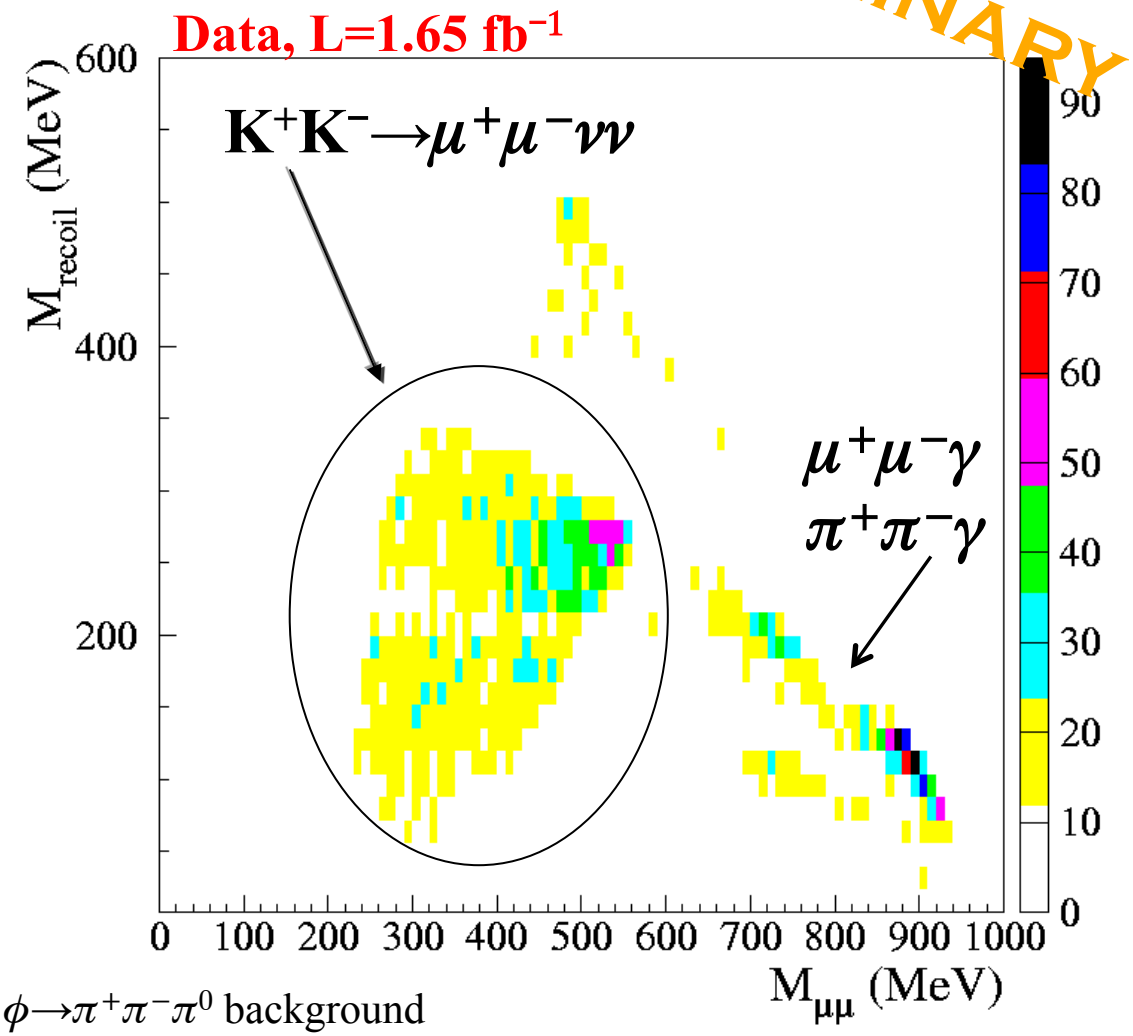
✓ **U→$\mu^+\mu^-$** selected with high efficiency for m_h<300 MeV → **Selected channel**

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

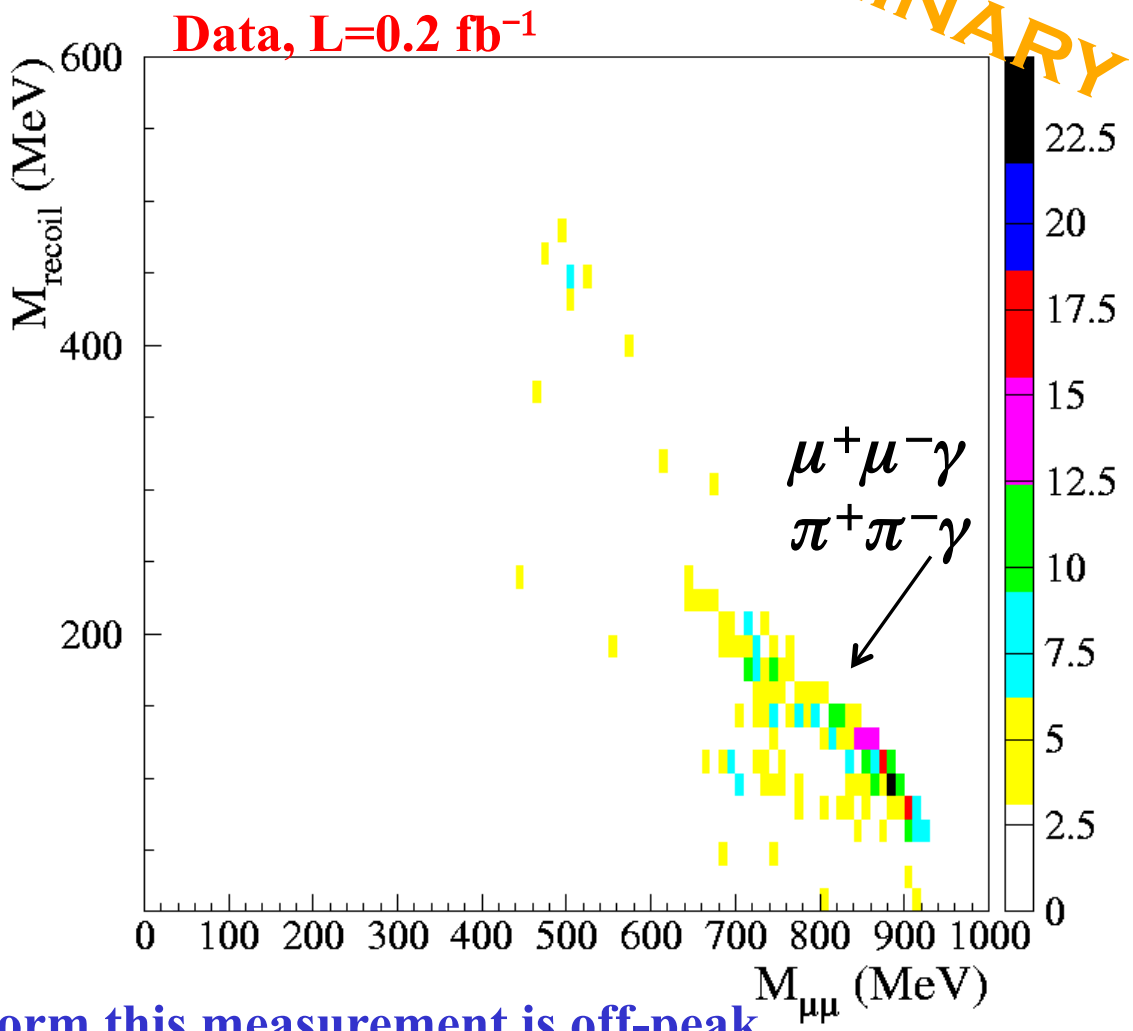
$e^+e^- \to hU$, $U \to \mu^+\mu^-$ for off-peak data

PRELIMINARY

Same analysis performed on data taken @ $\sqrt{s}$=1 GeV (200 pb^{-1})

Much cleaner environment: no $\phi \to K^+K^-/\pi^+\pi^-\pi^0$ backgrounds

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



- ✓ **The good place where to perform this measurement is off-peak, but L~O(fb^{-1}) needed**
- ✓ **Possibility for a long KLOE-2 run at $\sqrt{s}$=1 GeV under discussion**

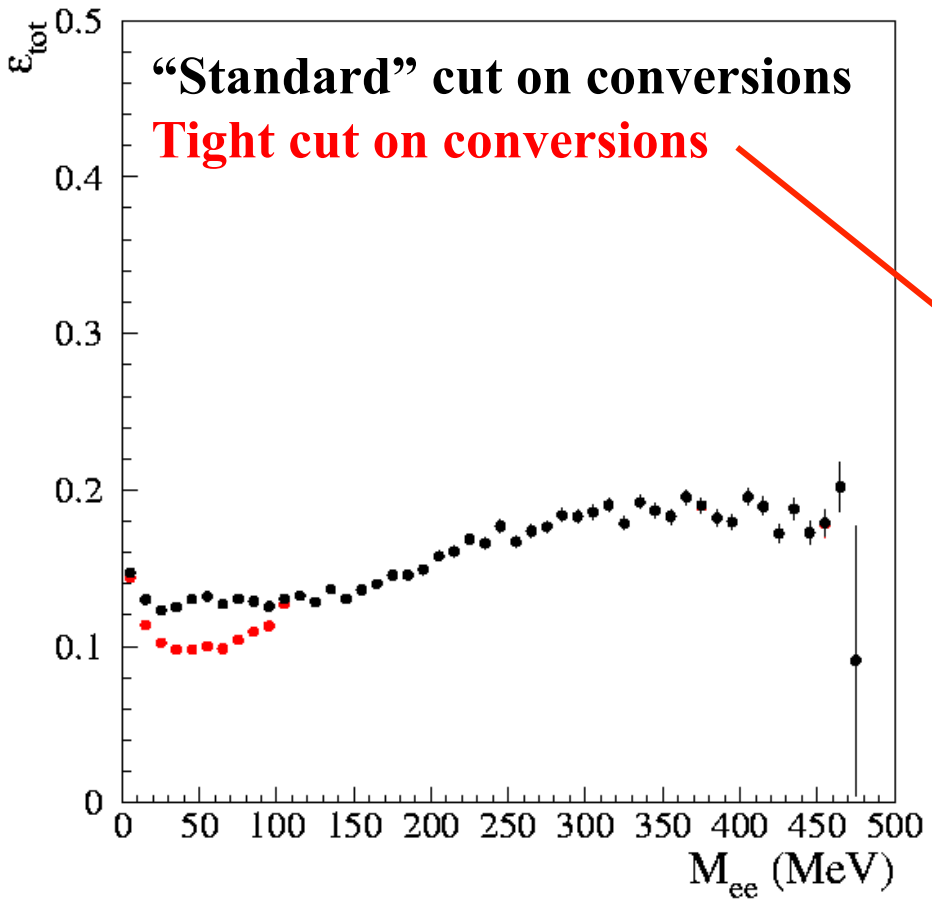
Summary/Outlook

- First measurements for U boson searches started at KLOE

- **$\phi \to \eta U$, $U \to e^+e^-$**
  - Preliminary result with 700 pb^{-1}, $\eta \to \pi^+\pi^-\pi^0$ channel:
    $\varepsilon < 3\times10^{-3}$ @ 95% C.L. for $25<M_{ee}<425$ MeV
    Systematics not yet included. Another factor 2.5 of data available
  - The 20 fb^{-1} expected @ KLOE-2 will allow to reach 1.3×10^{-3}
  - $\eta \to \gamma\gamma$ channel under study to increase statistics

- **Higgs'-strahlung: $e^+e^- \to Uh' \to \mu^+\mu^-$+"invisible"**
  - Hot region with difficult $\phi \to K^+K^-$ background. We are studying how to face it.
  - KLOE-2 plans: possibility for running at 1 GeV?
    dedicated streaming for $U \to e^+e^-$ channel

$\phi \to \eta e^+ e^-$: analysis efficiency *vs* M_{ee}



Cut	ε_{rel}	ε_{tot}
4 trks + 2 clu	26.36%	26.36%
$M_{\gamma\gamma}$	96.14%	25.35%
Mmiss(ee)	66.53%	16.86%
$M_{\pi\pi\pi}$	98.04%	16.53%
Conv. cut	92.58%	15.31%
ToF cut	86.59%	13.25%

Total analysis efficiency with "standard" cut on conversions: ε=14.25%

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 i^{th} 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]

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

$$CL_S = CL_{S+B} / CL_B$$

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 @ 95% C.L. when $CL_S<0.05$**

U.L. evaluation: Bayesian approach

- $\phi \to \eta$U MC sample divided in sub-samples of 1 MeV in M_{ee}(true)
- For each M_{ee}(true) bin, U.L. evaluated with Bayesian approach with:

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

Sum over five rec. bins around M_{ee}(true)

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

Prior p.d.f.: $\pi(S) = \begin{cases} 0[S < 0] \\ 1[S \geq 0] \end{cases}$

Upper limit S_{up} @ C.L. 1-α from:

$$1 - \alpha = \frac{\int_{-\infty}^{S_{up}} L(S) \times \pi(S) dS}{\int_{-\infty}^{+\infty} L(S) \times \pi(S) dS}$$

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%

$m_{\mu\mu}$